Hybrid, Electric & Fuel-Cell Vehicles

Jack Erjavec

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Hybrid, Electric & Fuel-Cell Vehicles,
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Jack Erjavec

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Preface

The U.S. government has set new standards that require new cars and light trucks to average the equivalent of 54.5 mpg in 2025 while reducing greenhouse gas emissions to 163 grams per mile. To achieve this, auto manufacturers are investing great amounts of time and money looking for practical ways to meet the new standards. Much of the research has been focused on battery-operated electric vehicles, hybrid electric vehicles, and fuel cell electric vehicles. These are the main subjects of this book.

Although refinements to internal combustion engines have made them more efficient, they will never be developed to the point where they emit zero emissions. Nor can an internal combustion engine ever be 100 percent energy efficient. To meet the new government standards, the industry cannot rely on refinements to an engine. Attention must also be spent on designing special-purpose all-electric vehicles and combinations of engine and electric. Although the total elimination of the internal combustion engine would meet the new standards, this is not yet practical.

Many different alternative fuels have been tested and used in conventional engines to reduce our dependency on fossil fuels and to reduce emission levels. All of these show promise and are briefly discussed in this book. However, the only technology that promises to drastically reduce emissions and provide excellent fuel economy is the electric drive vehicle.

A few manufacturers are currently offering all-electric, battery-operated vehicles. These will be discussed, as will a brief history of electric vehicles. Much of what was discovered in the past about electric vehicles is being used today in hybrid vehicles and will also be used in fuel cell vehicles.

Electric drive vehicles are powered by high-voltage systems. With the high voltages also come serious safety issues. The voltages of electric drive vehicles are high enough to kill anyone who does not respect them and does not carefully adhere to the precautions given by the manufacturers of these vehicles. If this book has one dominant theme, it is "respect the voltage!" Throughout this book, regardless of the topic, **CAUTIONS, NOTES,** and **WARNINGS** are given to remind everyone who reads this book to be very careful while doing anything on an electric drive vehicle.

Many assume that because some of the vehicle's systems are just like what has been used for years in conventional vehicles, they can just maintain and service electric drive vehicles unimpeded. This is not true. To prevent great personal injury and/or damage to the vehicle, you must do what you can to work safely on these vehicles.

Too often, technicians and others take some risks to complete a job quickly. On electric drive vehicles, moving too quickly or proceeding without checking a few things can end a career or a life quickly. These messages are not meant to scare anyone away from working on electric vehicles; rather they are intended to make one aware of the dangers. Knowing the dangers, I hope that everyone will enjoy the technology and the thrill of working with it.

Electric drive technologies are advancing very quickly. So much has changed between the time I started writing this and the time I thought I was finished. In fact, when I thought it was completed, and I reviewed what I had written, I saw some vehicles I did not write about that were running on the roads. Unfortunately, this will be the case for quite some time, so I decided to stop. If I waited to stop until the technology cooled down a bit, this book would not have been available for another 10 years or so. But I did try to cover the basics to allow you to understand those systems that cannot be covered in this book.

The topics are presented in a progression, from yesterday's technology to tomorrow's. The first chapter focuses on the basics. The various types of electric drive vehicles are defined and described. There is also a discussion of various alternative fuels that can be used in an internal combustion engine. This discussion may seem out of place for a book about electric vehicles, but these fuels can be used in hybrid vehicles and as sources of hydrogen for fuel cell vehicles. There is also a quick look at the history of electric drive vehicles.

Chapters 2 through **4** provide the basics for the rest of the book. Basic electricity, as it applies to these

vehicles, is covered from a theoretical and practical standpoint. The basics of electric motors and batteries are also covered, in separate chapters. Regardless of the type of electric drive vehicle being considered, the two most important items are the motor and battery. Many different designs of both are covered in these chapters because many designs have been and can be used in electric vehicles.

Chapter 5 covers pure electric vehicles. These battery-operated vehicles are currently available from different manufacturers, and more will be available in the future.

Since hybrid vehicles are quite popular today, there are five chapters, **Chapters 6** through **10,** dedicated to the subject. All hybrid vehicles available at the time of this writing are described and discussed. These are grouped by system and operational commonalities. **Chapter 10** addresses general service to these vehicles. That chapter does not go into extreme detail because the manufacturers do not want technicians going deeply into their systems without special training. However, because of the high voltages found in these vehicles, many common nonhybrid service procedures need to be modified to work safely. Many of these new procedures are presented in the chapter.

Chapter 11 is a look into the future. It contains a look at fuel cell vehicles and other potential technologies that may affect the operation of an automobile in the future. Manufacturers have built and tested many fuel cell vehicles, and this chapter looks at what worked and what did not in many of these vehicles.

I sincerely hope the information in this book opens doors of thought and rewards for you. The electric drive technology is different, rewarding, and exciting.

Jack Erjavec

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Contents

CHAPTER 1 An Introduction to Electric Vehicles

Learning Objectives

After reading and studying this chapter, you should be able to:

- Describe the various types of vehicles used for personal transportation.
- Describe the differences between vehicles that are powered by electricity and those powered by an internal combustion engine.
- Explain the basic advantages of having electric drive vehicles available to the public.
- Explain the advantages and disadvantages of using the commonly available alternative fuels in an internal combustion engine.
- Describe the basic components of all electric drive vehicles.
- Explain what regenerative braking does.
- Describe what a battery electric vehicle is.
- Describe what a hybrid electric vehicle is.
- Explain the basic operation of a fuel cell.
- Describe what a fuel cell electric vehicle is.
- Discuss the evolution of electric drive vehicles.

Key Terms

alternative fuels
compressed natural gas
energy density
ethanol
flexible-fuel vehicles
fuel cells
hybrid vehicles
liquefied natural gas
methanol
natural gas
parallel HEV
photovoltaic solar cells
propane
regenerative braking
series HEV

INTRODUCTION

Imagine a world without motorized transportation! Nearly everything we do depends on some sort of powered vehicle. This is obvious when we think of going somewhere that is too far to walk or when there things we use in our daily lives. All of these products were delivered somewhere so we could purchase them. Even if we go to the source to purchase them, we need a means to get to the source. Most motorized transportation today depends on burning fossil fuel. This book

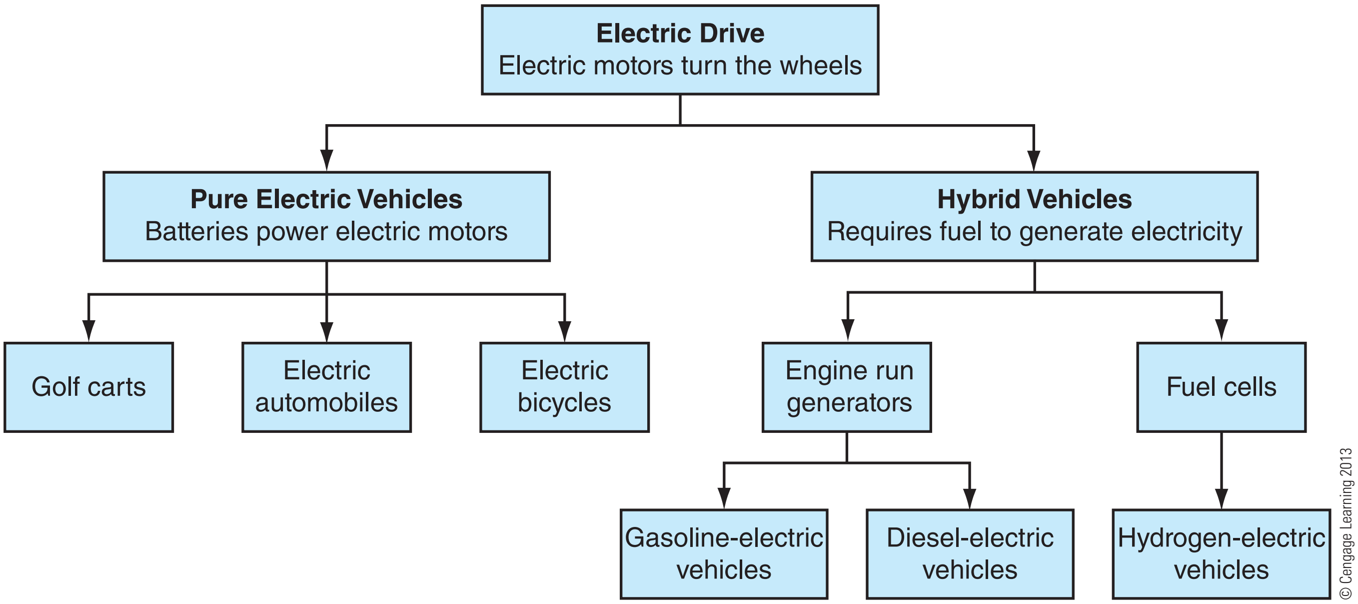

Figure 1-1 The common categories of electric drive vehicles.

explores the actual costs of this mode of transportation as well as for other alternative modes and fuel sources. Because this book is about electric vehicles (EVs), it will stress that electric vehicles offer a legitimate alternative to the internal combustion engine (ICE). In an attempt to categorize vehicles that depend on electricity for mobility, we will initially group the various designs as having electric drive **(Figure 1-1).**

Electric drive means that electricity is used to move the wheels of a vehicle. Electric drive is used on many different types of vehicles, including golf carts, bicycles, trains, forklifts, and automobiles. Automobiles with pure electric drive have electric motors that are powered only by batteries **(Figure 1-2).** These batteries are recharged by an external source of electricity, such as a wall plug.

Hybrid vehicles are automobiles with an electric motor and an ICE. An engine-driven generator and the energy captured during braking recharges the high-voltage batteries used in a hybrid vehicle. Another type of electric vehicle is the fuel cell electric vehicle. Although only experimental at this time, there is much promise for fuel cell electric vehicles. These vehicles are powered solely by electric motors, but the energy for the motors is produced by **fuel cells**, which use hydrogen to produce the electricity.

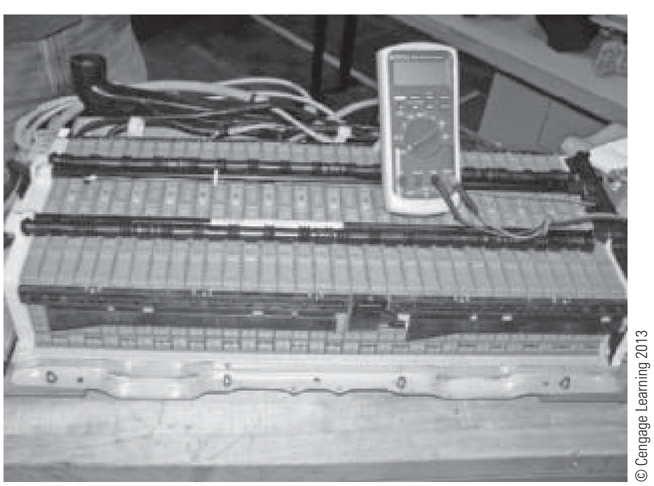

Figure 1-2 A battery pack for an electric drive vehicle is comprised of many individual battery cells.

WHY ELECTRIC DRIVE?

There is an automatic mental association of automobiles and internal combustion engines. For more than 100 years, drivers only knew gas-powered vehicles. When the cost of fuel is high, consumers want vehicles with better gasoline mileage. At times of lower fuel prices, those same consumers think little about the cost and continue to pump in gasoline and drive. Some, however, look at the true costs of gas-powered vehicles and know there is a better way.

The cost of using gasoline in our automobiles is not

factors, or costs, that need to be considered: our environment, our dependence on foreign oil supplies, and the depletion of future oil supplies. Any reduction in the use of fossil fuels will have benefits for our generation and generations to come. Electric drive vehicles can have an impact on our fossil fuel dependence, which is

why they are again being developed and produced. Before looking at the advantages of electric drive, let us first look at some simple facts:

- The number of household vehicles in the United States is growing and nearly tripled from 1969 to 2001. Last year, nearly 12 million new cars and light trucks were sold in the United States. In North America (including the United States, Canada, and Mexico), nearly 20 million new cars and light trucks were sold. These numbers do not include the automobiles already on the road that were not bought that year. There are well over 225 million vehicles on the road.
- It is estimated that the total miles covered by those automobiles, in one year, is well over 2 trillion. To put this in perspective, let us assume the average fuel mileage of all those vehicles is 20 miles per gallon (mpg). This means over 100 billion gallons of oil are burned by our automobiles each year.
- By 2020, oil consumption is expected to grow by nearly 40 percent and our dependence on foreign oil sources is projected to rise to more than 60 percent.
- A 10 percent reduction in fossil fuel consumption by cars and light trucks, achieved by the use of alternative fuels, electric drive, or improving fuel mileage, would result in using 24 million fewer gallons of oil each day.
- Americans spend close to $100,000 per minute to buy foreign oil, and oil purchases are a major contributor to the national trade deficit.
- Cars and light trucks are some of the largest sources of urban air pollution **(Figure 1-3).**
- Automobiles and gasoline are major contributors to environmental damage. Not only do automobiles emit pollutants **(Figure 1-4),** but the extraction, production, and marketing of gasoline also leads to air pollution, water pollution, and oil spills.
- Because of the heavy reliance on fossil fuels, the transportation industry is a major source of carbon dioxide (CO_2) and other heat-trapping gases that cause global warming. Note that burning 1 gallon of gasoline results in about 20 pounds

Vehicles powered by electric motors have low emissions, consume much less fuel or energy, and lessen our dependence on fossil fuels. The degree to which these are true depends on how the electricity for the vehicle is generated.

Figure 1-3 Cars and light trucks are among the largest sources of urban air pollution.

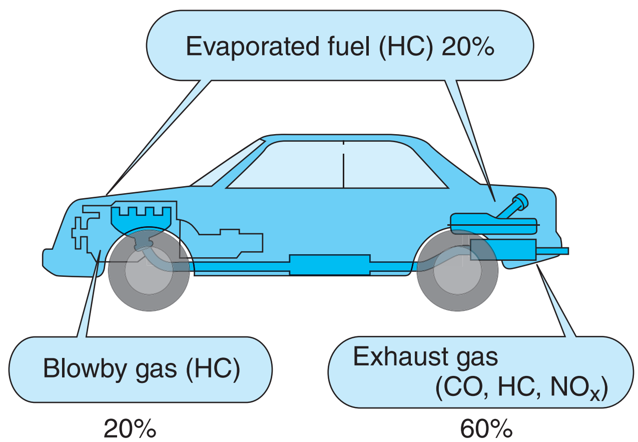

Figure 1-4 Sources of air pollution from an automobile.

ALTERNATIVE FUELS

It is important to know that there are ways to reduce our dependence on foreign oil, other than using electric drive. Much research has been and is being conducted on the use of **alternative fuels** in ICEs. Many of these fuels are also being considered as the fuel of choice for fuel cell electric vehicles. By using alternative fuels, we not only reduce our reliance on oil but we also reduce emissions and the effects an automobile's exhaust has on global warming.

Propane/LPG Vehicles

Propane, also referred to as liquefied petroleum gas (LPG), is the third most commonly used fuel for ICEs.

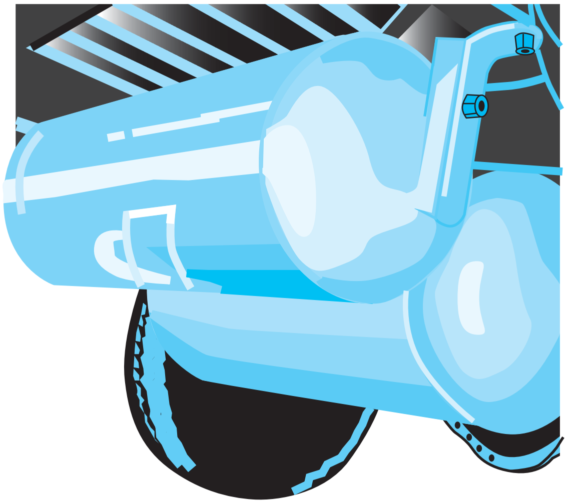

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Figure 1-5 LPG must be stored in special tanks or cylinders.

The most common are, obviously, gasoline and diesel fuel. Propane is used by many fleets around the world in taxis, police cars, school buses, and trucks.

Propane is a clean-burning fuel that offers a driving range closer to that of gasoline than other alternative fuels. Propane is a by-product of natural gas production and the petroleum refining process. In its natural state, propane is a gas. LPG vehicles have special tanks or cylinders to store the gas **(Figure 1-5).** However, the gas must be stored at about 200 pounds per square inch. Under this pressure, the gas turns into a liquid and is stored as a liquid. When the liquid propane is drawn from the tank, it expands back into a gas before it is burned in the engine.

Ethanol/Methanol Vehicles

Alcohol fuel was used to power Ford's Model T and has been used in a variety of applications since. However, its use in Model Ts was abruptly ended with the prohibition law in the 1920s. This law prevented the use and distribution of alcohol. Two types of alcohol have been used in ICEs: methyl alcohol (**methanol**) and ethyl alcohol (**ethanol**), the alcohol used in the Model T **(Figure 1-6).** These fuels are similar but have different chemical compositions.

Ethanol (CH_3CH_2OH), commonly called grain alcohol,

waste. Ethanol is a renewable fuel that can be made from nearly anything that contains carbon **(Figure 1-7).** Ethanol can be used as a high-octane fuel in vehicles and is often mixed with gasoline to boost its oxygen content. The latter results in what is referred to as oxygenated fuel. The fuel used for NASCAR events is now ethanol based.

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Figure 1-6 Ford's Model T was designed to use ethyl alcohol (ethanol).

Courtesy of Missouri Corn Growers Association

Figure 1-7 An ethanol pump.

Methanol (CH_3OH) is a clean-burning fuel that is most often made from natural gas, but it can also be produced from coal and biomass. Because North America has an abundance of these materials, the use of methanol can decrease the dependence on foreign oils. Methanol use as a fuel has declined through the years, but it may soon be used for fuel cell vehicles. It has

since 1965. However, beginning in 2007, Indy Racing League (IRL) cars switched to pure ethanol for all races. Today, for general consumer use, these alcohols are mixed with 15 percent gasoline, creating M85 and E85. The small amount of gasoline improves the cold-starting ability of the alcohols.

Flexible-fuel vehicles (FFVs) can use ethanol and/or gasoline, or methanol and/or gasoline. The alcohol fuel and gasoline are stored in the same tank, which enables the use of alcohol when it is available, or regular gasoline when it is not, or a combination of the two.

Natural Gas Vehicles

Natural gas, **compressed natural gas** (CNG), and **liquefied natural gas** (LNG) are very clean-burning fuels. There is an abundant supply of natural gas, and it is less expensive than gasoline. Both of these factors make natural gas an attractive alternative fuel, especially to companies with fleets of vehicles. In fact, most of the natural gas vehicles have been sold to fleets. Typically, CNG **(Figure 1-8)** is used in light- and medium-duty vehicles, whereas LNG is used in transit buses, train locomotives, and long-haul semi-trucks.

CNG must be safely stored in cylinders at pressures of 2,400, 3,000, or 3,600 pounds per square inch, which is the biggest disadvantage of using CNG as a fuel. The space occupied by these cylinders takes away luggage and, sometimes, passenger space. The size of storage tanks must be limited for practical reasons; therefore CNG vehicles have a shorter driving range than comparable gasoline vehicles. Bi-fuel vehicles are equipped to store both CNG and gasoline and will run on either.

Natural gas turns into a liquid when it is cooled to −263.2°F (–164°C). Because it is a liquid, a supply of LNG consumes less space in the vehicle than does CNG. Therefore, the driving range of a LNG vehicle is longer than a comparable CNG vehicle. However, the fuel must be dispensed and stored at extremely cold temperatures, which requires refrigeration units that also consume space and makes LNG impractical for personal use.

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Figure 1-8 A compressed natural gas filling station.

TABLE 1-1: ENERGY DENSITY OF COMMON SOURCES

Material	Approximate Energy per Kilogram
Uranium 238	20 terajoules
Hydrogen	143 megajoules
Natural gas	53.6 megajoules
LPG propane	49.6 megajoules
Gasoline	47.2 megajoules
Diesel fuel	46.2 megajoules
Gasohol E10	43.54 megajoules
Biodiesel	42.20 megajoules
Gasohol E85	33.1 megajoules
Coal	32.5 megajoules
Methanol	19.7 megajoules
Supercapacitor	100 kilojoules
Lead-acid battery	100 kilojoules
Capacitor	360 joules

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Energy Density

Each of these alternative fuels can be viewed in terms of **energy density**. This is the amount of energy provided by a standard weight of each. Energy density is typically rated as joules per kilogram. A joule can be defined as the energy required to produce one watt of power for one second. Refer to **Table 1-1** to review the energy densities of common energy sources.

THE BASICS OF ELECTRIC VEHICLES

Electric vehicles are commonly used in manufacturing, shipping, and other industrial plants, where the

illness or discomfort to the workers in the area. These vehicles are also used on golf courses, where the quiet operation adds to the relaxing atmosphere. EVs are also commonly used in the downtown areas of large cities and large campuses where peace, quiet, and fresh air are a priority.

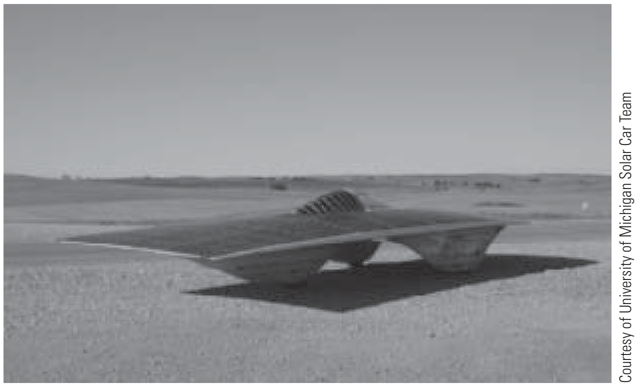

Figure 1-9 This is the University of Michigan Solar Car Team's race car. It is powered by electric motors that receive electrical energy from the sun. This car won the North American Solar Challenge in 2005. To do so, they traveled nearly 2,500 miles with only the sun as an energy source.

EVs are powered by one or more electric motors that are "fueled" by electricity. The source of the electricity may be rechargeable batteries, fuel cells, or **photovoltaic (PV) solar cells** that convert the sun's energy into electricity **(Figure 1-9).** The drivetrain of an electric drive vehicle is much more efficient than the drivetrain in an ICE vehicle. EVs also produce zero or near-zero tailpipe emissions.

When the electricity and fuels used in electric drive vehicles are produced from renewable energy sources (such as wind or hydroelectric plants), these vehicles provide additional reductions in fossil fuel energy consumption and emissions. An electric drive vehicle's source of power is typically stored in and dispensed from batteries **(Figure 1-10).**

Regenerative Braking

A law of nature that is critical to an understanding of anything that moves or does work is that energy cannot be created or destroyed. It can only be moved from one point to another, or changed from one form of energy to another. This is a critical law to consider when trying to understand the efficiencies of an electric drive vehicle.

The internal combustion engine is a much loved but very inefficient machine (meaning that much of the energy going into it is wasted). Although there are some energy losses with electric drive, the amount is very low if the vehicle is designed properly.

One of the keys to the overall efficiency of an electric drive vehicle is called **regenerative braking**. Regenerative braking is the process by which a vehicle's kinetic energy can be captured while it is decelerating and braking. Whenever the driver applies the brakes in a conventional car, friction converts the vehicle's kinetic energy into heat. That heat is useless to the car and becomes lost energy.

The operation of most electric drive vehicles is based on batteries, electric motors, and electric generators **(Figure 1-11).** Batteries supply the power to operate the motors. The motors take that electrical power and change it to mechanical energy, which rotates the wheels and allows the vehicle to move. A generator takes the kinetic energy, or the energy of something in motion, and changes it to electrical energy to charge the batteries.

When the generator is operating during regenerative braking, it helps slow down the vehicle. The rotation of the wheels turns the generator, which generates a voltage to charge the batteries. Because of

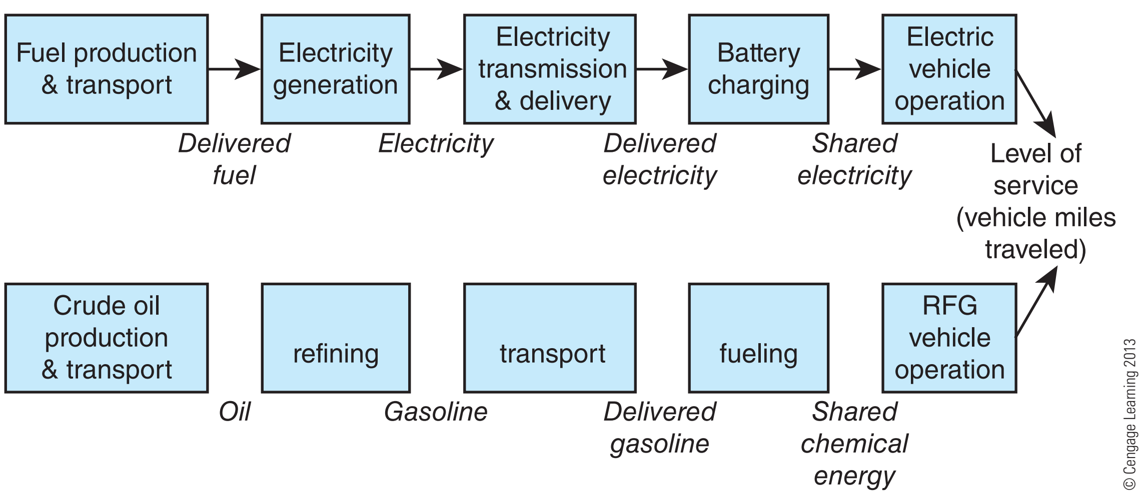

Figure 1-10 Comparison of the energy cycles for an electric drive vehicle and a gasoline vehicle.

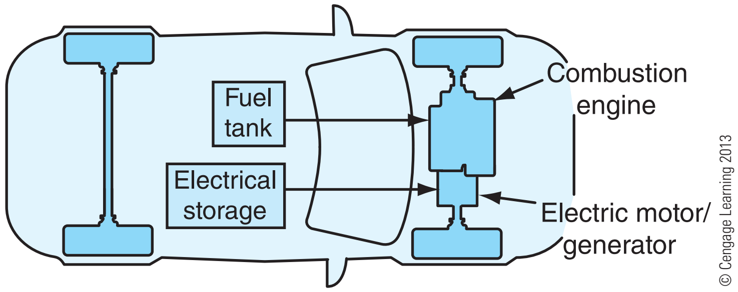

Figure 1-11 The motor/generators drive the wheels and absorb the vehicle's kinetic energy during slow-down and braking.

the magnetic forces within the generator, the vehicle slows down. A conventional brake system is used in conjunction with the regenerative brake system to bring the vehicle to a safe stop.

Regenerative braking can recover about 30 percent of the energy normally lost as heat when a vehicle is slowing down or braking.

BATTERY-OPERATED ELECTRIC VEHICLES

A battery-operated electric vehicle, sometimes referred to as a battery-electric vehicle (BEV), uses one or more electric motors to turn its drive wheels **(Figure 1-12).** The electricity for the motors is stored in a battery that must be recharged from an external electrical power source. This technology is used for passenger cars, forklifts, urban buses, airport ground support equipment, and off-the-road industrial equipment. BEVs are zero-emission vehicles because they do not directly pollute the air. The only pollution associated with them is the result of creating the electricity to charge their batteries. Even when those emissions are included, BEVs are significantly cleaner than the cleanest ICE vehicle.

Normally, a battery-operated vehicle drives the same as any other, but it is quiet and carries no fossil fuel. However, rather than filling a tank with fuel, you need to recharge the batteries. The batteries are recharged by plugging them into a recharging outlet at home **(Figure 1-13)** or at other locations. The recharging time varies with the type of charger, the size and type of battery, and other factors. Normal recharge time is four to eight hours.

After several years of BEVs not being available, manufacturers are now offering or planning to offer them to the public. Sold as commuter cars, BEVs are not practical for everyone because of their limited range and relatively high cost. Most have less than a 100-mile range before the batteries need to be recharged. Also, many find it hard to justify the higher purchase or lease costs, in spite of the advantages.

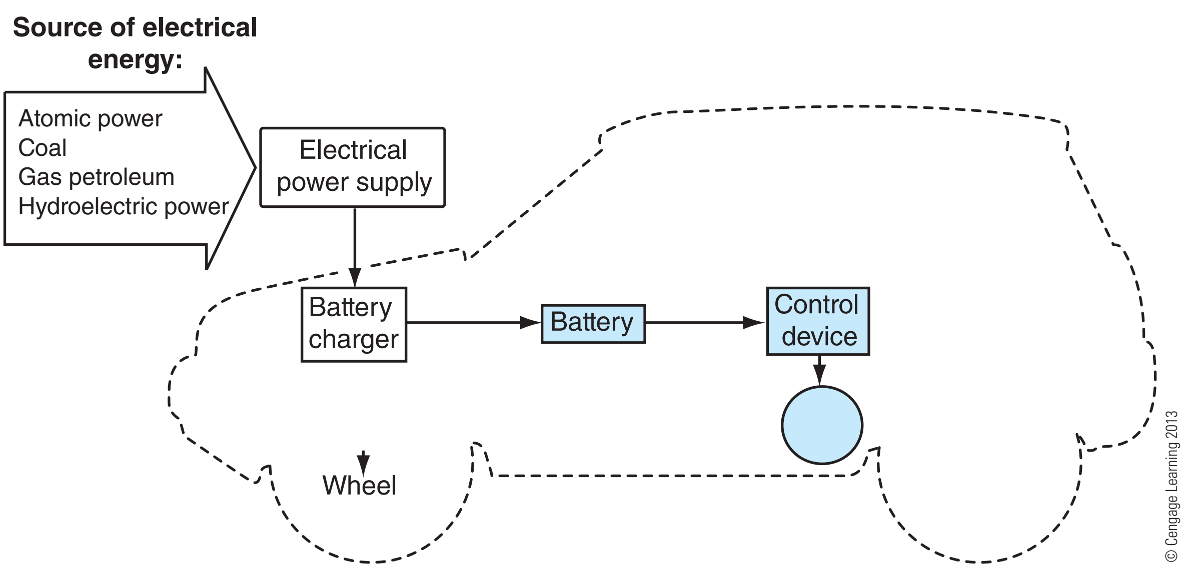

Figure 1-12 A battery-operated electric vehicle uses one or more electric motors to turn its wheels; the energy for the motor is stored in a battery.

Figure 1-13 The batteries of an EV need to be charged by an external source.

Whether battery-operated electric vehicles will have good sales numbers in the future depends on the development of new batteries. To be practical, electric vehicles need to have much longer driving ranges between recharges and must be able to sustain highway speeds for great distances. Although BEVs were not accepted in the past, many lessons were learned by building them. Manufacturers can use those lessons to again build BEVs and use that same technology to build hybrid electric and fuel cell electric vehicles.

HYBRID ELECTRIC VEHICLES

A hybrid electric vehicle (HEV) has more than one available power source to propel the vehicle—it uses one or more electric motors and an ICE. Depending on the design of the system, the ICE may propel the vehicle by itself, act together with the electric motor to propel the vehicle, or drive a generator to charge the vehicle's batteries. The electric motor may propel the vehicle by itself or assist the ICE while it is propelling the vehicle. Some hybrids rely exclusively on the electric motor(s) during slow-speed operation, on the ICE alone at higher speeds, and on both during some driving conditions.

A hybrid's electric motor is powered by batteries, which are continuously recharged by a generator that is driven by the ICE. The battery is also recharged through regenerative braking. Complex electronic controls monitor the operation of the vehicle. Based on the current operating conditions, electronics control the ICE, electric motor, and generator. The system recharges the batteries while driving; therefore plug-in charging is not required.

The engines used in hybrids are specially designed for the vehicle and for electric assist. Therefore, they can operate more efficiently, resulting in very good fuel economy and very low tailpipe emissions. Hybrids will never be true zero-emission vehicles, however, because they have an ICE.

HEVs have an extended range, going farther than a BEV can on just the charge in its batteries. They also have a longer driving range than a comparable ICE-equipped vehicle. HEVs also provide the same performance as the same vehicle equipped with a larger ICE, if not better. The delivery of power to the wheels is smooth and very responsive.

There are two major types of hybrids: the parallel and the series designs. A **parallel HEV** uses either the electric motor or the gas engine or both to propel the vehicle **(Figure 1-14).** A true **series HEV** only uses the ICE to power the generator to keep the batteries charged. The vehicle is powered only by the electric motor(s) **(Figure 1-15).** Most of today's hybrids rely

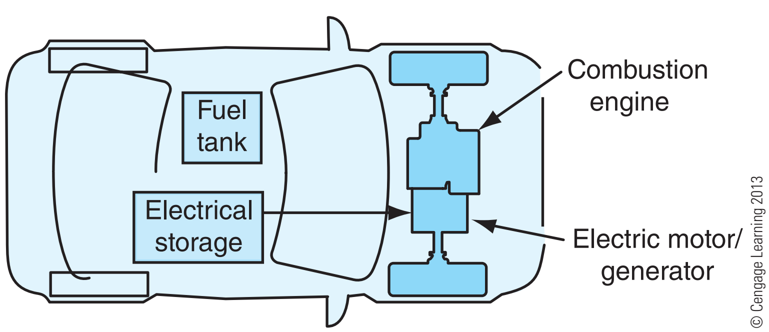

Figure 1-14 The configuration of a typical parallel hybrid vehicle.

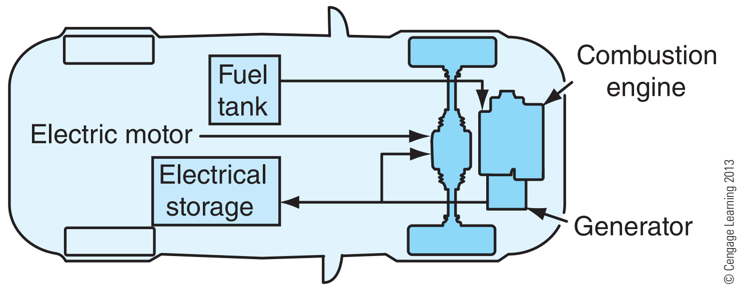

Figure 1-15 The configuration of a typical series hybrid vehicle.

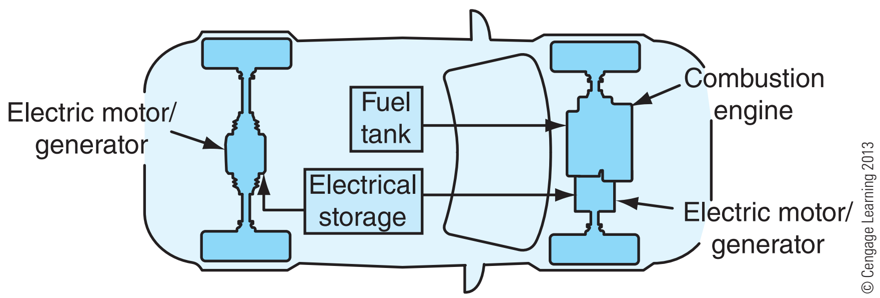

Figure 1-16 This hybrid powertrain allows for additional four-wheel drive control and power by having a motor/generator attached to the rear axle.

on a series/parallel configuration because they have the features of both designs.

As of early 2012, there was one mostly series hybrid, the Chevrolet Volt. This car is called an extended range electric vehicle because the ICE starts when the batteries are low. By charging the batteries with the ICE, the operating range of the car is extended. However, the engine never directly drives the car's wheels.

There are several hybrid cars on the market today, with more planned for the near future. Although most current hybrids are focused on fuel economy, the same construction is used to create high-performance vehicles. Hybrid technology has also influenced off-the-road performance. With the use of individual motors at the front and rear drive axles, additional power can be applied to certain drive wheels when needed **(Figure 1-16).**

Economics

HEVs are priced slightly higher than comparable ICE models. The difference in price can be offset by fuel savings over time. In addition, there are tax incentives to encourage consumers to purchase an alternative-fuel

FUEL CELL ELECTRIC VEHICLES

A possible alternative fuel for the future is hydrogen, which is the fuel for fuel cells. Basically, a fuel cell generates electrical power through a chemical reaction. A fuel cell electric vehicle (FCEV) uses the electricity produced by the fuel cell to power motors that drive the vehicle's wheels. FCEVs operate like most EVs, but their batteries do not need to be charged by an external source. FCEVs emit few, if any, pollutants. Fuel cell technology may also be used to provide energy for homes and businesses.

Fuel cells convert chemical energy to electrical energy by combining hydrogen with oxygen from the air **(Figure 1-17).** Hydrogen can be supplied directly as pure hydrogen gas or through a "fuel reformer" that pulls hydrogen from hydrocarbon fuels such as methanol, natural gas, or gasoline. A fuel cell is made up of two electrodes (the anode and the cathode) located on either side of an electrolyte. As hydrogen enters the fuel cell, the hydrogen atoms give up electrons at the anode and become hydrogen ions in the electrolyte. The electrons that were released at the anode move through an external circuit to the cathode. As the electrons are moving toward the cathode, they can be diverted and used to power the electric motors to move the vehicle. When the hydrogen ions combine with oxygen molecules at the cathode, water and heat

producing or greenhouse gases are generated and only water is emitted from the tailpipe of the fuel cell.

A fuel cell power system has many other parts **(Figure 1-18),** but central to them all is the fuel cell stack. The stack is made of many thin, flat fuel cells layered together. Each cell produces electricity, and the

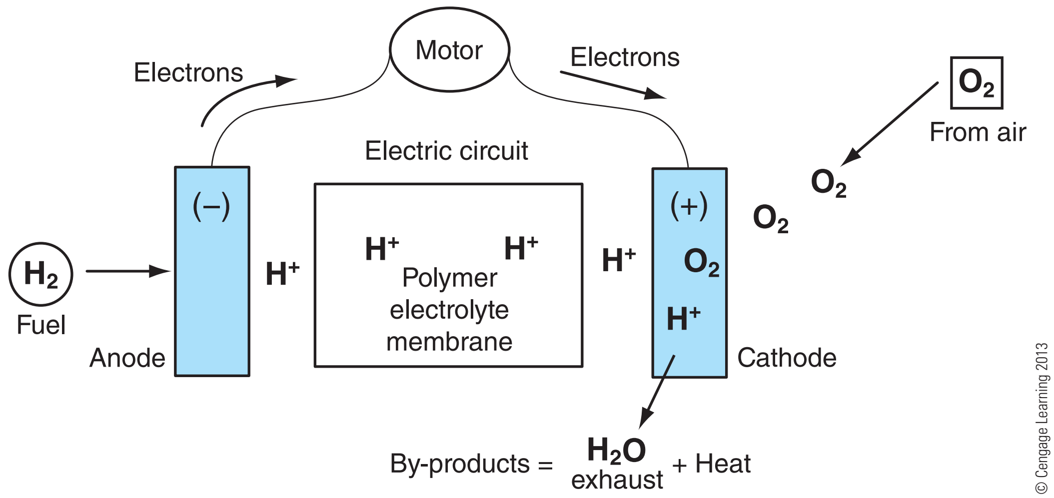

Figure 1-17 In a fuel cell, as hydrogen flows through the anode and oxygen flows through the cathode, charges are produced to power electrical loads.

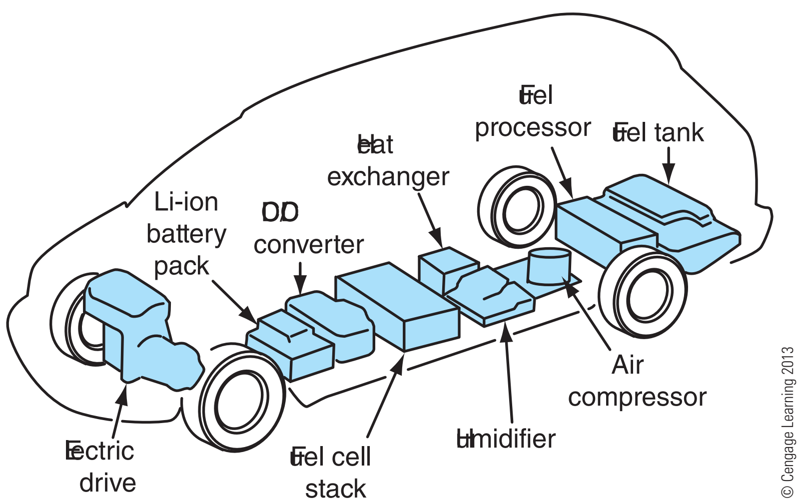

Figure 1-18 Components of a sodium borohydride fuel cell.

total output of all the cells is used to power the vehicle. The entire stack of fuel cells is often referred to as a fuel cell, although that is not technically correct. A fuel cell is one cell, whereas the stack is many cells.

Vehicles that run on pure hydrogen are true zero-emission vehicles. FCEVs that have reformers will emit some pollutants, but far less than an ICE vehicle. Without a reformer, FCEVs do not consume fossil fuels nor contribute to global warming. However, there may be some emissions related to the production of hydrogen. This is an area that must be addressed be- fore

Many obstacles need to be overcome before FCEVs become a truly viable option for personal transportation. These include:

- Storage—Because hydrogen is a gas, a large volume of it is needed to travel the same distance as a tank of gasoline.
- Weight and size—Current fuel cells are quite large and heavy; both need to be reduced to make FCEVs more practical.
- Cost—The cost of a fuel cell is high, and this must also be reduced.
- Startup time—Fuel cells operate best at a fixed moderate temperature.
- FCEVs must have systems that allow for quick reactions to changing operating temperatures and conditions.
- Hydrogen sources—Because fuel cells depend

ture to supply hydrogen and/or clean operating reformers.

Most auto manufacturers are actively researching fuel cell transportation technologies and testing prototype passenger vehicles. Many cities are testing fuel cell–powered transit buses. The advances made by

hybrid vehicle technology will benefit fuel cell vehicle development.

A LOOK AT HISTORY

Electric drive vehicles have been around for a long time. Early automobiles were mostly electric or steam powered. "Steamers" were the most common until the late 1800s. Early electric vehicles faced the same problems that plague pure EVs today, namely, battery technology and cost. The internal combustion engine became popular because it allowed a vehicle to travel great distances and achieve a decent top speed, and it was much less expensive to buy.

At the beginning of the twentieth century, thousands of hybrid and electric vehicles were made. In fact, they were the people's choice. In 1900, 38 percent of the cars sold were electrically powered; the others ran on steam or gasoline (just for reference, more steam-powered vehicles were sold than those powered by gasoline).

Electric vehicles did not have the vibration, smell, and noise of gasoline cars. Starting the engine and changing gears were the most difficult things about driving a gasoline-powered vehicle. Electric drive vehicles did not need to be manually cranked to get going and had no need for a transmission or change of gears. These were the primary reasons the public accepted electric drive over the ICE vehicles.

Let us take a quick look at some interesting developments of electric vehicles throughout history. It is said that the first practical electric road vehicle was probably made either by Thomas Davenport in the United States or by Robert Davidson in Edinburgh, Scotland in 1842. Both of these vehicles had nonrechargeable electric cells (batteries) and, therefore, had a limited travel range and were not accepted by consumers. In 1865, the storage battery was invented, and it was further improved in 1881. More significantly, between the years 1890 and 1910, battery technology drastically improved with the development of the modern lead-acid battery by Henri Tudor in 1881. Thomas Edison's nickel-iron alkaline battery was used to power the first electric drive vehicles 100 years ago.

Many different individuals and companies developed electric vehicles. In 1897, the London Electric Cab

signed by Walter Bersey. The Bersey Cab, which used a 40-cell battery and 3-horsepower electric motor, could be driven 50 miles between charges.

Also in 1897, Justus Entz, a chief engineer at a Philadelphia battery company, built the first vehicle powered by an ICE assisted by an electric motor. The carriage had very poor performance, but the basic idea was sound. Unfortunately, the experiment came to an end when an electrical spark ignited the fuel tank and destroyed the carriage.

A year later, Dr. Jacob Ferdinand Porsche, an engineer for Lohner & Company in Austria, built his first car, the Lohner-Porsche. This was the world's first front-wheel-drive vehicle. His second car is of more interest; it was a series hybrid vehicle, or, as Porsche called it, a vehicle with a "mixte" (mixed) propulsion system. This Porsche used an ICE to run a generator that provided the power for the electric motors that powered individual wheels through the hubs of the wheels.

In 1905, H. Piper filed a patent for a petrol-electric hybrid vehicle. His idea was to use an electric motor to assist an ICE, enabling the vehicle to accelerate to 25 mph in 10 seconds. This is thought to be the first parallel hybrid automobile. This claim may be stretching things a bit, because in 1900 a Belgian company, Pieper, fitted a small vehicle with a very small ICE and an electric motor. When the vehicle was operating under very low load, the electric motor served as a generator to charge the batteries. That generator then became a motor to assist the engine when there were heavy loads on the engine. Both of these used a system similar to the one used by Honda today.

One of the companies that had many variations of electric drive was the Woods Motor Vehicle Company. The 1902 Woods Phaeton was totally electric powered and had a range of 18 miles and a top speed of 14 mph. The 1905 Woods Interurban was also an electric vehicle, but it also had an ICE. This vehicle was designed to allow the driver and a mechanic to switch the driveline from the electric motor to the ICE in about 15 minutes. Although this vehicle had alternate power sources, it was not a hybrid. However, in 1917, Woods introduced the Woods Dual Power. This car had an ICE and an electric motor. It was probably the first parallel hybrid vehicle, since the ICE and motor were designed to work together or alone. It is claimed the Woods Dual Power had a top speed of 35 mph and achieved 48 mpg. But it cost as much as a Cadillac V-8 with electric starting, which also had twice as much power; therefore few Woods

In 1904, Henry Ford overcame some of the common objections to gasoline-powered cars (noise, vibration, and smells) and, thanks to assembly line production, offered gasoline-powered vehicles at very low prices ($500 to $1,000). The prices of electric vehicles were much higher and were rising each year.

In 1912, an average electric car sold for $1,750, while a gasoline-powered one sold for only $650.

The popularity of electric drive vehicles declined further in 1912, when Charles Franklin Kettering invented the self-starter for automobile engines. This electric starter was first offered on Cadillac cars in 1912 and on many other makes in 1913. Because one of the objections the public had about ICE vehicles was getting the engine started, this answered a problem directly—it made it easier for all drivers to start an ICE engine.

Some of the factors that contributed to the decline in electric drive vehicles include:

- Gasoline engines were becoming more refined and efficient.
- The United States had a weak infrastructure for supplying electricity for businesses and homes, much less for charging batteries. Additionally, electricity was quite expensive.
- The country had developed a system of roads that connected cities, and vehicles needed to provide a longer driving range than that offered by electric vehicles.
- The availability of gasoline had increased and it was inexpensive.

For the most part, electric drive vehicles were a thing of the past from 1920 to 1965. Although there were concerns in the 1960s about the environment and our dependence on foreign oil, there was not a noticeable rebirth of the electric car.

However in 1966, the United States Congress introduced the first bills recommending the use of electric vehicles as a way to reduce air pollution. Subsequent laws put mandates on auto manufacturers to clean up exhaust emissions. Initially, these laws led to the addition of various emission controls to the basic ICE. Because many of these modifications adversely affected performance and fuel economy, the manufacturers looked into alternative ways to provide transportation.

In 1973, the availability of gasoline decreased and its price drastically increased as the result of the Arab oil embargo. The rising cost led to increased attention to the development of electric drive vehicles. Manufacturers worked overtime to reduce fuel consumption to meet

they were unable to develop a practical electric vehicle. However, two small companies did. Sebring-Vanguard produced over 2,000 "CitiCars." The CitiCars were designed for commuters who drove short distances on city streets. The cars had a top speed of 44 mph and had a range of 50 to 60 miles. The Elcar Corporation produced another commuter car called the Elcar, which had a top speed of 45 mph and a range of 60 miles.

In 1975, AM General, a division of American Motors Company, began delivery of 350 electric jeeps to the U.S. Postal Service for testing. These jeeps had a top speed of 50 mph and a range of 40 miles at a speed of 40 mph.

The U.S. Congress passed into public law the Electric and Hybrid Vehicle Research, Development, and Demonstration Act of 1976. One objective of the law was to work with industry to improve batteries, motors, controllers, and other hybrid electric vehicle components. The goal was to double fuel efficiency in all vehicles. In 1980, Briggs & Stratton sponsored the construction of a six-wheel compact with a parallel-hybrid configuration. This vehicle had a combined horsepower rating of 26 and the vehicle could achieve 75 mph. But this vehicle never caught on.

In 1993, the U.S. government created a Partnership for a New Generation of Vehicles (PNGV) between the United States Council for Automotive Research (formed in 1992) and a network of universities, national labs, federal agencies, and suppliers. The goals were to have 80 mpg concept vehicles by 1999, followed by production-feasible prototypes by 2004. No prototypes emerged, although GM's Precept did achieve 90 mpg on diesel fuel.

Other legislation was passed through the years that provided incentives for manufacturers to produce cleaner-emission vehicles, such as electric drive vehicles. In addition, there have been several legislative and regulatory actions that have instigated the development of new electric vehicles.

The 1990 Clean Air Act Amendments, the 1992 Energy Policy Act, and regulations issued by the California Air Resources Board (CARB) had the most impact. CARB emissions certification places all passenger vehicles into the following major groups. Each group is defined by a number of factors, primarily the measurable emissions of particular substances:

- LEV—Low Emission Vehicle
- ULEV—Ultra Low Emission Vehicle
- SULEV—Super Ultra Low Emission Vehicle
- PZEV—Partial Zero Emission Vehicle
- AT PZEV—Advance Technology Partial Zero Emission Vehicle
- ZEV—Zero Emission Vehicle

In 1990, CARB adopted a requirement that 10 percent of all new cars offered for sale in California in 2003 and beyond must be zero-emission vehicles (ZEVs). In 1998, the Air Resources Board modified the requirements for 2004 **(Figure 1-19).** The change allowed manufacturers

	CV	TLEV	LEV	ULEV	ZEV
NMOG	0.25*	0.125	0.075	0.040	0.0
CO	3.4	3.4	3.4	1.7	0.0
NO_x	0.4	0.4	0.2	0.2	0.0

(*) Emission standards of NMHC

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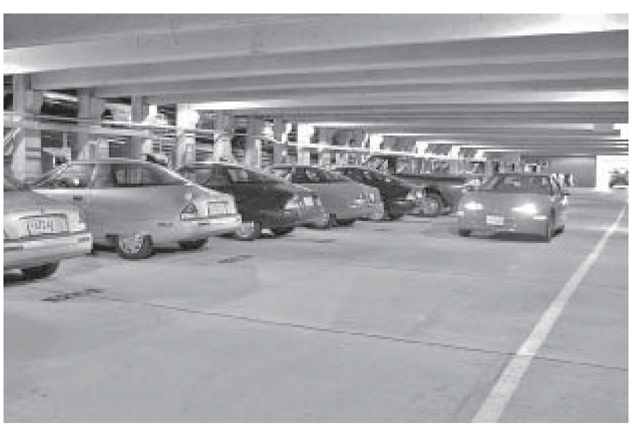
Figure 1-19 CARB's emissions standards in grams per mile at 50,000 miles.

to satisfy up to 6 percent of their ZEV requirement with automobiles that qualify as partial ZEVs. A ZEV is one that has no tailpipe emissions, no evaporative emissions, no emissions from gasoline refining or sales, and no on-board emission-control systems that can deteriorate over time. Today, only FCEVs running on pure hydrogen and BEVs qualify as ZEVs.

In 1991, the United States Advanced Battery Consortium (USABC), a Department of Energy program, began a project that would lead to the production of a battery that would make electric vehicles a viable option for consumers. The initial result was the development of the nickel-hydride (NiMH) battery. This battery can accept three times as many charge cycles as lead acid, and it can work better in cold weather.

In 1997, Toyota Motor Corporation offered the first modern hybrid automobile available to the public in Japan. Also during that time, a few models of all-electric cars were made available in the United States, including Honda's EV Plus, GM's EV1 **(Figure 1-20)** and S-10 electric pickup, a Ford Ranger pickup, and Toyota's RAV4 EV **(Figure 1-21).** All of these EVs are no longer available because of poor acceptance by the market. However, several generations of Toyota's hybrids have been available since.



Courtesy of Georgia Power Company

Figure 1-20 GM's EV1.

Courtesy of Dewhurst Photography and Toyota Motor Sales, U.S.A., Inc.

Figure 1-21 Toyota's RAV4 EV.

Courtesy of American Honda Motor Co., Inc.

Figure 1-22 The Honda Insight.

Testing the market in the United States, Honda released the two-door, two-seat Insight **(Figure 1-22)** in 1999. This was the first hybrid car to hit the mass market, and it received much positive press coverage. It won many awards and was rated at 61 mpg city and 70 mpg highway by the U.S. Environmental Protection Agency (EPA). Although it was a different looking and very small car, it did fairly well in the marketplace.

In 2000, Toyota introduced the Prius to the United States. Again, the public responded positively, in spite of the fact it was another hybrid that looked different. Comfortable with the public's acceptance of hybrid technology, Honda introduced the Honda Civic Hybrid in 2002. The appearance and drivability of the Civic Hybrid were identical to the conventional Civic.

After some success with the first model, Toyota introduced its second-generation Prius in 2004 **(Figure 1-23).** This model looked like most other vehicles and was more practical than the previous model. It won numerous awards, including *Motor*

was so great that Toyota had to increase production, and buyers had to wait up to six months to get one. Toyota also released two hybrid SUVs and a Camry hybrid.

Ford released a hybrid version of its great selling small SUV, the Escape. This was the first American

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Figure 1-23 The Toyota Prius was the world's first mass-produced modern hybrid vehicle.

hybrid and the first SUV hybrid. The demand for the hybrid model has also been great. In recent years Ford took that system, modified it, and installed it into some of its mid-sized cars.

Chevrolet also released a hybrid Silverado and mild hybrid versions of the Malibu. In 2010, Chevrolet introduced an "extended range" BEV called the Volt. For 2012, an eAssist mild hybrid Buick Regal was available.

Also in 2012, Nissan released a BEV called the Leaf and some mid-sized hybrids. Mitsubishi also released a BEV called the Ti-MEV.

Many other hybrids have been released, and most manufacturers plan to introduce their versions of a hybrid in the near future. The list of available hybrids and fuel cell vehicles is growing so quickly that it is impossible to include them all in this book before it is printed. In addition, several manufacturers are working on fuel cell vehicles. In fact Honda, as well as other manufacturers, has released some to the general public for testing **(Figure 1-24).**

Courtesy of American Honda Motor Co., Inc.

Figure 1-24 A Honda fuel cell vehicle.

PRECAUTIONS FOR WORKING ON ELECTRIC DRIVE VEHICLES

Electric drive vehicles (BEVs, HEVs, and FCEVs) have high-voltage electrical systems (from 42 volts to 650 volts). These high voltages and their high amperages can kill you! Fortunately, most high-voltage circuits are identifiable by size and color. The cables have thicker insulation and are typically colored orange. The connectors are also colored orange. On some vehicles, the high-voltage cables are enclosed in an orange shielding or casing; again orange indicates high voltage. Be careful not to touch these wires when they are connected to their power source. The battery pack and most high-voltage components also have "High Voltage" caution labels. Be careful when working around these parts. There are other safety precautions that should always be adhered to when working on an electric drive vehicle:

- Always adhere to the safety guidelines given by the manufacturer.
- If a repair operation is incorrectly performed on an EV, a dangerous situation can result; always perform each repair operation correctly.
- Disable or disconnect the high-voltage system before working on or near the system. Always follow the procedures for doing this given by the manufacturer.
- Some systems have a high-voltage capacitor that must be discharged after the high-voltage system is isolated. Make sure to wait the prescribed amount of time (normally about 10 minutes) before working on or around the high-voltage system.
- After removing a high-voltage cable, cover the terminal with vinyl electrical tape.
- Always use insulated tools.
- Always follow the test procedures defined by the equipment manufacturer.
- Alert other technicians that you are working on high-voltage systems with a warning sign such as "**HIGH-VOLTAGE WORK: DO NOT TOUCH.**"
- Follow the manufacturer's instructions for removing the battery packs.
- When disconnecting electrical connectors, do not pull on the wires. When reconnecting the

  specifications.
- Do not wear metallic objects such as rings and necklaces while working around these systems.
- Do not carry metal objects, such as a mechanical pencil or a measuring tape, that could fall and cause a short circuit.

- Wear insulating gloves, commonly called "lineman's gloves," when working on or around the high-voltage system. Make sure the gloves have no tears, holes, or cracks and that they are dry. The integrity of the gloves should be checked before using them.
- Always install the correct type of circuit protection device into a high-voltage circuit.
- Use only the tools, test equipment, and service procedures specified by the manufacturer.
- Many electric motors contain a strong permanent magnet; individuals with pacemakers should not handle these parts.
- Before doing any service to an electric drive vehicle, make sure the power from the battery is disconnected or disabled.
- Any time the engine is running in a hybrid vehicle, the generator is producing high voltage, and care must be taken to prevent shocks.
- When an electric drive vehicle needs to be towed into the shop for repairs, make sure it is not towed by its drive wheels. Doing this will drive the generator(s), which can overcharge the batteries and cause them to explode. Always tow these vehicles with the drive wheels off the ground or move them on a flatbed.
- In the case of a fire, use a Class ABC powder-type extinguisher or very large quantities of water.

Battery Precautions

Because the electrical power for an electric drive vehicle is stored in a battery pack, special handling precautions must be followed when working with or near batteries.

- Make sure to wear safety glasses (preferably a face shield) and protective clothing when working around and with batteries.
- Keep all flames, sparks, and excessive heat away from the battery at all times, especially when it is being charged.
- Never smoke near the top of a battery.
- Remove wristwatches and rings before servicing any part of the electrical system. This helps prevent the possibility of electrical arcing and burns.
- Never lay metal tools or other objects on the battery.
- All batteries have an electrolyte, which is very corrosive. It can cause severe injuries if it comes in contact with your skin or eyes. If electrolyte gets on you, immediately wash with baking soda and water. If the acid gets in your eyes, immediately flush them with cool water for a minimum of 15 minutes and get immediate medical attention.
- When removing a battery from a vehicle, always disconnect the battery ground cable first. When installing a battery, connect the ground cable last.
- Always use a battery carrier or lifting strap to make moving and handling batteries easier and safer.
- Always disconnect the battery's ground cable when working on the electrical system or engine. This prevents sparks from short circuits and prevents accidental starting of the engine.
- Always charge a battery in well-ventilated areas.
- Never connect or disconnect charger leads to a battery when the charger is turned on.
- Never recharge the battery when the system is on.
- Turn off all accessories before charging the battery and correct any parasitic drain problems.
- Always disconnect the battery ground cable before fast charging the battery on the vehicle.

Review Questions

1. Define the term *electric drive.*
2. *True or False*: Although electric vehicles played an important part in the development of the modern
3. List three alternative fuels for an ICE and briefly explain the source of each.
4. What is the basic difference between a series hybrid vehicle and a parallel one?

5. What is the basic fuel used to produce electrical energy in a fuel cell?
   A. Hydrogen
   B. Methanol
   C. Electricity
   D. Gasoline

6. What is regenerative braking?

7. List three factors that have elicited a renewed interest in developing electric drive vehicles.

8. What is a Zero Emission Vehicle (ZEV)?

9. Name three possible energy sources for future electric vehicles.

10. Explain why hybrid vehicles will never be considered ZEVs.

CHAPTER 2 Electrical Basics

Learning Objectives

After reading and studying this chapter, you should be able to:

- Define the terms normally used to describe electricity.
- Explain what is defined by Ohm's law.
- Explain the differences between AC and DC.
- Describe the differences between a series and a parallel circuit.
- Name the various electrical components and their uses in electrical circuits.
- Explain the principles of magnetism and electromagnetism.

Key Terms

alternating current (AC)
base (transistor)
capacitors
chassis ground
clamping diode
closed circuit
collector
conductors
continuity
current
dielectric material
diode
direct current (DC)
electrically inert
electromotive force (EMF)
emitter
fixed-value resistors
flux density
flux field
forward bias
ground wire
impurities
induction
insulated gate bipolar transistor
insulators
kilowatt
NPN transistor
ohm
Ohm's law
open circuit
parallel circuit
PNP transistor
potentiometers
relay
reluctance
resistance
reverse bias
rheostats
semiconductor
sensors
series circuit
sine wave
solenoids
stepped resistors
tapped resistor
thermistor
transformer
transistor
variable resistors
voltage
zener diode

INTRODUCTION

To understand how electric drive vehicles work and how to maintain them, you must have an understanding of electricity. This chapter will not cover this topic in depth; rather, it covers the fundamentals.

All things are made up of atoms, which are extremely small particles. In the center of every atom is a nucleus. The nucleus contains positively charged particles called protons and particles called neutrons that have no charge. Negatively charged particles called electrons orbit around every nucleus. The electrons stay in orbit around the nucleus because they are naturally attracted to the protons.

Electricity is the flow of electrons from one atom to another **(Figure 2-1).** The release of energy as one electron leaves the orbit of one atom and jumps into the orbit of another is electrical energy. The key to creating electricity is to provide a reason for the electrons to move to another atom.

Electrons have a negative charge and are attracted to something with a positive charge. When an electron leaves the orbit of an atom, the atom then has a positive charge. An electron moves from one atom to another because the atom next to it appears to be more positive than the one it is orbiting around. To have a continuous flow of electricity, three things must be present: an excess of electrons in one place, a lack of electrons in another place, and a path between the two places.

Chemicals that have the potential to produce electricity are stored in batteries **(Figure 2-2).** Batteries have two terminals, a positive and a negative terminal. A chemical reaction in the battery causes a lack of electrons at the positive terminal and an excess at the negative terminal. This creates an electrical imbalance, causing the electrons to flow through the path provided by the vehicle's wiring.

The chemical process in the battery continues to provide electrons until the chemicals become weak. At that time, either the battery has run out of electrons or all of the protons are matched with electrons. When this happens, there is no longer a reason for the electrons to want to move to the positive side of the battery. Charging the battery restores the chemicals to their original state allowing them to once again provide electrons.

ELECTRICAL TERMS

Electrical **current** describes the movement or flow of electricity. The greater the number of electrons flowing past a given point in a given amount of time, the more current the circuit has. The unit for measuring electrical current is the ampere, usually called an amp. The instrument used to measure electrical current flow in a circuit is called an ammeter **(Figure 2-3).**

There are two types of current: **direct current (DC)** and **alternating current (AC)**. In direct current, the electrons flow in one direction only. In alternating current, the electrons change direction at a fixed rate. Typically, an automobile uses DC, whereas the current in homes and buildings is AC. Some components of the automobile generate or use AC. Most drive motors used in electrical vehicles are powered by AC. The storage batteries are DC devices; therefore, to use the stored electricity to run the AC devices, the DC must be converted to AC. Likewise, to use the electrical energy generated by an AC device to charge a battery, AC must be changed to DC.

Voltage is electrical pressure **(Figure 2-4).** It is the force developed by the attraction of the electrons to protons. The more positive one side of the circuit is, the more voltage is present in the circuit. Voltage does not flow; it is the pressure that causes current flow. This force is the pressure that exists between a positive and negative point within an electrical circuit. This force or pressure, also called **electromotive force (EMF)**, is measured in units called volts. Voltage is measured by an instrument called a voltmeter.

When any substance flows, it meets resistance. The **resistance** to electrical flow produces heat and can be measured. A unit of measured resistance is called an **ohm**. Resistance can be measured by an instrument called an ohmmeter.

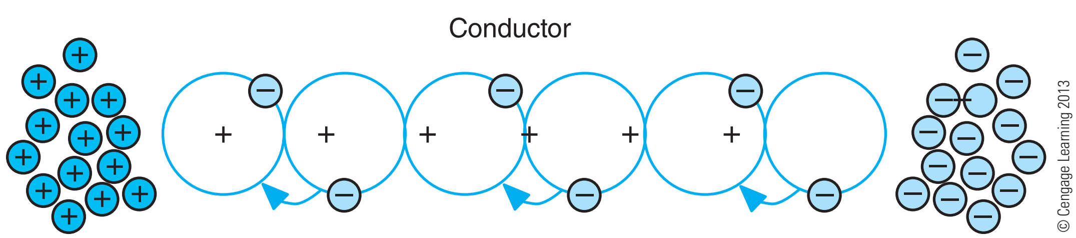

Figure 2-1 Electricity results from the flow of electrons from one atom to another.

Figure 2-2 The electrical energy required by automobiles is stored in batteries.

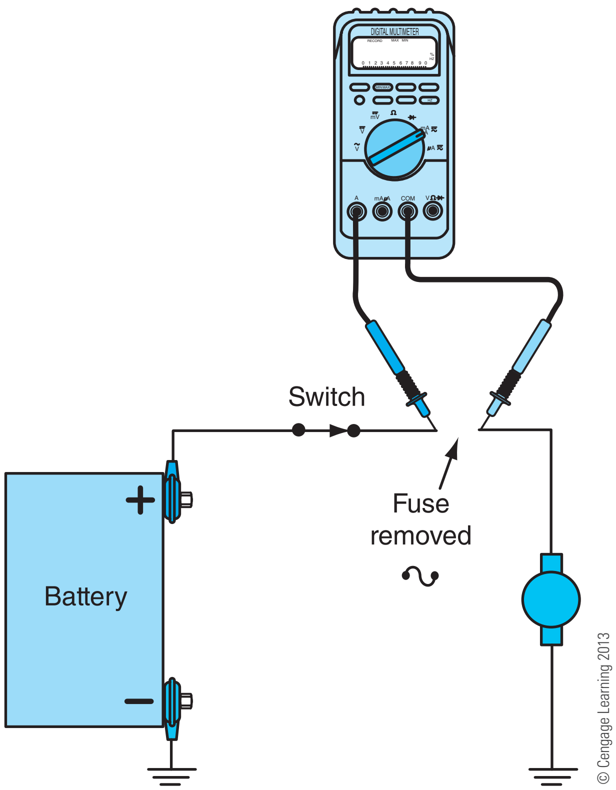

Figure 2-3 To measure the current or amperage in a circuit, the ammeter should be connected in series with the circuit.

Ohm's Law

In 1827, a German mathematics professor, Georg Ohm, published a book that included his explanation of the behavior of electricity. His thoughts have become the basis for a true understanding of electricity. He found that it takes 1 volt of electrical pressure to push 1 ampere of electrical current through 1 ohm of resistance. This statement is the basic law of electricity and is known as **Ohm's law**.

In any electrical circuit, current (I), resistance (R), and voltage (E) work together in a mathematical relationship. This relationship is expressed in a mathematical statement of Ohm's law **(Figure 2-5).** Ohm's law can be applied to the entire circuit or to any part of a circuit. When any two factors are known, the third factor can be found by using Ohm's law.

Power

Electrical power, or the rate of work, is found by multiplying the amount of voltage by the amount of current flow (Power = Voltage × Amperage). Power is measured in watts **(Figure 2-6).** Most often the power available in an electric drive vehicle is stated in kW or **kilowatts** (1,000 watts).

Most batteries and motors used in electric drive vehicles are rated in kilowatt-hours (kWh). This is an expression of the amount of power or energy that is consumed or provided by a component over time. For example, when a motor rated at 5,000 watts (5 kW) is operated for one hour, it uses 5 kWh. Likewise, if that motor ran for five hours, it used 25 kWh.

Circuit Terminology

An electrical circuit is considered complete when there is a path that connects the positive and negative terminals of the electrical power source. A completed circuit is called a **closed circuit**, whereas an incomplete circuit is called an **open circuit**. When a circuit is complete, it is said to have **continuity**.

In many wiring diagrams or electrical schematics, the return wire from the load or resistor is shown as

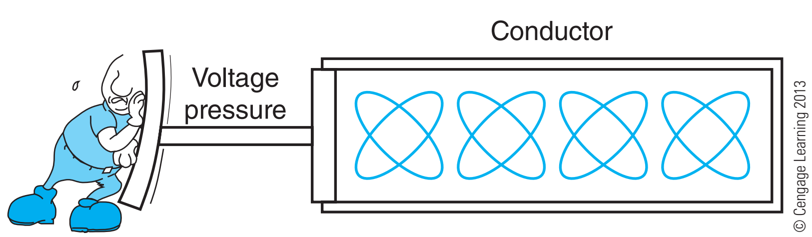

Figure 2-4 Voltage is electrical pressure.

Voltage (E) = Current (I) times Resistance (R), therefore

E = I x R.

Current (I) = Voltage (E) divided by Resistance (R), therefore

I = E / R.

Resistance (R) = Voltage (E) divided by Current (I), therefore

R = E / I.

Figure 2-5 The mathematical expression for Ohm's law.

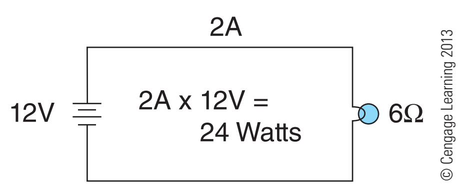

Figure 2-6 The power output of the lamp in this simple circuit is 24 watts.

being connected directly to the negative terminal of the battery. If this were the case in an actual vehicle, there would be literally hundreds of wires connected to the negative battery terminal. To avoid this, manufacturers use a wiring style that uses the vehicle's metal frame as part of the return circuit. Using the chassis as the negative wire is often referred to as "grounding," and the connection is called a **chassis ground**. The wire or metal mounting that serves as the contact to the chassis is commonly called the **ground wire** or lead **(Figure 2-7).**

An electrical component may be mounted directly to the engine block, transmission case, or frame. This direct mounting effectively grounds the component without the use of a separate ground wire. In other cases, however, a separate ground wire must be run from the component to the frame or another metal part to ensure a good connection for the return path. The increased use of plastics and other nonmetallic materials in body panels and engine parts has made electrical grounding more difficult. To ensure good grounding back to the battery, some manufacturers now use a network of common grounding terminals and wires.

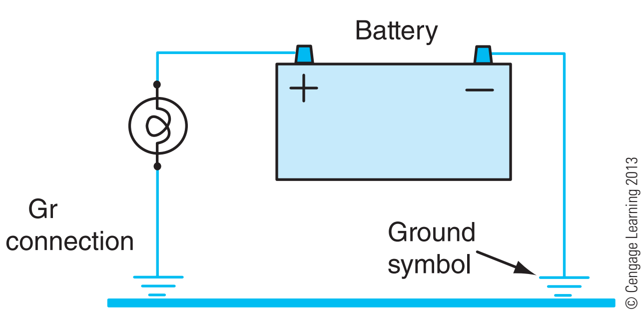

Figure 2-7 A simple light circuit that uses the vehicle's chassis as the negative conductor through ground connections.

In a complete circuit, the flow of electricity can be controlled and applied to do useful work, such as light a headlamp or turn on a motor. Components that use electrical power put a load on the circuit and consume electrical energy. These components are often referred to as electrical loads.

The amount of current that flows in a circuit is determined by the resistance in that circuit, if the voltage is constant. As resistance goes up, current goes down. The total resistance in a circuit determines how much current will flow through the circuit at a given voltage. The energy used by a load is measured in volts. Amperage stays constant in a circuit, but the voltage is dropped as it powers a load. Measuring voltage drop tells you how much electrical energy is being consumed by a load **(Figure 2-8).**

Alternating Current

Alternating current is current that constantly changes in voltage and direction. Direct current, on the other hand, always moves in the same direction, and the voltage is constant until it reaches a resistance. Direct current always moves from a point of higher potential (voltage) to a point of lower potential (voltage).

If a graph is used to represent the amount of DC voltage available from a battery during a fixed period of time, the line on the graph will be flat, which represents a constant voltage. If AC voltage is shown on a graph, it will appear as a **sine wave**. The sine wave shows AC changing in amplitude (strength) and direction **(Figure 2-9).** The highest positive voltage equals the highest negative voltage. The movement of the AC from its peak at the positive side of the graph to the negative side and then back to the positive peak is commonly referred to as "peak-to-peak" value. This value represents the amount of voltage available at a point. During each complete cycle of AC, there are always two maximum or peak values, one for the positive half cycle and the other for the negative half cycle. The difference between the peak positive value and the peak negative value is used to measure AC voltages.

passes through a resistance, nearly 29 percent less heat is produced when compared to DC. This is one reason AC is preferred over DC for powering motors and other electrical devices.

The lack of heat also causes us to look at AC values differently than the same values in a DC circuit.

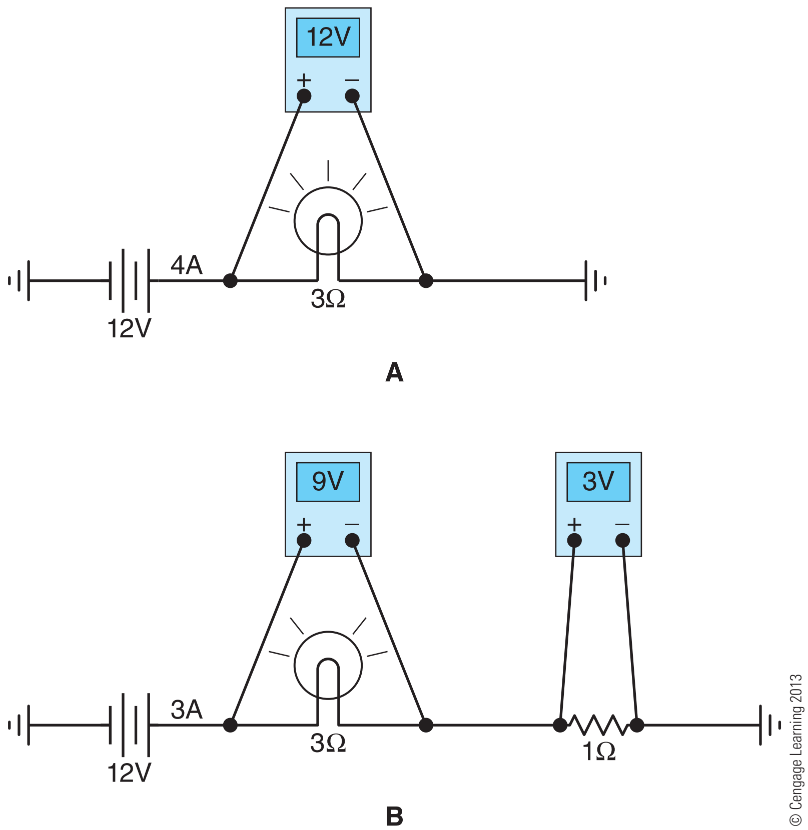

Figure 2-8 Connecting a voltmeter across a load measures the voltage drop across that load.

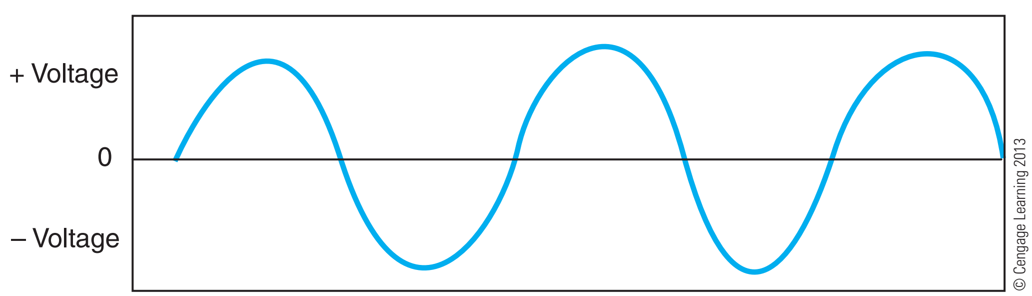

Figure 2-9 This sine wave results from alternating current.

An alternating current has an effective value of one ampere when it produces heat in a given resistance at the same rate, as does 1 ampere of direct current. The effective value of an alternating current is equal to 0.707 times its maximum or peak current value. Because alternating current is caused by an alternating voltage, the ratio of the effective voltage value to the maximum voltage value is the

maximum current or 0.707 times the maximum value.

According to Ohm's law, current is directly proportional to the voltage applied to the circuit. This remains true for AC circuits as well. However, AC voltage and current change constantly, and AC values must be viewed as average or effective values. When AC is applied to a resistance, as the actual voltage changes in value and direction, so does the current. In fact, the change of current is in phase with the change in voltage. An "in-phase" condition exists when the sine waves of voltage and current are precisely in step with one another.

If a circuit has two or more voltage pulses but each has its own sine wave that begins and ends its cycle at

sine waves are 180 degrees out-of-phase, they will cancel each other out if they are of the same voltage and current. If two or more sine waves are not 180 degrees out-of-phase, the effective voltage and current are determined by the position and direction of the sine waves at a given point within the circuit.

CONDUCTORS AND INSULATORS

Controlling and routing the flow of electricity requires the use of materials known as conductors and insulators. **Conductors** are materials with a low resistance to the flow of current. Most metals, such as copper, silver, and aluminum, are excellent conductors.

WARNING *Your body is a good conductor of electricity. Remember this when working on a vehicle's electrical system. Always observe all electrical safety rules.*

Insulators resist the flow of current. Thermal plastics are the most common electrical insulators used today. They can resist heat, moisture, and corrosion without breaking down. The insulation of a vehicle's various wires is colored or marked to allow for circuit identification **(Figure 2-10).**

Copper wire is by far the most common conductor used in automotive electrical systems. Where flexibility is required, the copper wire will be made of a large number of very small strands of wire woven or twisted together.

The resistance of a uniform, circular copper wire depends on the length of the wire, the diameter of the wire, and the temperature of the wire. If the length is doubled, the resistance between the wire ends is doubled. The longer the wire, the greater the resistance. If the diameter of a wire is doubled, the resistance for any given length is cut in half. The larger the wire's diameter, the lower the resistance.

Heat is developed in any conductor carrying current because of the resistance in the wire. Resistance occurs when electrons collide as current flows through the conductor. These collisions cause friction that in turn generates heat. If the heat becomes excessive, the insulation will be damaged.

Circuits

Nearly all automotive circuits are comprised of four basic parts:

1. Power sources, such as batteries, that provide the energy needed to cause electron flow.
2. Conductors, such as copper wires and the chassis ground, that provide a path for current flow.
3. Loads or devices that use electricity to perform work, such as light bulbs, electric motors, or resistors.
4. Controllers, such as switches or relays, which control or direct the flow of electrons.

There are also two basic types of circuits used in electrical systems: series and parallel circuits. Each circuit type has its own characteristics regarding amperage, voltage, and resistance.

A **series circuit** consists of one or more resistors (loads) connected to a voltage source with a single path for electron flow **(Figure 2-11).** In a series circuit, the amount of current flow is constant throughout the circuit. The amount of current that flows through one resistor also flows through any other resistors in the circuit. As the current leaves the battery, it flows

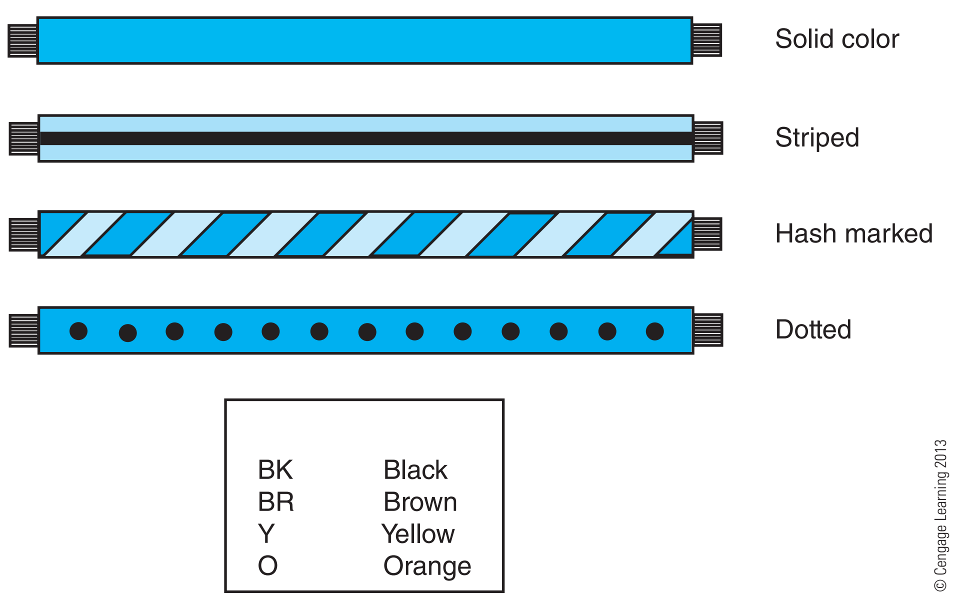

Figure 2-10 The insulation of the vehicle's various wires is colored or marked to allow for circuit identification.

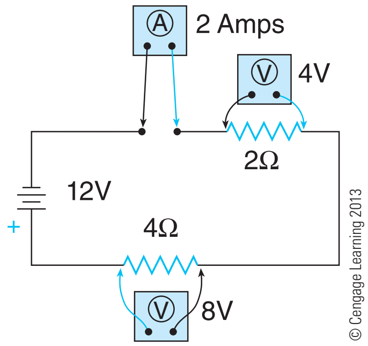

Figure 2-11 The characteristics of a series circuit.

through the conductor to the first resistor. At that resistor, some electrical energy or voltage is consumed (known as voltage drop) as the current flows through it. The decreased amount of voltage is then applied to the next resistor as current flows to it. By the time the current flows back to the battery, all available source voltage will have been consumed.

In a series circuit, the total amount of resistance in the circuit is equal to the sum of all the individual resistors, and the sum of all voltage drops in a series circuit equals source voltage.

A **parallel circuit** provides two or more different paths for the current flow. Each path has separate resistors (loads) and can operate independently of the other paths **(Figure 2-12).** The different paths for current flow are commonly called the legs of a parallel circuit.

A parallel circuit is characterized by the following facts:

- Total circuit resistance is always lower than the resistance of the leg with the lowest total resistance.
- The current through each leg will be different if the resistance values are different.
- The sum of the current on each leg equals the total circuit current.
- The voltage applied to each leg of the circuit will be dropped across the leg.

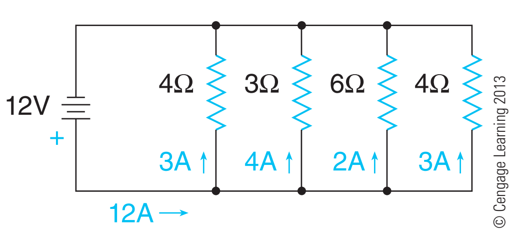

Figure 2-12 The characteristics of a parallel circuit.

CIRCUIT COMPONENTS

Automotive electrical circuits contain a number of different types of electrical devices. The more common components are outlined here.

Resistors

Resistors are used to limit current flow (and thereby voltage) in circuits where full current flow and voltage are not needed or desired. Resistors are devices specially constructed to put a specific amount of resistance into a circuit. In addition, some other components use resistance to produce heat and even light. An electric window defroster is a specialized type of resistor that produces heat. Electric lights are resistors that get so hot they produce light.

Fixed-value resistors are designed to have only one rating, which should not change. These resistors are used to decrease the amount of voltage applied to a component. **Tapped** or **stepped resistors** are designed to have two or more fixed values. Different amounts of voltage are available at the several taps of the resistor **(Figure 2-13).** Heater blower motor resistor packs, which provide for different fan speeds, are an example of this type of resistor.

Variable resistors are designed to have a range of resistances available through two or more taps and a control. Two examples of this type of resistor are **rheostats** and **potentiometers**. Rheostats have two connections, one to the fixed end of a resistor and one to a sliding contact with the resistor **(Figure 2-14).** Moving the control moves the sliding contact away from or toward the fixed-end tap, increasing or decreasing the resistance. Potentiometers have three connections, one at each end of the resistance and one

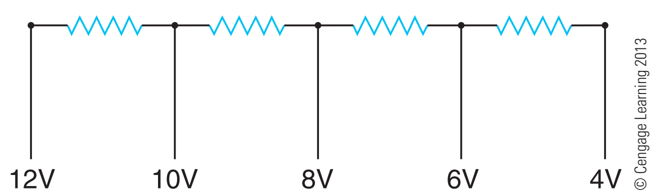

Figure 2-13 A row of 2-ohm resistors with taps. Notice how the available voltage is different at each tap.

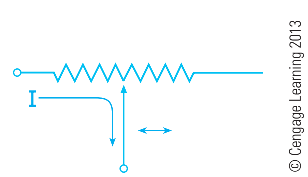

Figure 2-14 A rheostat.

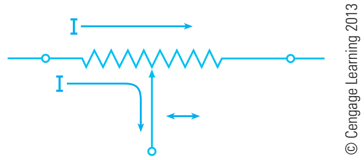

Figure 2-15 A potentiometer.

connected to a sliding contact with the resistor **(Figure 2-15).** Moving the control moves the sliding contact away from one end of the resistance, but toward the other end. These are called potentiometers because different amounts of potential or voltage can be sent to another circuit. As the sliding contact moves, it picks up a voltage that is equal to the source voltage minus the amount dropped by the resistance at that point across the resistor.

Another type of variable resistor is the **thermistor**. This resistor is designed to change its resistance value as its temperature changes **(Figure 2-16).** Although most resistors are carefully constructed to maintain their rating within a few ohms through a range of temperatures, the thermistor is designed to change in response to changing temperatures. Thermistors are

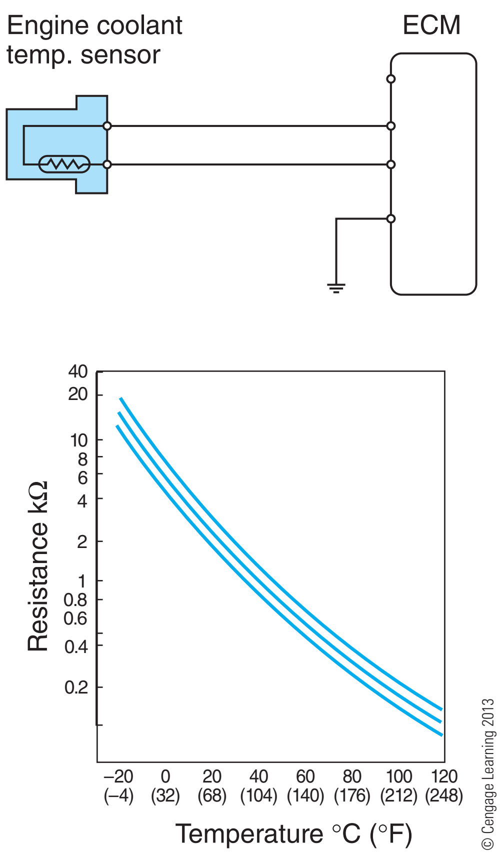

Figure 2-16 This engine coolant temperature sensor is an example of a thermistor. Notice how the resistance changes with temperature.

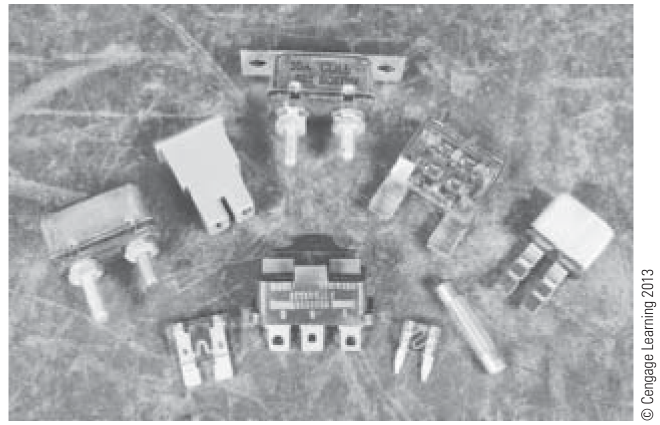

Figure 2-17 Various circuit protection devices.

used to provide compensating voltage in components or to determine temperature.

Circuit Protective Devices

When overloads or shorts in a circuit cause too much current to flow, the wiring in the circuit heats up, the insulation melts, and a fire can result, unless the circuit has some kind of protective device. Fuses, fuse links, maxi-fuses, and circuit breakers are designed to provide protection from excessive current **(Figure 2-17).** They may be used singularly or in combination.

> **CAUTION** *For 42-volt and higher systems, such as those used in electric and hybrid vehicles, there is a unique problem with circuit protection; most circuit protection devices used in 12-volt systems are actually rated at 32 volts. If these protection devices were used in a 42+-volt system, problems such as severe damage to the vehicle's wiring and electrical components could result. The burning of the components and wiring could also cause a fire. Higher-voltage systems must be protected with devices that have a higher voltage rating than the normal system voltage.*

Switches

Electrical circuits are usually controlled by some type of switch. Switches do two things. They turn the

of current in a circuit. Switches can be under the control of the driver or they can be self-operating through a condition of the circuit, the vehicle, or the environment. A temperature-sensitive switch usually contains a bimetallic element heated either electrically or by another component. This type switch is often

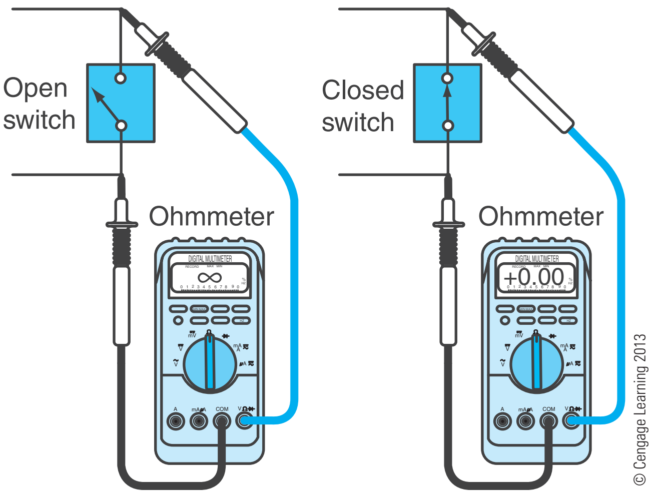

Figure 2-18 The action of a simple switch.

used as a **sensor**. When engine coolant is below or at normal operating temperature, the engine coolant temperature sensor is in its normally open condition. If the coolant exceeds the temperature limit, the bimetallic element bends the two contacts together and the switch closes and causes the indicator on the instrument panel to illuminate. Other applications for heat-sensitive switches are time-delay switches and turn signal flashers.

Relays

A **relay** is an electric switch that allows a small amount of current to control a high-current circuit **(Figure 2-19).** When the control circuit switch is open, no current flows to the coil of the relay, so the windings are de-energized. When the switch is closed, the coil is energized, turning the soft iron core and surrounding wire coil into an electromagnet. This draws the relay's armature (core) down against spring pressure, to close the power circuit contacts, connecting power to the load circuit. When the control switch is opened, current stops flowing in the coil and the strength of the electromagnet disappears. This releases the armature, which breaks the power circuit contacts.

Solenoids

Solenoids are electromagnets with movable cores; they are used to change electrical energy into mechanical movement. They can also close contacts, acting as relays at the same time.

Capacitors

Capacitors (condensers) are comprised of two or more sheets of electrically conducting material with a nonconducting or **dielectric** (anti-electric) **material** placed between them. Conductors are connected to the two sheets. Capacitors are devices that oppose a change of voltage or current.

If a battery is connected to a capacitor, the capacitor will be charged when current flows from the battery to the plates **(Figure 2-20).** This current flow will continue until the plates have the same voltage as the battery. At this time, the capacitor is charged and remains charged until a circuit is completed between the two plates. The capacitor will discharge when the circuit connects the positive lead to the negative lead.

When a capacitor is connected to AC voltage, it will accumulate only a limited amount of charge before the voltage changes polarity and the charge dissipates. The higher the frequency of the AC voltage, the less charge will accumulate, and there will be less opposition to current flow.

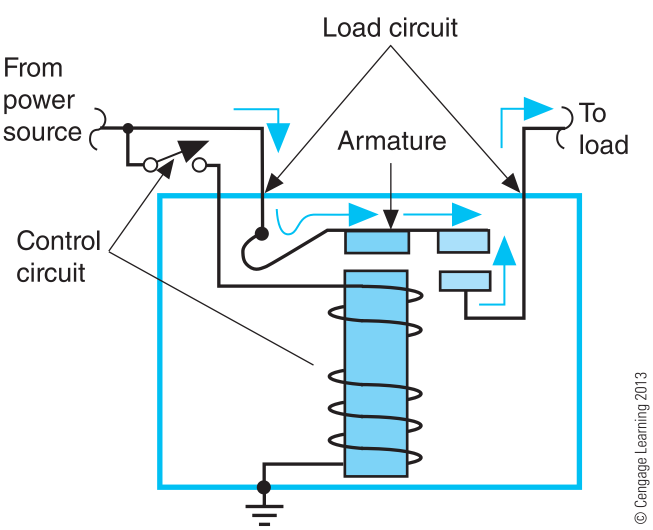

Figure 2-19 A relay.

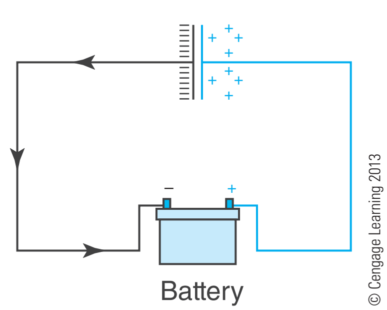

Figure 2-20 The action of a capacitor.

Semiconductors

A **semiconductor** is a material or device that can serve as a conductor or an insulator. Semiconductors have no moving parts; therefore, they seldom wear out or need adjustment. Semiconductors, or solid-state devices, are also small, require little power to operate, are reliable, and generate relatively little heat. However, current to them must be limited, as must heat.

Because a semiconductor can function as both a conductor and an insulator, it is often used as a switching device. How it behaves depends on what it is made of and which way current flows (or tries to flow) through it. Two common semiconductor devices are diodes and transistors. Diodes are used for isolation of components or circuits, clamping (voltage limiting), or rectification of AC to DC. Transistors are used for amplification or switching.

Semiconductor materials have a crystal structure. This means their atoms do not lose and gain electrons as conductors do. Instead, the atoms in semiconductors share outer electrons with each other. In this type of atomic structure, the electrons are tightly held and the element is stable. Common semiconductor materials are silicon (Si) and germanium (Ge).

Because the electrons are not free, the crystals cannot conduct current, and so they are called **electrically inert** materials. For these materials to function as semiconductors, a small amount of trace element, called **impurities**, must be added. This is referred to as doping. The type of impurity determines the type of semiconductor.

N-type semiconductors have loose, or excess, electrons **(Figure 2-21).** They have a negative charge and can carry current. N-type semiconductors have an impurity with five electrons in its outer ring (that is, it is composed of pentavalent atoms). Four of these electrons fit into the crystal structure, but the fifth is free. This excess of electrons produces the negative charge.

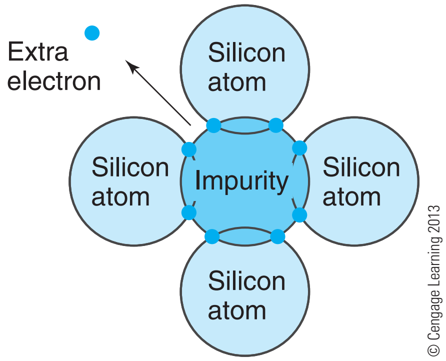

Figure 2-21 N-type semiconductors have extra electrons in their outer ring, which gives the material a negative charge.

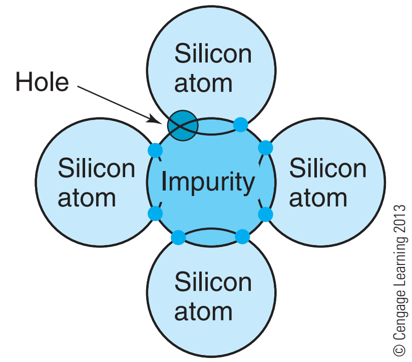

Figure 2-22 A P-type semiconductor has an impurity that leaves a hole for an additional electron to fit into the outer ring.

P-type semiconductors are positively charged materials **(Figure 2-22).** They are made by adding an impurity with three electrons in its outer ring (trivalent atoms). When this element is added to silicon or germanium, the three outer electrons fit into the pattern of the crystal, leaving a hole where a fourth electron would fit. This hole is actually a positively charged empty space. This hole carries the current in the P-type semiconductor.

Diodes

The **diode** is a simple semiconductor **(Figure 2-23).** The most commonly used are regular diodes, light-emitting diodes (LEDs), zener diodes, clamping diodes, and photo diodes. A diode allows current to flow in one direction; therefore, it can serve as a conductor or insulator, depending on the direction of current flow. In an AC generator, voltage is rectified to DC by diodes **(Figure 2-24).** The diodes are arranged so that current can leave the AC generator in one direction only (as direct current).

Inside a diode are positive and negative areas that are separated by a boundary area. The boundary area is

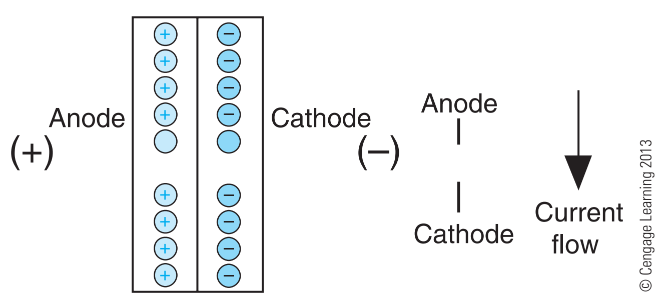

Figure 2-23 The basic construction, electrical symbol, and direction of current flow of a diode.

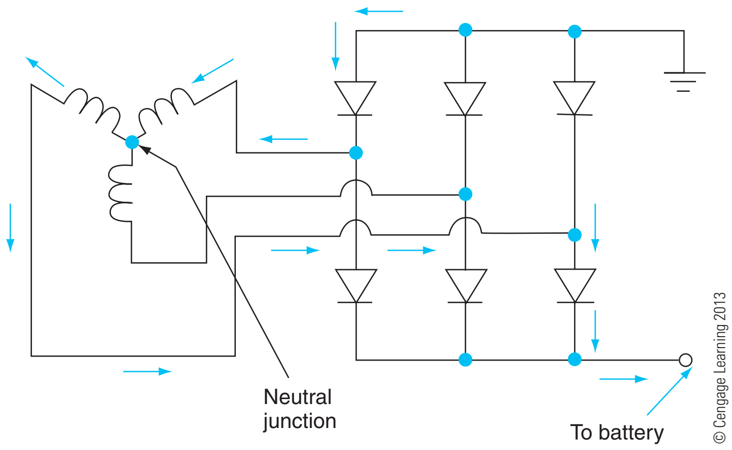

Figure 2-24 Diodes are used to change the AC voltage from a generator into DC.

called the PN junction. When the positive side of a diode is connected to the positive side of the circuit, it is said to have **forward bias**.

Unlike electrical charges are attracted to each other and like charges repel each other. Therefore, the positive charge from the circuit is attracted to the negative side. The circuit's voltage is much stronger than the charges inside the diode, which causes the diode's charges to move. The diode's P material is repelled by the positive charge of the circuit and is pushed toward the N material and the N material is pushed toward the P. This causes the PN junction to become a conductor, allowing current to flow.

When **reverse bias** is applied to the diode, the P and N areas are connected to opposite charges. Since opposites attract, the P material moves toward the negative part of the circuit and the N material moves toward the positive part of the circuit. This empties the PN junction, and current flow stops.

A **zener diode** works like a standard diode until a certain voltage is reached. When the voltage reaches this point, the diode allows current to flow in the reverse direction. Zener diodes are often used in electronic voltage regulators.

LEDs emit light as current passes through them **(Figure 2-25).** The color of the emitted light depends on the material used to make the LED. Typically, LEDs are made from a variety of inorganic semiconductor materials that produce different colors.

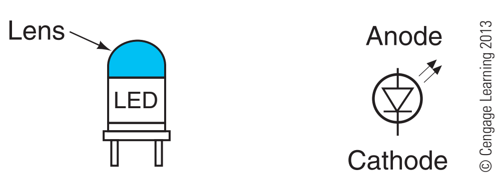

Figure 2-25 An LED and its electrical symbol.

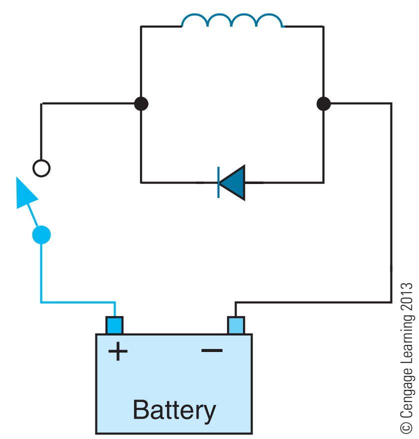

Figure 2-26 A clamping diode is connected in parallel with a coil to prevent voltage spikes that normally occur when the switch is opened.

Whenever the current flow through a coil of wire (such as that used in a solenoid or relay) stops, a voltage surge or spike is produced. This surge results from the collapsing of the magnetic field around the coil. The movement of the field across the winding induces a very high voltage spike, which can damage electronic components. In the past, a capacitor was used as a "shock absorber" to prevent component damage from this surge. On today's vehicles, a **clamping diode** is commonly used to prevent this voltage spike **(Figure 2-26).** Installing a clamping diode in parallel with the coil provides a bypass for the electrons during the time the circuit is opened.

Transistors

A **transistor** is produced by joining three sections of semiconductor materials. Like the diode, it is used as a switching amplifying device, functioning as either a conductor or an insulator. A transistor resembles a

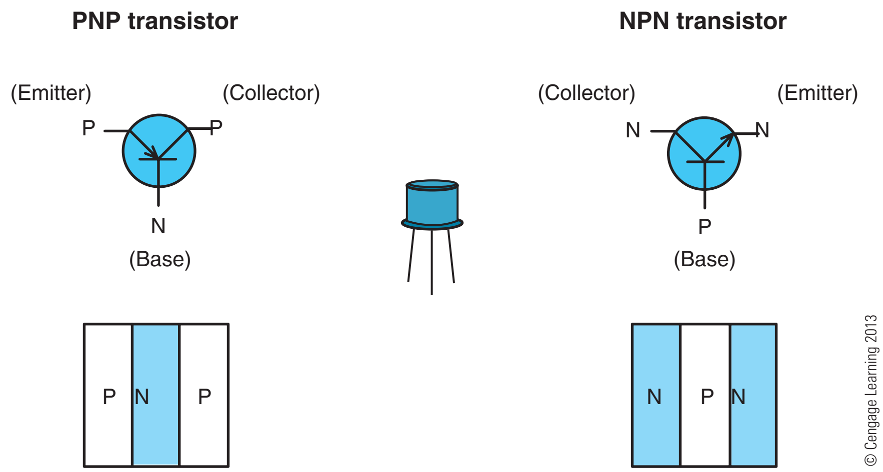

Figure 2-27 PNP and NPN transistors.

diode with an extra side. It can consist of two P-type materials and one N-type material or two N-type materials and one P-type material. These are called **PNP** and **NPN** types **(Figure 2-27).** In both types, junctions occur where the materials are joined. Each of the three sections has a lead connected to it. This allows any of the three sections to be connected to the circuit. The different names for the legs are the **emitter**, **base**, and **collector**.

The center section is called the base and is the controlling part of the circuit or the place where the larger controlled part of the circuit is switched. The path to ground is through the emitter. A resistor is normally in the base circuit to keep current flow low. This prevents damage to the transistor. The emitter and collector make up the control circuit. When a transistor is drawn in an electrical schematic, there is an arrow on the emitter. Current always flows against the arrow.

The base of a PNP transistor is controlled by its ground. Current flows from the emitter through the base, then to ground. A negative voltage or ground must be applied to the base to turn on a PNP transistor. When the transistor is on, the circuit from the emitter to the collector is complete.

An NPN transistor is the opposite of a PNP. When positive voltage is applied to the base of an NPN transistor, the collector-to-emitter circuit is turned on **(Figure 2-28).**

Transistors can also function as variable switches. When

completeness of the emitter and collector circuit will also vary. This is done simply by the presence of a variable resistor in the base circuit. This principle is used in light-dimming circuits.

A transistor commonly used in the control circuit of electric drive vehicles is the **insulated gate bipolar transistor** (IGBT). This is a high-current transistor **(Figure 2-29).** A single IGBT can handle large amounts of current. They most often are liquid cooled to control the heat generated by the high current.

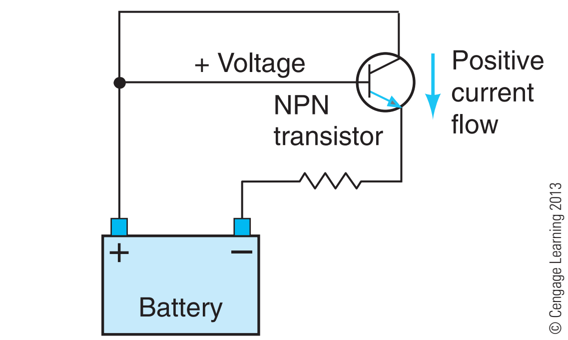

Figure 2-28 When the base is forward biased with a more positive voltage, the collector-to-emitter circuit is turned on.

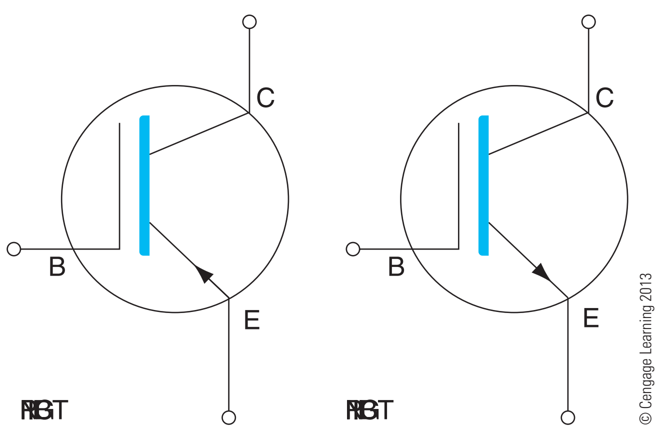

Figure 2-29 The electrical symbols for a PNP and NPN

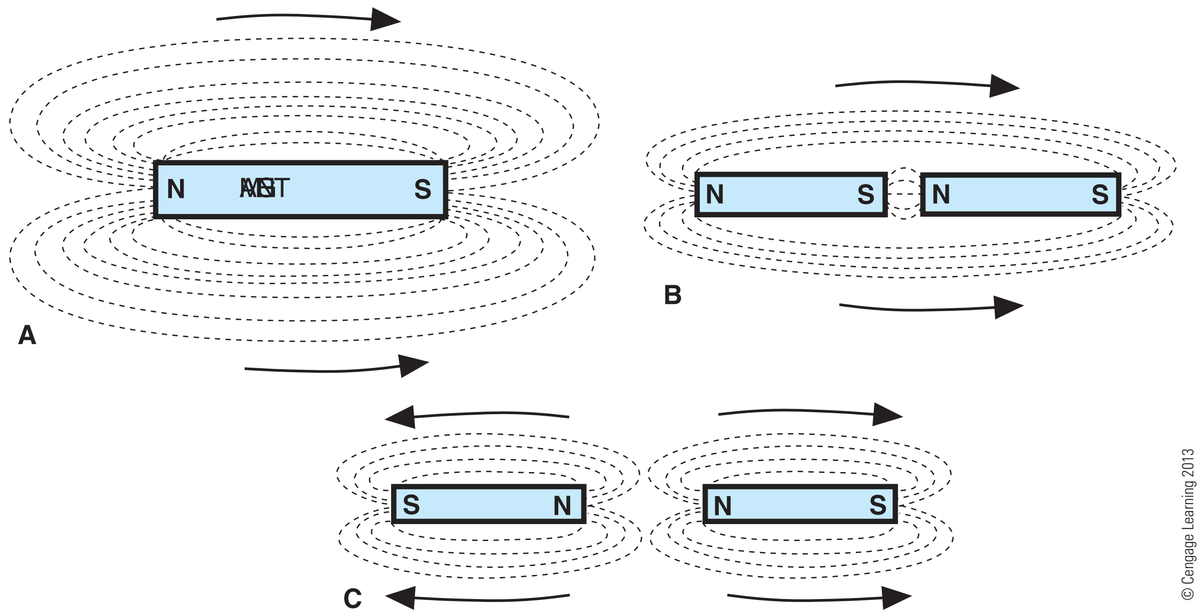

Figure 2-30 (A) The field of flux around a magnet. (B) Unlike poles attract each other. (C) Like poles repel.

ELECTROMAGNETISM BASICS

Electricity and magnetism are related. One can be used to create the other. Current flowing through a wire creates a magnetic field around the wire. Moving a wire through a magnetic field creates current flow in the wire. Many automotive components, such as generators, operate using these principles of electromagnetism.

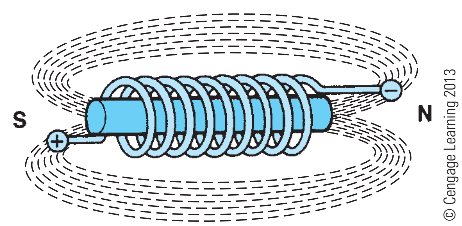

Figure 2-31 An electromagnet.

Fundamentals of Magnetism

A substance is said to be a magnet if it has the property of magnetism—the ability to attract substances such as iron, steel, nickel, or cobalt. These are called magnetic materials. A magnet has two points of maximum attraction, one at each end of the magnet. These points are called poles; one is designated as the north pole and the other is the south pole. When two magnets are brought together, opposite poles attract, whereas similar poles repel each other **(Figure 2-30).**

A magnetic field, called a **flux field**, exists around every magnet. The field consists of imaginary lines along which the magnetic force acts. These lines emerge from the north pole and enter the south pole, returning to the north pole through the magnet itself. All lines of force leave the magnet at right angles to the magnet.
all lines are complete.

Magnets can occur naturally in the form of a mineral called magnetite. Artificial magnets can be made by inserting a bar of magnetic material inside a coil of insulated wire and passing direct current through the coil **(Figure 2-31).** This principle is important in understanding certain automotive electrical components. Another way of creating a magnet is by stroking the magnetic material with a bar magnet. Both methods force the randomly arranged molecules of the magnetic material to align themselves along north and south poles.

Artificial magnets can be either temporary or permanent. Temporary magnets are usually made of soft iron. They are easily magnetized but quickly lose their magnetic properties. Permanent magnets are difficult to magnetize. However, once magnetized, they retain this property for long periods.

The more flux lines, the stronger the magnetic field. Increasing current through an electromagnet will increase **flux density**. Also, two conducting

same direction create a magnetic field equal in strength to one conductor carrying twice the current. Adding more wires also increases the magnetic field **(Figure 2-32).**

Looping a wire into a coil concentrates the lines of force around the wire. The resulting magnetic field

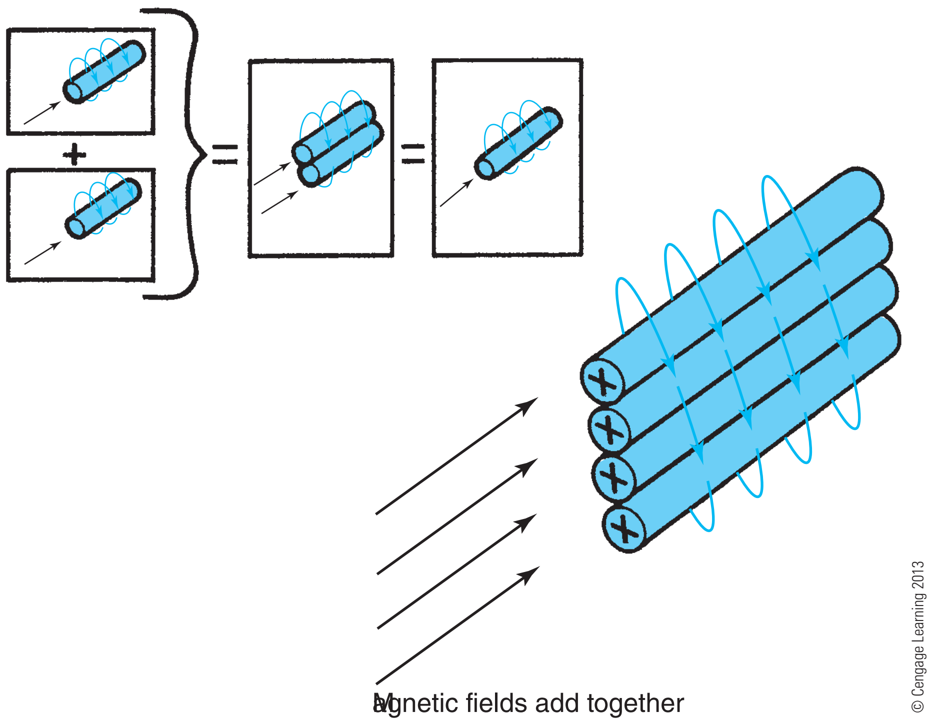

Figure 2-32 When conducting wires carrying equal currents in the same direction are placed next to each other, the strength of the magnetic field increases.

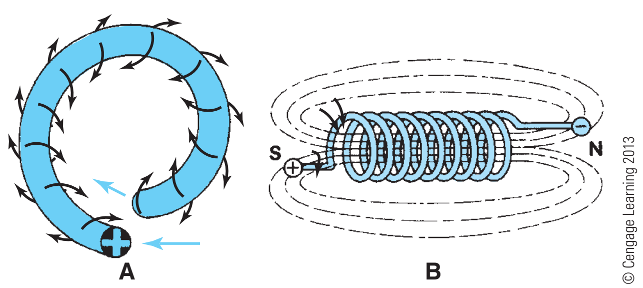

Figure 2-33 Looping a wire into a coil concentrates the lines of force around the wire.

is the sum of all the single-loop magnetic fields **(Figure 2-33).** The overall effect is the same as placing many wires side by side, each carrying current in the same direction.

Magnetic Circuits and Reluctance

Just as current can only flow through a complete circuit,

occupy a closed magnetic circuit. The resistance that a magnetic circuit offers to a line of flux is called **reluctance**. Magnetic reluctance can be compared to electrical resistance.

When a coil is wound around an iron core, it becomes a usable electromagnet. The strength of the magnetic poles in an electromagnet is directly proportional to the number of turns of wire and the current flowing through them. The behavior of an electromagnet can be summarized by these points:

- Field strength increases if current through the coil increases.
- Field strength increases if the number of coil turns increases.
- If reluctance increases, field strength decreases.

Induced Voltage

Now that we have explained how current can be used to generate a magnetic field, it is time to examine the opposite effect of how magnetic fields can produce electricity through a process called **induction**.

Figure 2-34 shows a straight piece of wire with the terminals of a voltmeter attached to both ends. If the wire is moved across a magnetic field, the voltmeter registers a small voltage reading. A voltage has been

It is important to realize that the wire must cut across the flux lines to induce a voltage. Moving the wire parallel to the lines of flux will not induce voltage. Voltage can also be induced by holding the wire still and moving the magnetic field at right angles to the wire. This is the exact setup used in most generators.

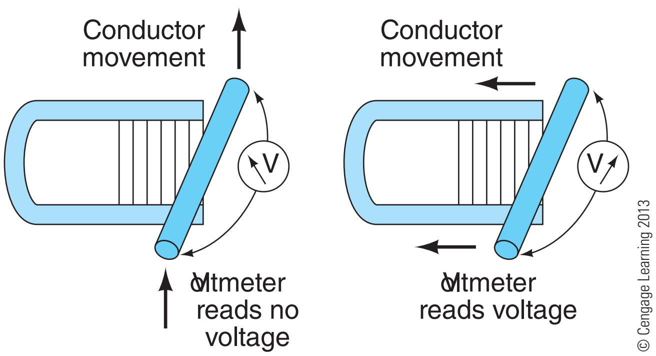

Figure 2-34 Moving a conductor through a magnetic field generates a voltage in the conductor.

A magnetic field is made to cut across stationary conductors to produce voltage.

The wire becomes a source of electricity and has a polarity or distinct positive and negative end. However, this polarity is switched as the wire moves in and out of the magnetic field. This is why charging devices produce alternating current.

The amount of voltage that is induced depends on four factors:

- The amount of voltage that can be induced is directly proportional to the strength of the magnetic field.
- The faster the field is being cut and the more lines of flux that are cut, the greater the amounts of induced voltage.
- The greater the number of conductors passing through the field, the greater the amount of voltage that can be induced.
- The closer the conductor(s) and magnetic field are to right angles (perpendicular) to one another, the greater the induced voltage.

Transformers

A **transformer** transfers electrical energy from one circuit to another through its windings. When a varying current is applied to the transformer's primary winding, varying magnetic flux lines are produced at the core of the transformer. This causes a varying magnetic field to cut through the transformer's secondary windings. This results in the induction of a varying amount of voltage in the secondary windi

The amount of induced voltage in the secondary winding is proportional to the primary voltage and the number of turns in the secondary winding compared to the number of turns in the primary. When the secondary winding has fewer turns than the primary, the voltage is stepped down. Voltage is stepped up when the secondary has more turns than the primary.

ELECTRICAL SYSTEMS

Typical automotive voltages are approximately 12 volts. In a typical internal combustion engine (ICE) vehicle, this voltage is used to operate everything electrical on the car. Although this is called a 12-volt system, the battery actually stores about 14 volts and the charging system puts out 14 to 15 volts while the engine is running. Because the primary source of electrical power when the engine is running is the charging system, it is fair to say an automobile's electrical system is a 14-volt system.

Today's vehicles, with their electronics, put a good deal of drain on the 12-volt charging system. This has led to the development of 42-volt systems **(Figure 2-35),** which represent three 12-volt batteries (3 times 14 volts equals 42 volts). A 42-volt system is also desirable for safety reasons. Sixty volts can stop a person's heart from beating; therefore, 42-volt systems allow for a margin of safety. The higher voltages also allow for smaller conductors because operating current is lower.

High-Voltage Systems

High-voltage systems are those electrical systems that operate with more than 50 volts, including battery-electric vehicles (BEVs), hybrid electric vehicles (HEVs), and fuel cell electric vehicles (FCEVs). These vehicles need very high voltages to operate the electric motors and keep current levels low. Most electric drive vehicles

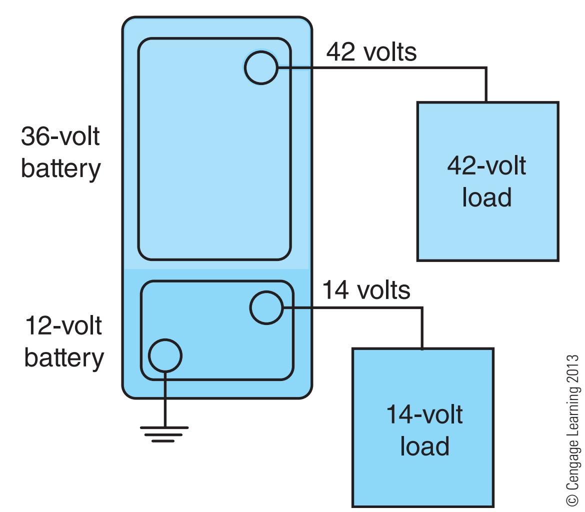

Figure 2-35 A 42-volt battery with a tap for 14-volt loads.

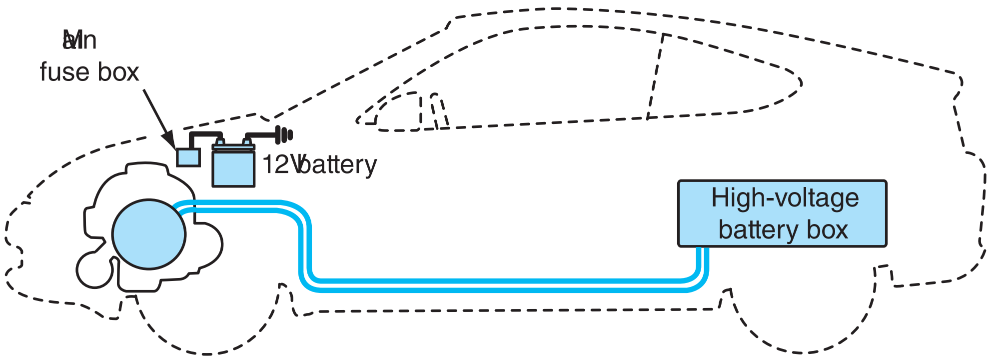

Figure 2-36 A hybrid car with two batteries, one low-voltage and the other high-voltage.

also have a separate 12-volt system to operate the lights and other common accessories **(Figure 2-36).** The high voltages range from 144 to 650, depending on the system. With these high voltages come special precautions, including the following:

- If a repair operation is incorrectly performed, an electrical shock, leakage, or explosion can be caused. Be sure to perform repair operations correctly.
- Always follow the manufacturer's procedures to disconnect the power source before working on the high-voltage system.
- Systems may have a high-voltage capacitor that must be discharged after the high-voltage system has been isolated. Make sure to wait the prescribed amount of time (about 10 minutes) before working on or around the high-voltage system.
- Wear insulating gloves that are protected by leather outer gloves when working on or around the high-voltage system. Make sure the gloves have no tears, holes, or cracks, and that they are dry.
- The wire harnesses and connectors with high-voltage circuits are colored orange. In addition, high-voltage parts have a "high voltage" caution label. Be careful not to touch these wires.
- After removing a high-voltage cable, cover the terminal with vinyl tape.
- Always use insulated tools.
- Alert other technicians that you are working on high-voltage systems with a warning sign such as "High-voltage work: do not touch."
- Do not carry any metal objects such as a pen or a measuring tape that could fall and cause a short circuit.

Review Questions

1. What is the name for the formula E = IR?
2. *True or False:* In a series circuit, circuit current is the same throughout the circuit.
3. What type of wire is most commonly used in automobiles?
4. What are the four factors that determine how much voltage can be induced with a magnet?
5. How can you identify high-voltage circuits in an electric drive vehicle?
6. ______________.
7. What happens in an electrical circuit when its resistance increases?
8. What is the difference between voltage and current?

9. *True or False:* The strength of the magnetic poles in an electromagnet decreases with an increase in the number of turns of wire and the current flowing through them.

10. Which of the following is a characteristic of all parallel circuits?

    A. Total circuit resistance is always higher than the resistance of the leg with the lowest total resistance.

    B. The current through each leg will be different if the resistance values are different.

    C. The sum of the resistance on each leg equals the total circuit resistance.

    D. The voltage applied to each leg of the circuit will be dropped across the legs if there are loads in series with the parallel circuit.

CHAPTER 3 Motor and Generator Basics

Learning Objectives

After reading and studying this chapter, you should be able to:

- Describe the basic operation of all electric motors.
- Understand the importance of magnetic principles in the operation of a motor and generator.
- Summarize the principles of magnetism described by Faraday's and Lenz's laws.
- Identify the major parts of a DC motor.
- Compare the operation of a brushless DC motor to a brushed DC motor.
- Understand the characteristics of three-phase AC voltage and describe the operation of a three-phase AC motor.
- Explain the differences between a motor and a generator (AC and DC).
- Explain the purposes of a controller in a motor/generator circuit.
- Define the purpose of an inverter.

Key Terms

controller	half-wave rectification	sensing voltage
converter	induction motor	sine wave
counter-EMF (CEMF)	inverter	synchronous motor
delta configuration	pulse width modulation (PWM)	three-phase voltage
duty cycle	reactance	torque
full-wave rectification	self-inductance	wye configuration

INTRODUCTION

The operation of an electric motor (and generator) is based on the basic principles of magnetism. The most important principle is that like magnetic poles repel each other and unlike poles are attracted to each other. Motors use the interaction of magnetic fields to change electrical energy into mechanical energy. A generator, which is constructed much like a motor, changes mechanical energy into electrical energy.

This means they are magnetic in their natural state or they have the ability to become magnets when stimulated. Metals such as iron, nickel, and cobalt have a natural ability to become magnets. When these metals are placed into an external magnetic field, their

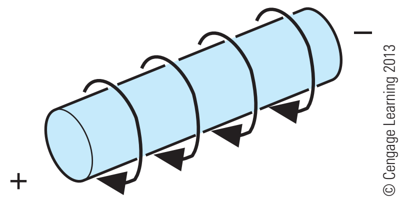

Figure 3-1 When electric current passes through a conductor, a magnetic field is created around that conductor.

magnetic properties align, and they become strong permanent magnets. Other metals do not have the same magnetic properties but can become magnets when electrical current is passed through them. However, when the electrical current through the material is stopped, the metal is no longer a magnet. Examples of these metals are aluminum and copper.

When electric current passes through a conductor, a magnetic field is created around that conductor **(Figure 3-1).** The magnetic field around a single straight wire forms loops around the wire—the current's magnetic field would push a magnetic pole near it around in a circle about the wire. If loops of current-carrying wire are wound around something that is easily magnetized, the metal becomes magnetized. This current-carrying coil develops a north pole at one end of the coil and a south pole at the other. The polarity of the coil depends on the direction of current flow through the loop.

If a conductor is passed through a magnetic field, voltage is induced in that wire. This is the basis for the operation of a generator.

For both generators and motors there is a relationship between the direction of the magnetic flux lines, the direction of motion of the conductor or force acting on the conductor, and the direction of the applied voltage.

Simple Explanation of Basic Motor Types

Electric drive vehicles can use AC voltage or DC voltage motors:

- If the motor is a DC motor, then it may run on anything from 36 to 192 volts. Many of the DC motors used in electric cars come from the

- If it is an AC motor, then it probably is a three-phase AC motor. The operating voltages vary with manufacturer and application. For example, the Toyota Hybrid Highlander has three motor/generators—all are permanent magnet AC units running at a maximum of 650 volts.

The Distant Past

To get an accurate look at the history of motors and generators, we need to look at the origin of certain terms. The first generators and motors were called "dynamos" or "dynamoelectric" machines. Dynamo is from the Greek word *dynamis*, which means power. Dynamoelectric is defined as "relating to the conversion of mechanical energy into electrical energy or vice versa." The word *motor* is from the Latin word *motus*, which means one that imparts motion or prime mover. The dynamo was the result of the efforts of several people, in different countries in the mid-nineteenth century, to make electricity work for them. A generator is a device that changes mechanical energy into electrical energy. Although generators can be either AC or DC, a generator is normally considered a device that provides DC current. An alternator is a device that changes mechanical energy into alternating current electrical energy, which means it is an AC generator. Here are some important dates regarding the development of motors and generators:

- 1820: The discovery of electromagnetism by Hans Christian Oersted.
- 1827: The statement of the law of electric conduction, Ohm's law, by Georg S. Ohm.
- 1830: The discovery of electromagnetic induction by Joseph Henry and Michael Faraday.
- 1867: The development of the first practical dynamo.

These developments took place after another important event in history. During the eighteenth century in England, Thomas Newcomen invented a steam engine that was used to pump water from coal mines. In 1769, James Watt from Scotland improved the steam engine and applied it to other uses. In order to sell the practicality of the engine, he needed to show that his engine could do the work of a horse. Through much testing, he determined a standard that is commonly used today. He found that a horse can work at a rate of 33,000 foot-pounds per minute. This is the standard for measuring horsepower. Today, electric motors are rated in horsepower and watts (voltage multiplied by current output [1,000 W = 1 kW, which equals approximately 1-⅓ HP]).

BASIC MOTOR OPERATION

An electric motor converts electric energy into mechanical energy. Through the years, electric motors have changed substantially in design; however, the basic operational principles have remained the same.

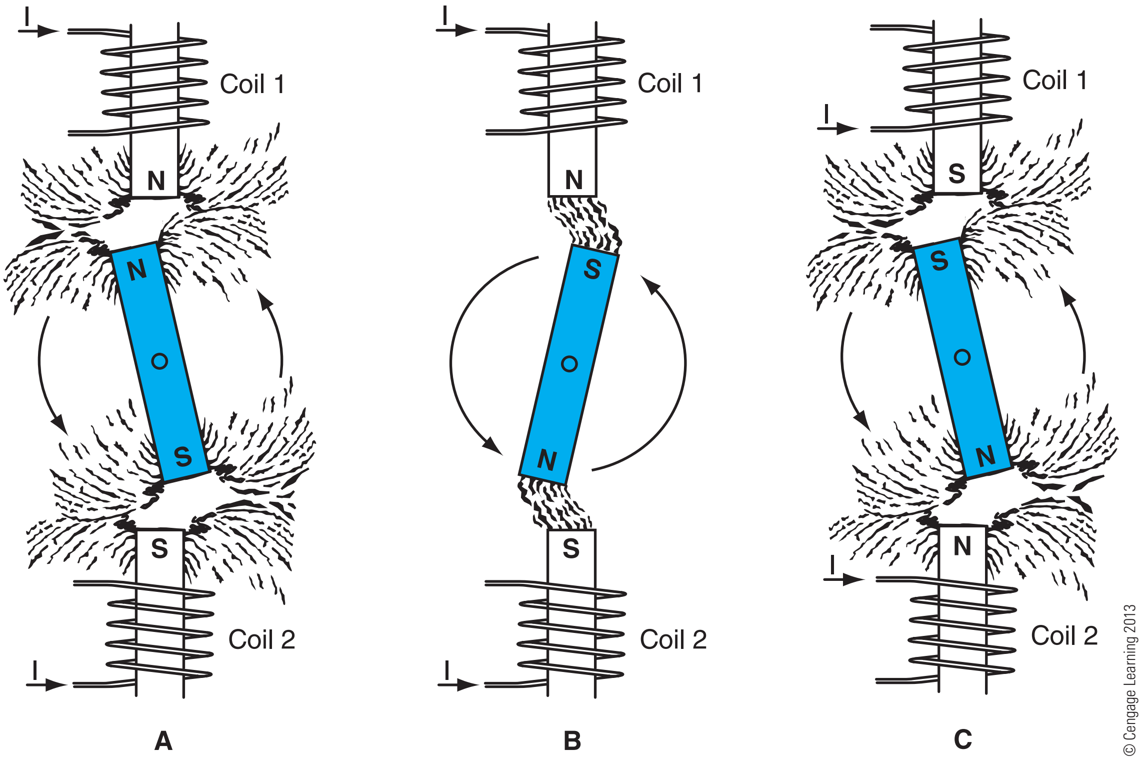

Figure 3-2 (A) Like poles repel, (B) unlike poles are attracted to each other, and if we change the polarity of the coils, (C) the like poles again repel.

That principle is easily observed by taking two bar magnets and placing them end-to-end with each other. If the ends have the same polarity, they will push away from each other. If the ends have the opposite polarity, they will move toward each other and form one magnet.

If we put a pivot through the center of one of the magnets to allow it to spin, and moved the other magnet toward it, the first magnet will either rotate away from the second or move toward it **(Figure 3-2).** This is basically how a motor works. Although we do not observe a complete rotation, we do see part of one, perhaps a half turn. If we could change the polarity of the second magnet, we would get another half turn. So in order to keep the first magnet spinning, we need to change the polarity immediately after it moves halfway. If we continued to do this, we would have a motor.

In a real motor, an electromagnet is fitted on a shaft. The shaft is supported by bearings or bushings to allow

motor. Surrounding, but not touching, this inner magnet is a stationary permanent magnet or an electromagnet. Actually, there is more than one magnet or magnetic field in both components. The polarity of these magnetic fields is quickly switched, and we have a constant opposition and attraction of magnetic fields. Therefore, we have a constantly rotating inner magnetic field, the shaft of which can do work due to the forces causing it to rotate **(Figure 3-3).** This force is called **torque**. The torque of a motor varies with rotational speed, motor design, and the amount of current draw the motor has. The speed of the rotation depends on a number of factors, such as the current draw of the motor, the design of the motor, and the load on the motor's rotating shaft.

Other basic principles must be explained before going into detail about the operation of the basic types of motors: DC and AC.

Electromagnets

When electrical current passes through a wire, a magnetic field is formed around that wire. The flux lines of the magnetic field form in concentric circles around the wire. The direction of the magnetic field can be determined by the *left hand rule*. This rule

the direction of the current flow, your fingers will point in the direction of the magnetic field **(Figure 3-4).** Remember, the attraction of poles is from north to south.

When the wire is shaped into a coil or winding, the individual flux lines produced by each section of wire

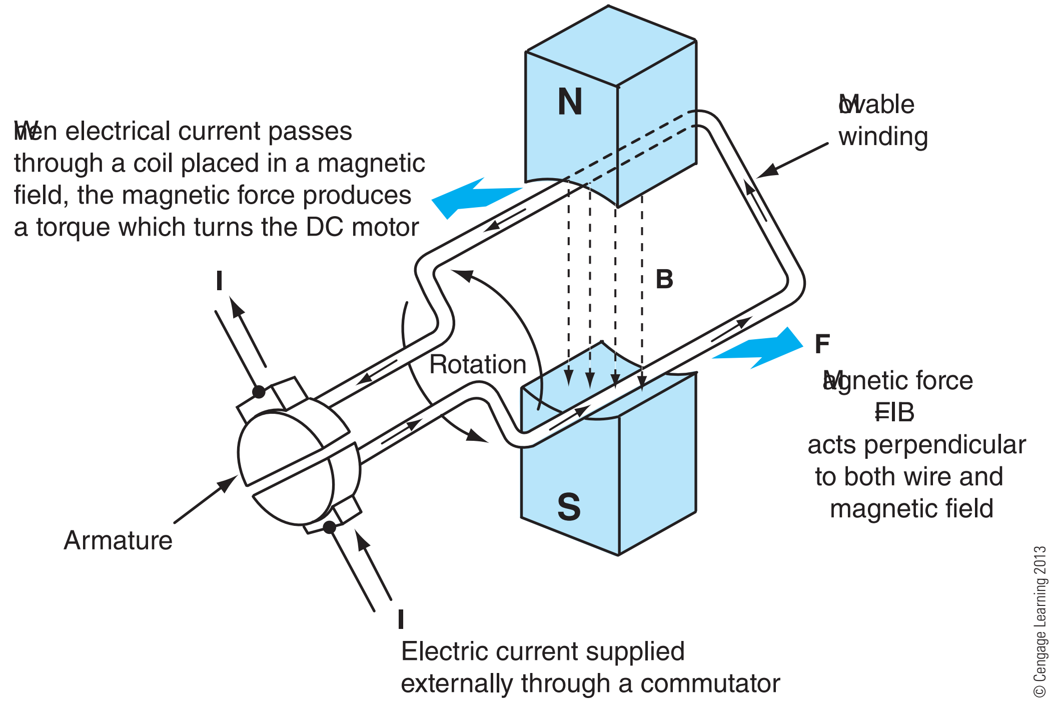

Figure 3-3 A simple look at what keeps a motor running.

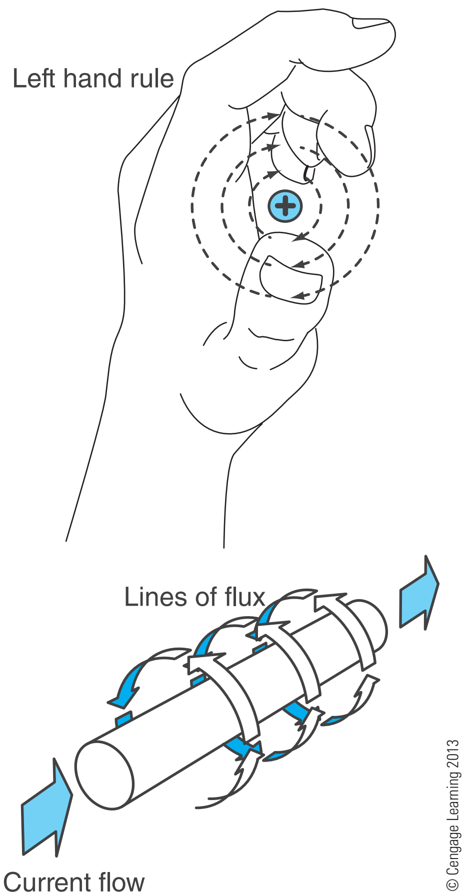

Figure 3-4 The magnetic lines of flux around a current-carrying conductor leave from the north pole and reenter at the south pole.

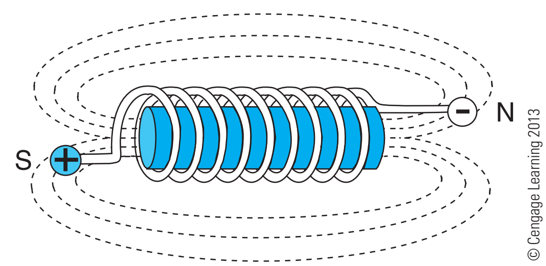

Figure 3-5 The magnetic field around the coil can be strengthened by placing a core of iron or similar metal in the center of the coil.

join together to form one large magnetic field around the total coil. The magnetic field around the coil can be strengthened by placing a core of iron or similar metal in the center of the coil **(Figure 3-5).** The iron core presents less resistance to the lines of flux than air, and the magnetic field's strength increases.

The basic components of a motor are the stator or field windings that are the stationary part of the motor and the rotor or armature that is the rotating part **(Figure 3-6).** The stator is comprised of slotted cores

copper wire to form one or more pairs of magnetic poles. Some motors have the field windings wound around iron anchors, called pole shoes. The rotor is comprised of loops of current-carrying wire, or it can be a series of permanent magnets. The magnetic fields in the rotor are pushed away by the magnetic field in

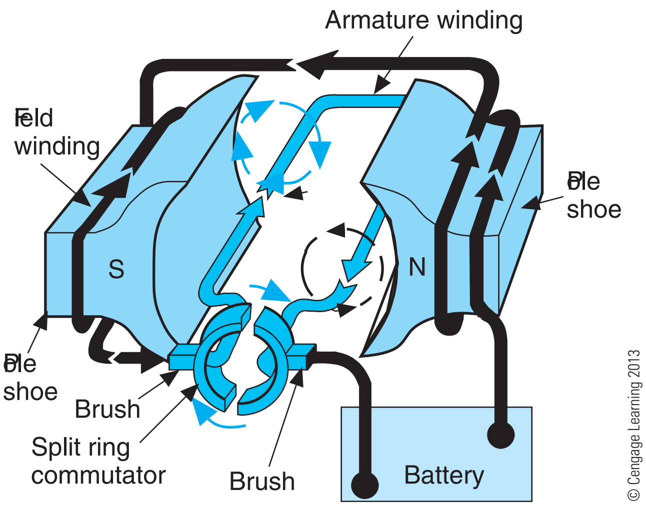

Figure 3-6 A simple DC motor.

the stator, causing the rotor to rotate away from the stator field.

The use of an electromagnet in a motor makes it easy to change polarity in a magnetic field and keep a motor spinning. By changing the direction of current flow, the magnetic polarities are changed.

Generators

Just as electricity can be used to create a magnetic field, a magnetic field can be used to produce electricity. If a conductor is passed through the flux lines of a magnet, voltage is induced. Electrical current will result if that voltage has a path to and from a load and if the voltage is strong enough to push through the load.

The polarity of the induced voltage depends on the direction of the movement of the conductor through the magnetic field. In one direction a positive voltage is induced; in the other, a negative voltage is induced **(Figure 3-7).** Moving the conductor back and forth through the field produces both, which is AC voltage. The amount of voltage induced increases as the magnetic field becomes stronger, as the field is being cut faster or more lines of flux are cut, and as the conductor(s) and magnetic field move closer to each other while they are at right angles to one another.

Faraday's Law

Faraday's law is a summary of the ways in which a voltage can be generated by a changing magnetic field. Michael Faraday (1791–1867) was a British physicist and chemist who is best known for his laws regarding electromagnetic induction and electrolysis.

Faraday's law states that, "the EMF (electromotive force [voltage]) induced between the ends of a loop or coil is proportional to the rate of change of magnetic flux enclosed by the coil; or the EMF induced between the ends of a bar conductor is proportional to the time rate at which magnetic flux is cut by the conductor." Faraday discovered that voltage can be established between the ends of a conductor by doing three things:

- By a conductor moving or cutting across a stationary magnetic field (DC generator)
- By a moving magnetic field cutting across a stationary conductor (AC generator)
- By a change in the number of magnetic lines enclosed by a stationary loop or coil (transformer or ignition coil)

Self-Inductance

When DC voltage is applied to a coil of wire, current does not immediately flow at its maximum rate.

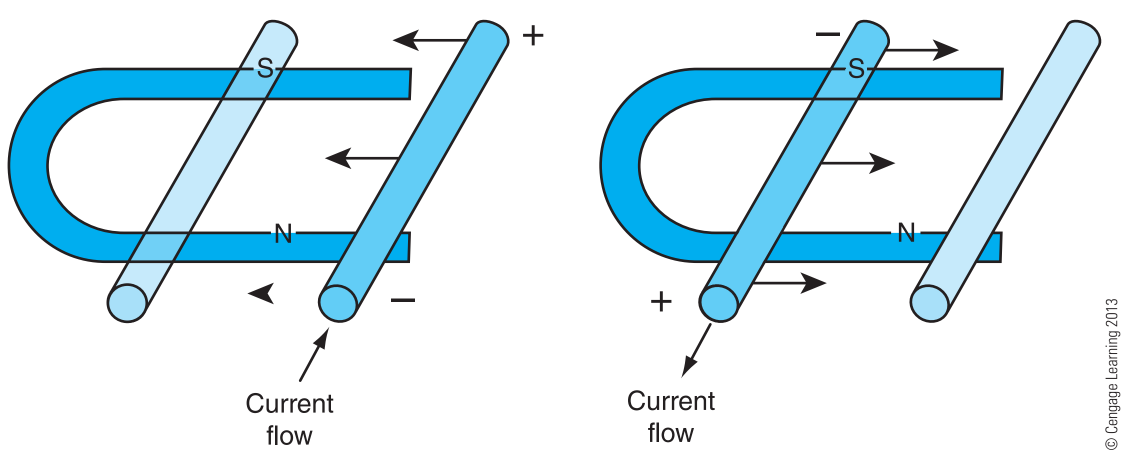

Figure 3-7 The polarity of the induced voltage depends on the direction in which the conductor moves as it cuts across the magnetic field.

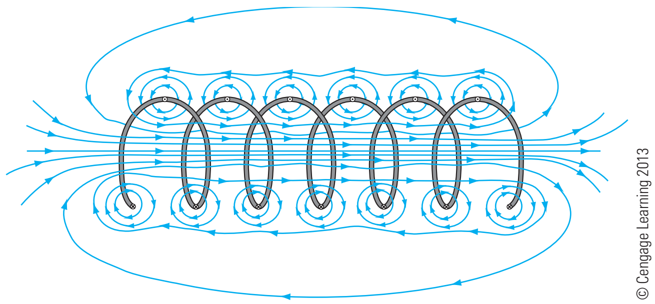

Figure 3-8 As current passes through a coil, CEMF is formed.

The rate of current buildup is determined by the amount of **counter-EMF (CEMF)** that is induced in the coil. This counter-EMF is the result of self-inductance in the coil. **Self-inductance** is the induction of an opposite voltage in a current-carrying wire by adjacent coils when the conductor is wound in a coil.

When AC is introduced, a magnetic field created by the changing current in the circuit induces a voltage in that circuit. Therefore, voltage is self-induced. The AC flowing through the coil creates a magnetic field in and around the coil that increases and decreases as the current changes. The magnetic field forms concentric loops that surround the wire and join together to form larger loops that surround the coil **(Figure 3-8).** When current increases in one loop, the expanding magnetic field cuts across some or all of the other loops, inducing a voltage in them opposing the external voltage applied to the coil. This induction is explained by Lenz's law.

Lenz's Law

In 1834, Heinrich Lenz of Germany further defined the characteristics of electromagnetic induction. Lenz's law states that when a voltage is generated by a change in magnetic flux according to Faraday's law, the polarity of the induced voltage will produce a current with a magnetic field that opposes the change that produces it.

CEMF is evidence of Lenz's law. Counter-EMF is a force that opposes EMF or voltage. CEMF limits the voltage that is induced and serves as an electrical resistance to current flow in a motor. CEMF limits current

formed around the loops or wire, the magnetic fields form in opposite directions on the sides of the loop. This action induces a small voltage in the wire, and that voltage opposes the regular voltage of the circuit.

Current through a length of straight wire will be much greater than the current through a coiled wire of

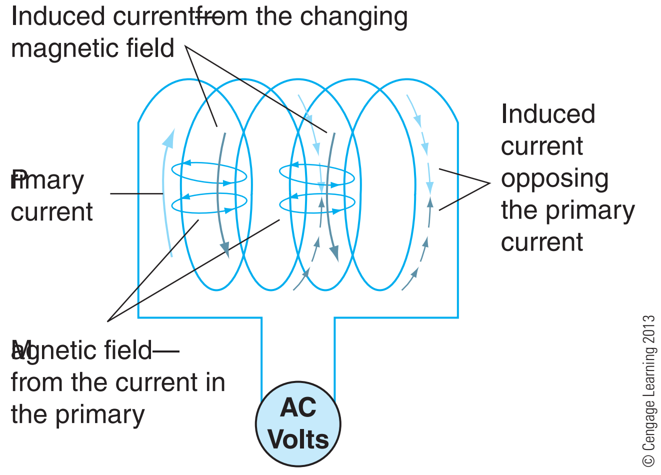

Figure 3-9 When AC voltage is applied to a coil, the induced current opposes the primary current.

the same length. This is the result of CEMF. This occurrence affects the current draw of a motor and the output of a generator.

Both Faraday's and Lenz's laws explain why the output of a generator is naturally limited and why the torque and output speed of a motor are also limited. During operation, a magnetic field or CEMF is created that limits both. The faster the rotor or armature rotates within the windings or stator, the more CEMF is produced. The higher CEMF limits or reduces the amount of current that can flow through the windings.

When the AC changes direction, the magnetic field it produces also changes. This changing field creates a voltage which opposes the direction of the primary current. As a result, the alternating current induces an alternating magnetic field in the coil that increases the opposition to the normal flow of current **(Figure 3-9).** The magnetic field, and the inductive reactance that results, can be amplified by inserting an iron core through the center of the coil.

Inductive Reactance

When current flows through a circuit, it is opposed by two things: resistance and reactance. The term *resistance* is always associated with DC circuits. **Reactance** only occurs with AC or other forms of varying current, and it controls current in the same way resistance does. In AC

reactance. Also in an AC circuit, current through a coil is opposed by induction and the frequency of the AC waveform.

As the voltage increases and decreases with the waveform's frequency, the self-induced CEMF also increases and decreases in the coil in response to this change.

The CEMF is directly proportional to the rate of current change through the coil. The CEMF reaches its greatest strength when the voltage waveform crosses over from its positive half cycle to its negative half cycle or vice versa at points. Therefore, there is little change in the voltage when the sine wave is at its maximum or minimum peaks.

DC MOTORS

The design of a DC motor is quite simple. It has a housing, field coils (windings), an armature, a commutator and brushes, bearings, brush supports, and end frames. The motor has a stationary magnetic field and a rotating magnetic field. The stationary field is created by permanent magnets or electromagnetic windings. When current flows through the armature (rotating) windings, a magnetic field is present around the armature windings. Because the armature windings are formed in loops or coils, current flows outward in one direction and returns in the opposite direction. Because of this, the magnetic lines of force are oriented in opposite directions in each of the two sides of the loop. When placed into the field coils, one part of the armature coil is pushed in one direction and the other is pushed in the opposite direction. This causes the coil and its shaft to rotate.

Motor Housing

The motor housing or frame encloses the internal components and protects them from damage, moisture, and foreign materials. The housing also holds the field coils. The housing and end frames are usually made of steel, aluminum, or magnesium. The armature is mounted on a steel shaft supported by two bushings or bearings in the end frames. The shaft's bushings and bearings are typically lubricated by grease or oil. An end frame is a metal plate that bolts to the end of the motor housing.

Field Windings

The field windings or coils are normally made of copper wire and are insulated from but wrapped around metal plates, called pole shoes. The field coils and

of the housing **(Figure 3-10).** The field coils are designed to produce strong stationary electromagnetic fields as current is passed through them. These magnetic fields are concentrated at the pole shoes. Fields have a north or south magnetic polarity depending on the direction of current flow. The coils are wound around respective pole shoes in opposite directions to generate opposing magnetic fields **(Figure 3-11).** The field coils may be either shunt windings (in parallel with the armature winding), series windings (in series with the armature winding), or a combination of both.

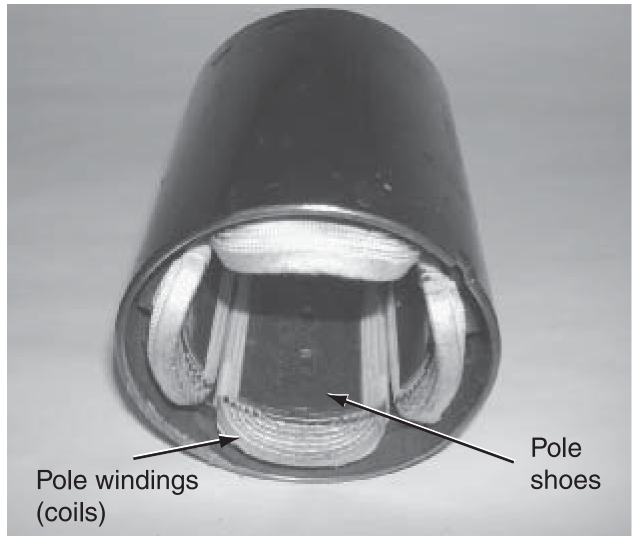

Figure 3-10 The field (pole) windings are secured to the inside of the motor's housing.

Permanent Magnet Windings. Often motors use permanent magnets instead of electromagnets for the field windings. Doing this eliminates the need for an electrical circuit to power the windings. Permanent magnets provide consistent magnetic flux lines and can last many years. Permanent magnet motors require special handling because the permanent magnet material is quite brittle and can be destroyed if it receives a sharp blow or if the motor is dropped.

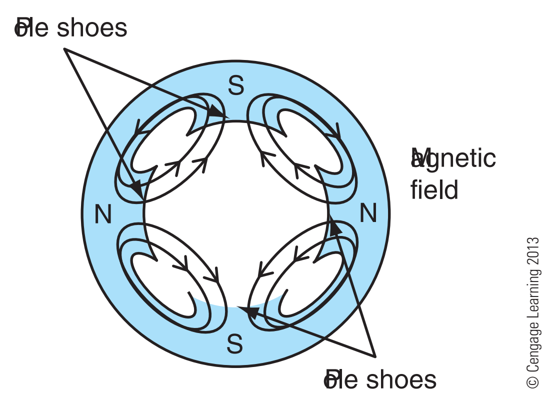

Figure 3-11 The coils are wound around respective pole shoes in opposite directions to generate opposing magnetic fields.

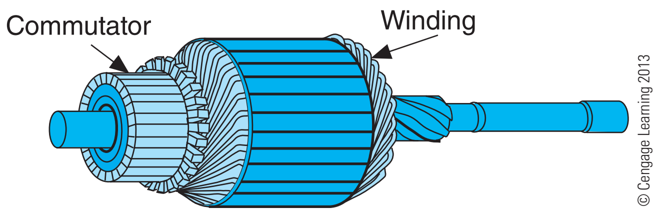

Figure 3-12 A typical armature for a DC motor.

Armatures

The armature is made by coiling wire around two or more poles of the metal core fixed to a shaft. The armature is the only rotating component of a motor. It is located in the center of the motor housing. One factor that determines the power output of a motor is the number of loops or windings in the armature.

The armature is made up of two main components: the armature windings and the commutator **(Figure 3-12).** The armature windings are usually made of heavy round or rectangular copper strips to handle high current and are shaped into a single loop. The ends of the loops fit into slots in the armature core or shaft, but they are insulated from it. Between the windings are metal strips that increase the strength of the magnetic field.

The commutator is attached to one end of the shaft and provides a contact for the ends of each loop. The windings of the armature begin and end at the commutator. The commutator has slots to receive the ends, as well as a surface for the brushes to ride on. The number and size of slots depend upon the design and purpose of the motor. Normally, there are as many coils as there are slots. This means that each slot holds two coil ends, one side of each coil being at the top of a slot and the other at the bottom of a slot. Each coil may consist of one or more turns depending on the applied voltage of the motor.

Commutator

In order to keep the armature of a motor rotating, the polarity of its magnetic field must change. To do this, the armature of DC motors is fitted with a commutator, which has plates connected to each of the armature loops. Electrical current enters and leaves the armature through a set of brushes that slide over the commutator's
pass from one segment of the commutator to another, current flow through a loop of the armature is established. As the armature rotates, the brushes connect with a different segment of the commutator, and a magnetic field is set up in another loop or the field in the previously excited loop is reversed.

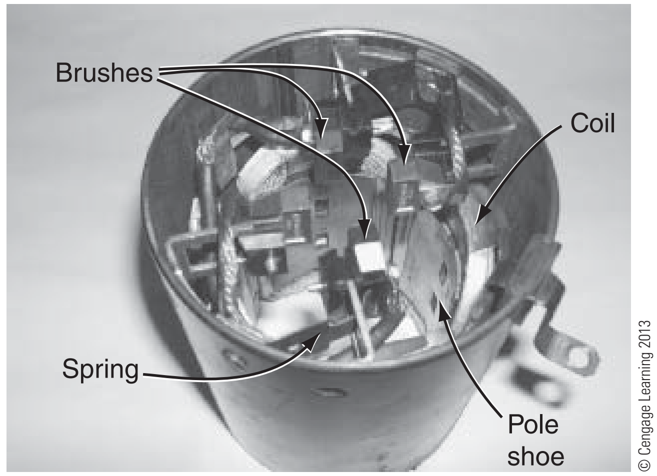

Figure 3-13 Brushes are placed in holders and have springs so they can keep good contact with the commutator.

As the armature rotates due to magnetic influences, the commutator segment attached to each coil end has traveled past one brush and is now in contact with the other. As one segment rotates past the brushes, another segment immediately takes its place. The turning motion is made uniform, and the torque needed to rotate the armature is constant rather than fluctuating as it would be if only a few armature coils were used.

The segments of the commutator are made of copper and are insulated from each other and from the armature shaft. The segments connect to the ends of the armature windings. The brushes are graphite-copper or carbon contacts that ride on the commutator. Most motors have two to six brushes that carry the current flow from the field windings or from a power source to the armature windings.

Brush holders are used to keep the brushes in position around the commutator. These holders may be separate metal or plastic assemblies, or they may be part of the end frame of the motor. Springs are used to keep the brushes against the segments of the commutator with the correct pressure **(Figure 3-13).** The brush holders for the positive brushes are insulated from the housing and end frame of the motor. The negative brush holders may be grounded directly to the

Field Winding Designs

The number of armature coils and brushes vary with the design and purpose of the motor, as does how the armature and field coils are wired together

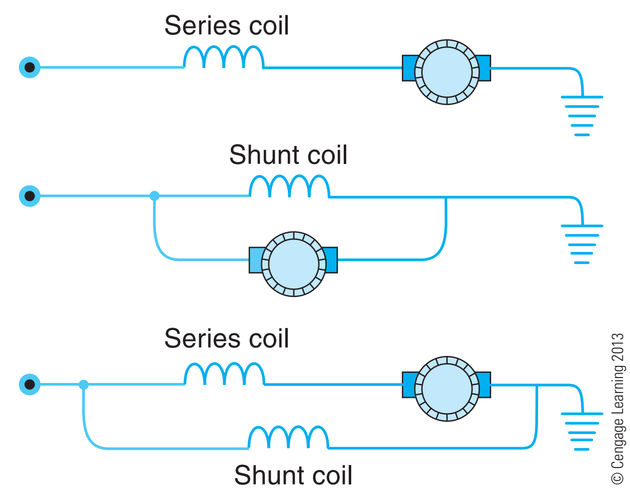

Figure 3-14 The various ways the field windings may be connected to the brushes in DC motors.

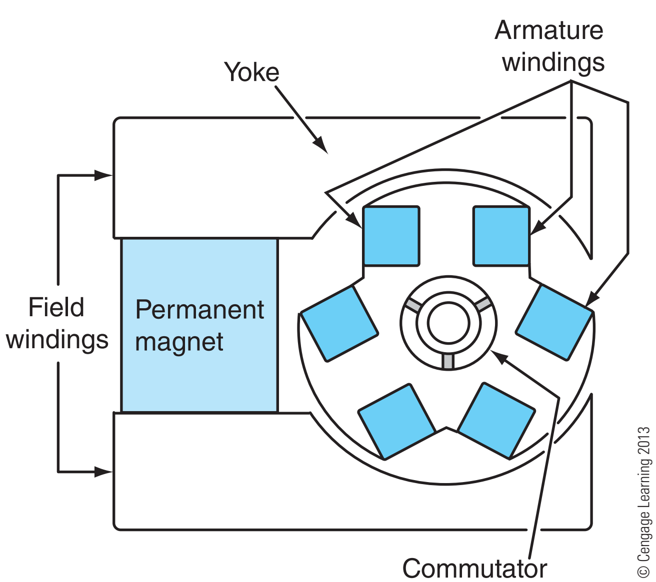

Figure 3-15 A DC motor with permanent magnet field windings.

(Figure 3-14). The armature may be wired in series with the field coils (series motor); the field coils may be wired parallel or shunted across the armature (shunt motors); or a combination of series and shunt wiring may be used (compound motors). In addition to the field winding designs, permanent magnet fields are used

have separate power sources for the field windings and the armature. The windings of these motors are referred to as "separately excited windings."

Series Windings. When the windings are connected in series with the armature, all current that passes through the field windings also passes through the armature windings. This type of winding allows the motor to develop maximum torque output at the time of initial start and when it is overloaded. As the speed of the motor increases, however, its torque output decreases. This is due to the CEMF created by self-induction. The speed of a series-wound motor changes greatly with a change in load. A series motor is often used in applications where there are heavy starting loads.

Shunt Windings. Shunt motors have field windings wired in parallel with the armature. A shunt winding usually consists of a large number of turns of thin wire, but fewer turns than the series winding. A shunt motor does not decrease in its torque output as speeds increase. This is because the CEMF produced in the armature does not decrease the field coil strength. Shunt motors develop considerably less startup torque but maintain a constant speed at all operating loads.

Compound Windings. This type of winding has a shunt winding and a series winding. This type of winding has good starting and constant-speed torque. The compound design is used where heavy loads are suddenly applied. In a compound motor, some of the field coils are connected to the armature in series, and the rest are connected in parallel with the battery and the armature.

Work

By controlling the voltage to the armature, the speed of a DC motor is controlled. The higher the voltage to the armature, the faster it will rotate. Likewise, the torque output of a DC motor is controlled by the current to the windings and armature.

Counter-EMF also affects the torque output of a motor. It limits the current flow based on the load on the motor. When the load is increased, the rotation of the armature will slow down. This drop in rotational speed causes a decrease in CEMF, which allows for an increase in current flow. As a result, the motor turns with more torque. The reverse is also true; if the load on the motor is decreased, the armature speed in-

flows through the motor. There is less torque from the motor because less is needed.

A motor that has a constant speed, regardless of load, is called a **synchronous motor**. Although these are often shunt-wound DC motors, they can also be brushless DC or AC motors.

Brushless DC Motors

A brushless DC motor is like a brushed DC motor, but the purposes of the rotor and field windings (stator) are reversed. The rotor is made up of a set of permanent magnets and the stator has controllable electromagnets **(Figure 3-16).** Obviously, a brushless motor has no brushes and no commutator. The electrical arcing that takes place between the brushes and commutator is also eliminated with the brushless design. This arcing not only decreased the usable life of the motor but also created electromagnetic interference that is detrimental to advanced electronic systems.

In place of brushes, an electronic circuit switches current flow to the different stator windings as needed to keep the rotor turning. The reversing of current flow through the windings is done by power transistors that switch according to the position of the rotor.

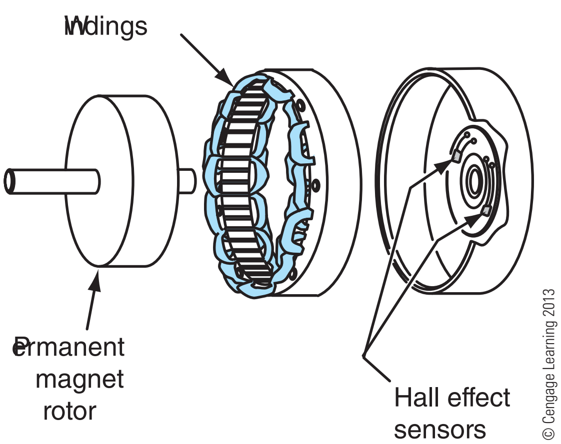

Figure 3-16 The main components of a brushless DC motor.

Many brushless DC motors use Hall effect sensors to monitor the position of the rotor. Other brushless motors monitor the CEMF in unexcited field windings to determine the position of the rotor. The current to the various stator windings is typically controlled by a **pulse width modulation (PWM)** frequency inverter. The voltage to the windings is changed by altering the duty cycle.

The **duty cycle** of something is the length of time the device is turned on compared to the time it is off **(Figure 3-17).** Duty cycle can be expressed as a ratio or as a percentage. By quickly opening and closing the power circuit to the motor, the speed of the motor is controlled. This is called pulse width modulation. These power pulses vary in duration to change the speed of the motor. The longer the pulses, the faster the motor turns.

Brushless DC motors, when compared to brushed DC motors, are more reliable, more powerful, and more expensive. The expense is largely due to the cost of the electronic controls. High-output brushless DC motors are used in some electric drive vehicles **(Figure 3-18).**

AC MOTORS

With AC voltage, the direction of current flow changes but does not change immediately. Rather, as the current is getting ready to change directions, it decreases until it reaches zero and then gradually builds up in the other direction. Therefore, the amount of current in an AC circuit always varies. When AC is given as a value, it is referred to as a "root mean square (RMS)" value **(Figure 3-19).** In other words, the value of AC voltage is not stated according to its

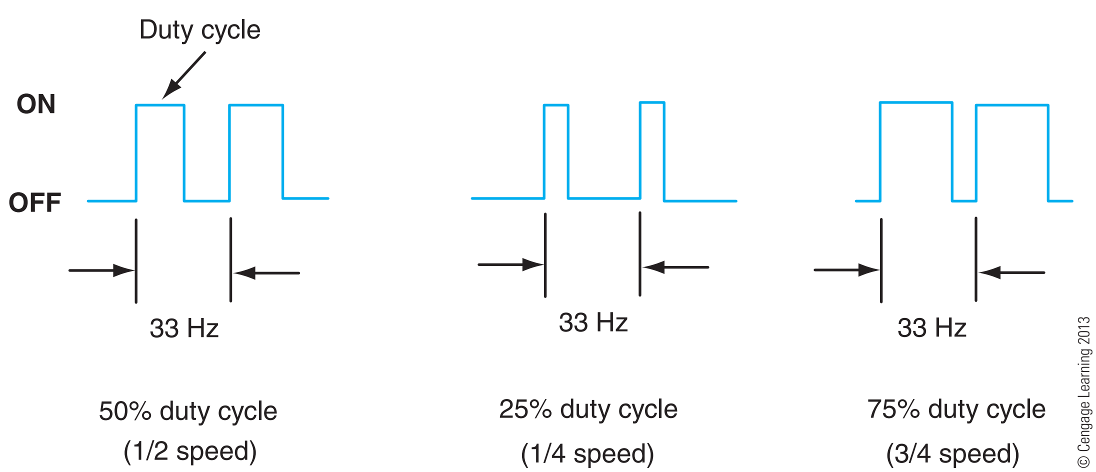

Figure 3-17 The action of various duty cycles.

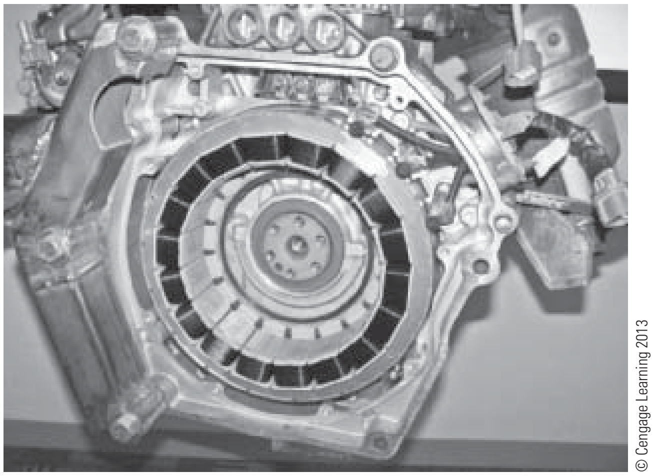

Figure 3-18 Honda's hybrid vehicles use a brushless motor.

positive and negative voltage peaks. The RMS value expresses the effective value of the AC voltage or current and is determined by multiplying the peak voltage by 70.7 percent.

Basic Construction

An AC motor has two basic electrical parts: a stator and a rotor **(Figure 3-20).** The stator, the stationary field, is comprised of individual electromagnets electrically connected to each other or connected in groups. The rotor is the rotating magnetic field and can be an electromagnet or a permanent magnet. The rotor is located within the stator fields. Like in a DC motor, the rotor will rotate as a result of the repulsion and attraction of the magnetic poles. The way this works is quite different from how a DC motor works.

Basic Operation

A current is passed through the stator and rotor, causing the rotor to spin. Because the current is alternating, the polarity in the windings constantly changes. A synchronous AC motor will run at the frequency of the AC voltage. Many AC motors are induction types. In these motors, electrical current is induced in the rotor as it rotates, rather than having current delivered to it from an external source. Obviously, this type of motor needs to begin spinning before the rotor induces current, so these motors are equipped with a variety of starting aids.

The rotor in an AC motor rotates because it is pulled along by a rotating magnetic field in the stator. The stator does not physically move. The magnetic field does. If the windings of the stator are wired in series, current passes through them one at a time and because it is AC, the polarity and strength of the field around them is constantly changing **(Figure 3-21).** The magnetic field of the rotor reacts and moves along with the "rotating magnetic field" of the stator.

To better understand this concept, let us look at a three-phase motor. Three-phase AC voltage is commonly used in motors because it provides a smoother and more constant supply of power. Three-phase AC

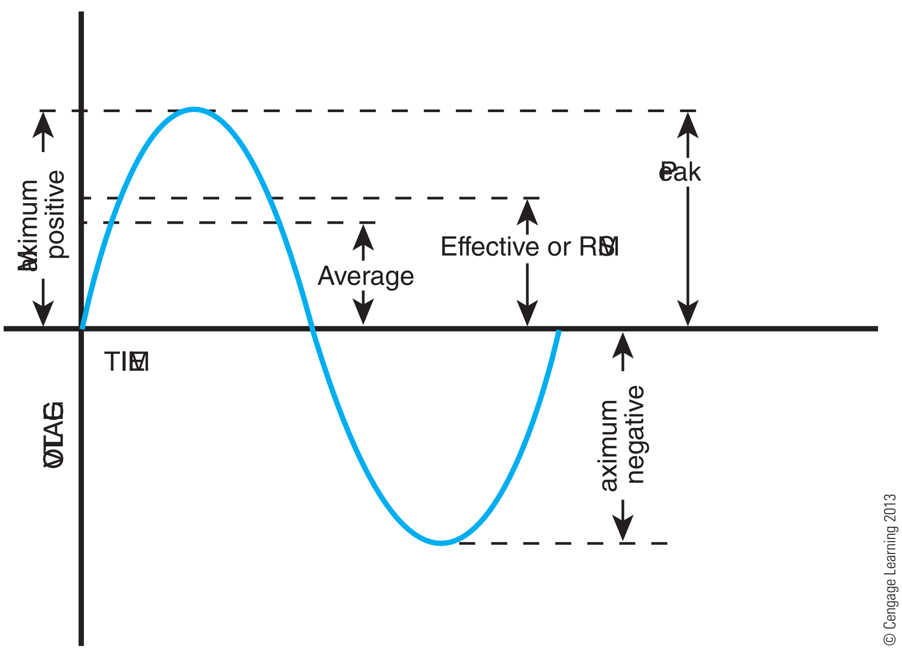

Figure 3-19 An explanation of how AC is rated.

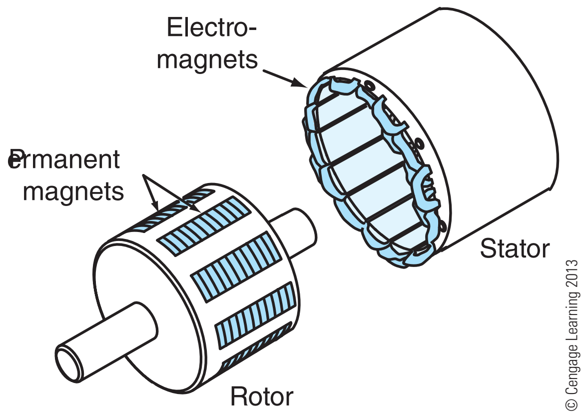

Figure 3-20 The construction of the rotor and stator of an AC motor.

voltage is much like having three independent AC power sources, which have the same amplitude and frequency but are 120 degrees out of phase with each other **(Figure 3-22).**

To produce a rotating magnetic field in the stator of a three-phase AC motor, each phase of the three-phase power source is connected to separate stator windings. Because each phase reaches its peak at successively later times, the magnetic field is at its strongest point in each winding in succession as well. This creates the effect of the magnetic field continually moving around the stator. This rotating magnetic field will rotate around the stator once for every cycle of the voltage in each phase **(Figure 3-23).** This means the field is rotating at the frequency of the source voltage. Remember that as the magnetic field moves, new magnetic polarities are present. As each polarity change is made, the poles of the rotor are attracted by the opposite poles on the stator. Therefore, as the magnetic field of the stator rotates, the rotor rotates with it.

In most cases, the speed of an AC motor depends on:

1. The number of windings and poles built into the motor.
2. The frequency of the AC supply voltage. Controllers are used to change this frequency and allow for a change in motor speed.
3. The load on the rotor's shaft.

Synchronous Motor

A synchronous motor operates at a constant speed regardless of load. Rotor speed is equal to the speed of the stator's rotating magnetic field. A synchronous motor is used when the exact speed of a motor must be maintained. Often, synchronous motors have magnets built into the rotor assembly. These magnets allow the rotor to easily align itself with the rotating magnetic field of the stator.

When three-phase AC is fed to the three sets of windings in the stator coil, a rotating magnetic field is present around the stator. The rotor simply rotates with that rotating magnetic field. The torque output of the rotor, therefore, is dependent on the strength of the magnetic field around the stator. The speed of the rotor

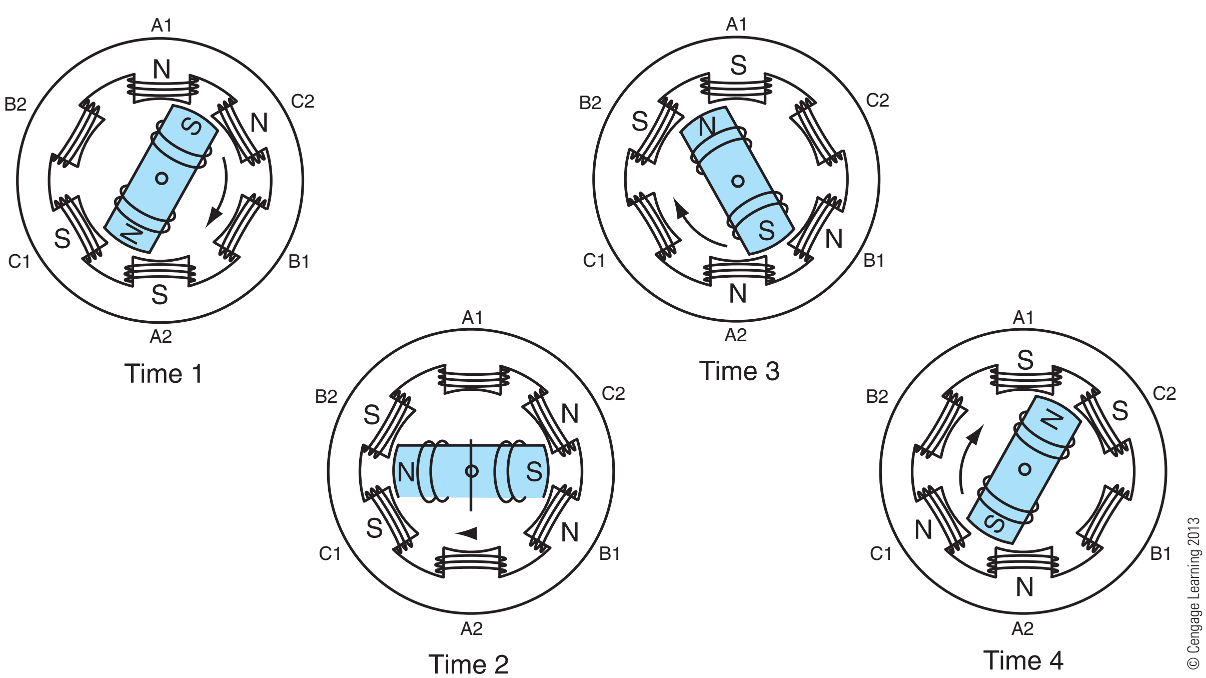

Figure 3-21 Notice how the polarity of the stator and rotor changes over time.

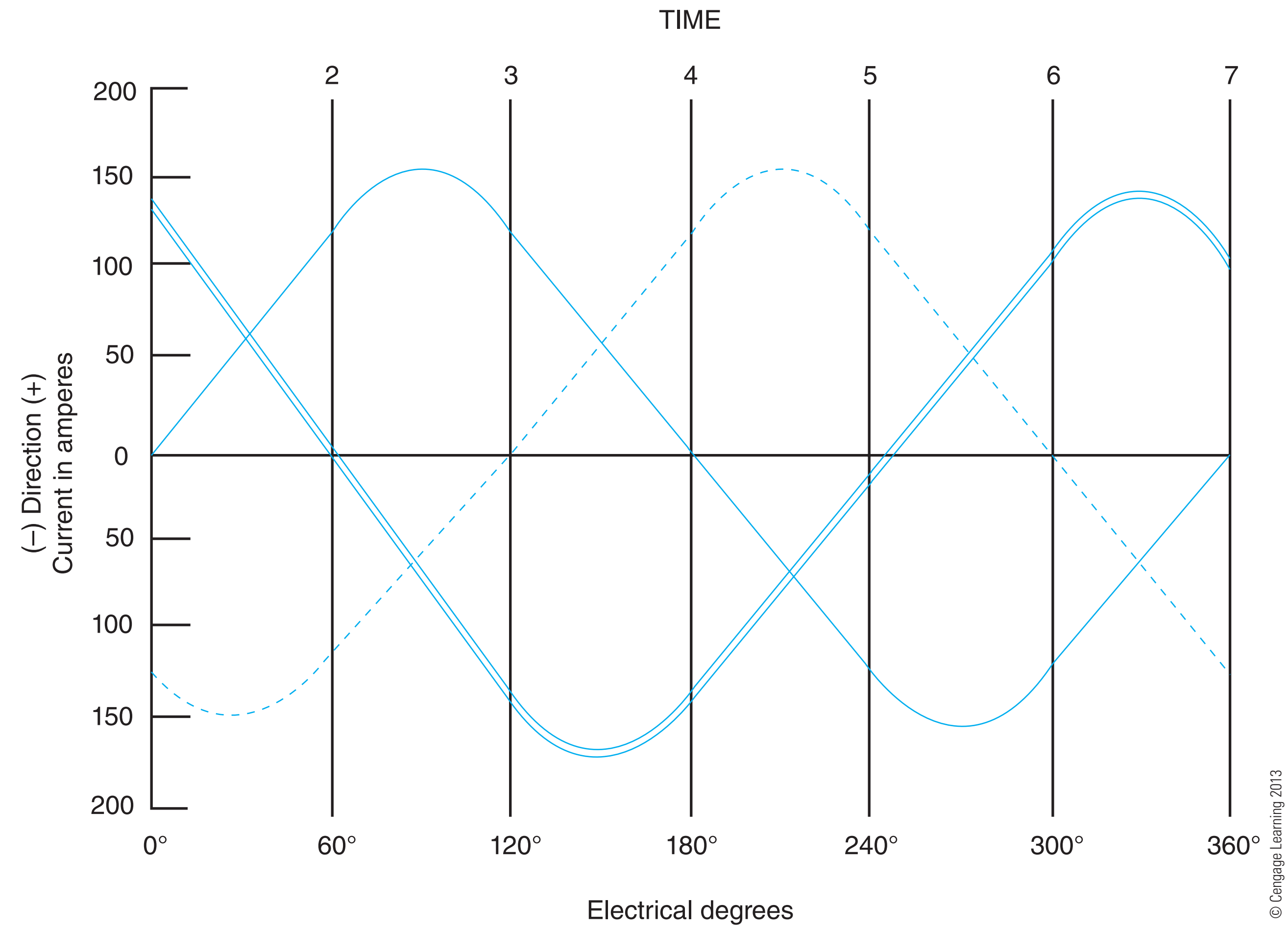

Figure 3-22 A look at the three separate phases of the three-phase AC.

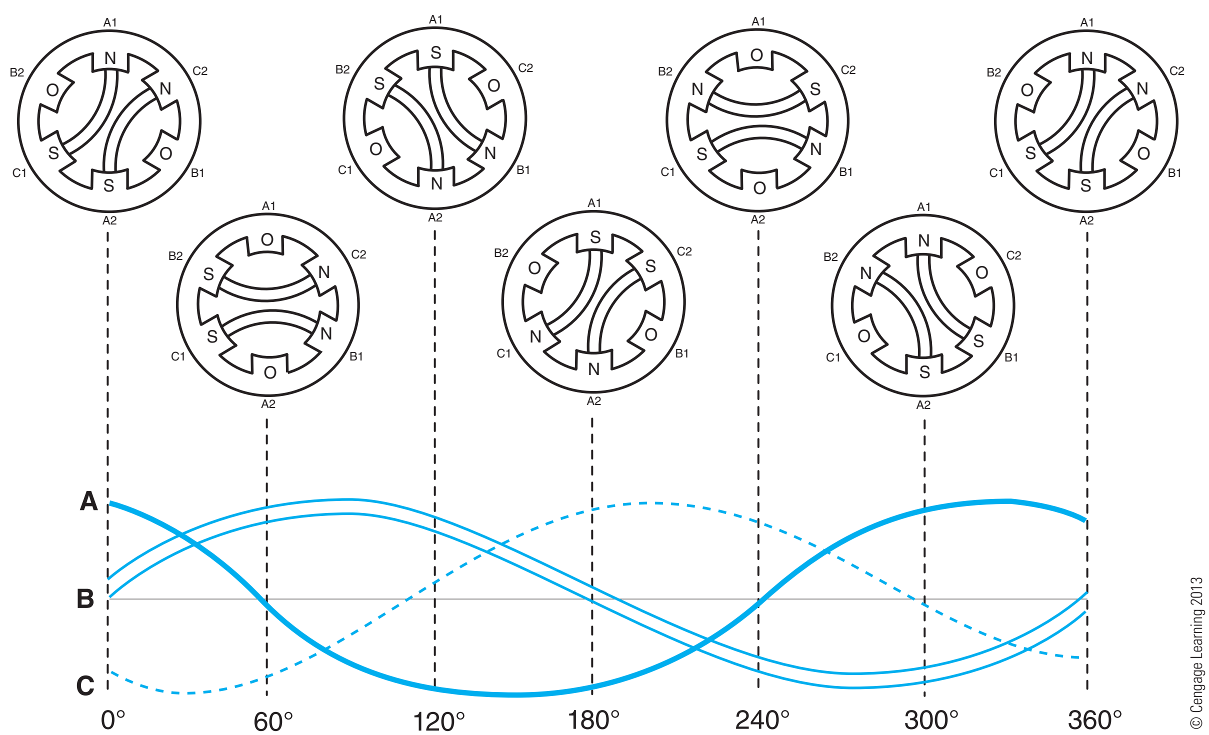

Figure 3-23 The rotor turns in response to the changing polarities caused by the three-phase AC.

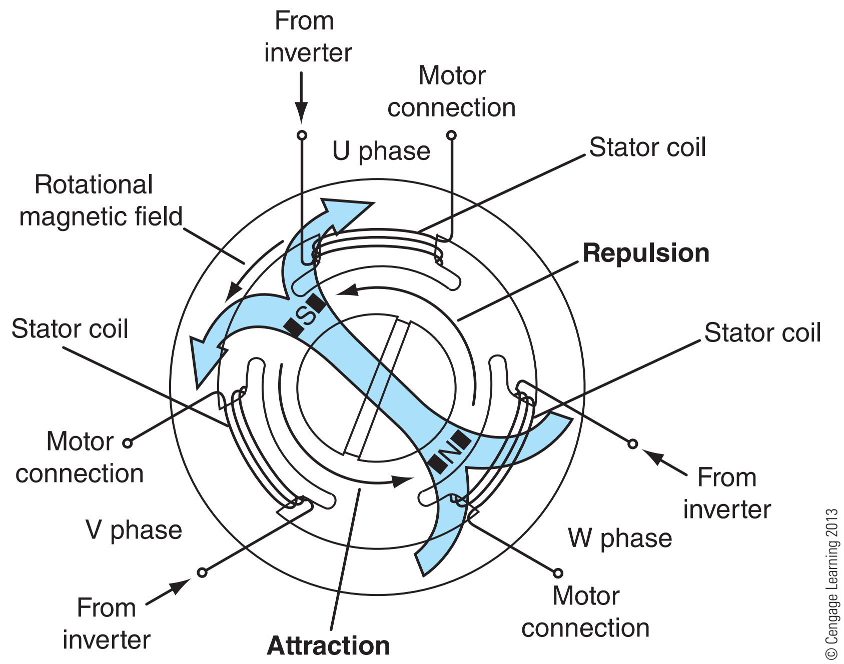

Figure 3-24 The synchronous motor used in Toyota's hybrid vehicles is controlled by the vehicle's inverter, which is part of the hybrid control system.

is determined by the frequency of the AC input to the stator. Synchronous motors are available with outputs up to thousands of horsepower.

One of the disadvantages of most synchronous motors is that they cannot be started by merely applying three-phase AC power to the stator. When AC is applied to the stator, a high-speed rotating magnetic field is present immediately. This field rushes past the rotor so quickly that the rotor cannot get started. The rotor is first repelled in one direction and then, very quickly, in another. There are many ways of addressing this issue, but for hybrid and electric vehicles the problem is solved by complex electronics that begin rotating the magnetic field in such a way and at such speed that the rotor simply follows the field **(Figure 3-24).** Once the rotor is spinning, normal synchronous operation begins.

Induction Motor

The most common industrial motor is the three-phase AC **induction motor**. This motor has a low cost and a simple design. The motor works on the principle of rotating magnetic fields in the stator windings. The stator has three windings separated by 120 degrees. A magnetic

stator and around in the stator windings. The stator is connected to the power source and the rotor **(Figure 3-25).** The three-phase AC sets up a rotating magnetic field around the stator. The rotor has permanent magnets and is the output shaft of the motor. The rotor rotates and follows the rotating magnetic field in the stator.

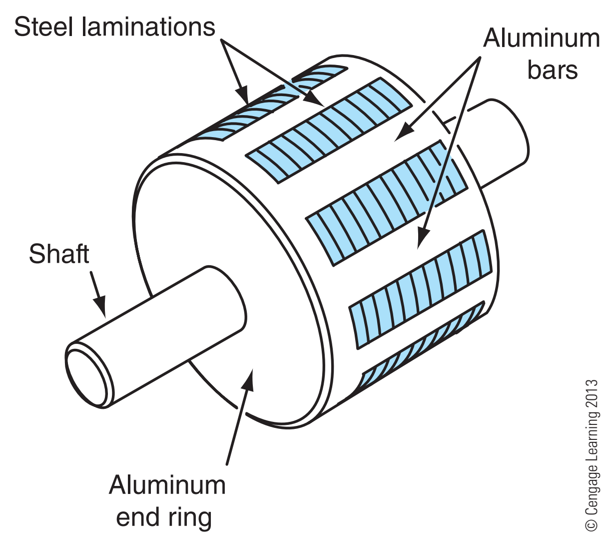

Figure 3-25 The construction of a rotor for an AC induction motor.

An induction motor generates its own rotor current. The current is induced in the rotor windings as the rotor cuts through the magnetic flux lines of the rotating stator field **(Figure 3-26).** The induced current causes each

magnetic field of the stator rotates, the magnetic field of the rotor follows the rotating magnetic field of the stator. It should be obvious that this type of motor needs some forced rotation of the rotor before it can rotate on its own. Various methods are used to start these motors, including capacitors and separate starting windings.

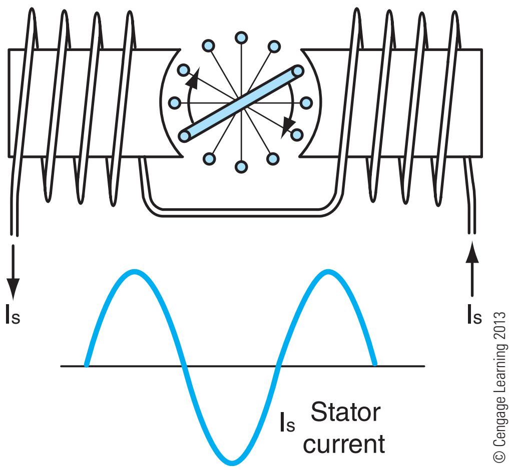

Figure 3-26 This is a look at a simple induction motor during rotation. The direction of the current and the voltage induced in the rotor are shown.

It is impossible for the rotor of an induction motor to rotate at synchronous speed. If the rotor were to turn at the same speed as the rotating field, there would be no relative motion between the stator and rotor fields. As a result, no lines of force would be cut by the rotor's conductors, and there would be no induced voltage in the rotor. In an induction motor, the rotor must rotate at a speed slower than that of the rotating magnetic field.

The difference between the synchronous speed and actual rotor speed is called slip. Slip is directly proportional to the load on the motor. When loads are on the rotor's shaft, the rotor tends to slow and slip increases. The slip then induces more current in the rotor and the rotor turns with more torque, but at a slower speed and therefore produces less CEMF.

Other AC induction motors rely on a rotor position sensor to begin and maintain rotor rotation **(Figure 3-27).** The sensor tells a control unit precisely where the rotor is inside the stator. The control unit then energizes the appropriate circuits to begin sending AC voltage at the correct stator winding. Once the rotor begins to spin, the sensor keeps track of the position of the rotor and continuously sends signals to the control unit. The control unit, in turn, energizes the next winding to maintain rotor torque.

Switched Reluctance Motors

A variable switched reluctance motor can be powered by AC or DC. Like other motors, it has a rotor and a coil winding in the stator. The toothed rotor has no coil windings or permanent magnets. The stator typically has slots containing a series of coil windings. The energizing of the stator is done by an electronic controller. The controller establishes a rotating magnetic field around the stator as it activates one coil set in the stator at one time. The timing of this activation is based on rotor angle; therefore, sensors monitoring the position of the rotor are used.

When one coil winding is energized, a magnetic field is formed around it. The metal rotor tooth that is

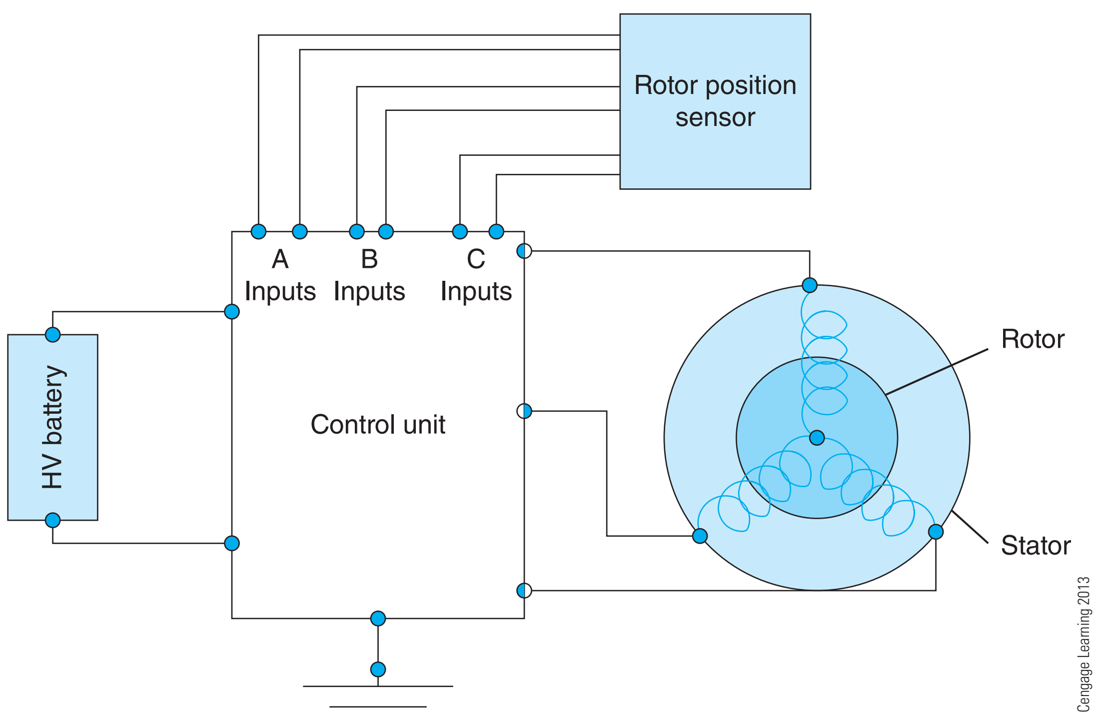

Figure 3-27 An electric diagram for an induction motor with a rotor position sensor.

closest to the magnetic field moves toward that field. When the tooth is close, current is switched to another winding in the stator and the tooth moves to it. As the current is sent to the consecutively placed windings, the rotor rotates. By controlling the current and timing through the stator windings, the rotor can be forced to rotate at any desired speed and torque.

GENERATORS

A generator is similar to a motor. However, a motor changes electrical energy to mechanical energy, whereas a generator changes mechanical energy to electrical energy. To generate voltage, a conductor is moved through a magnetic field or a magnetic field is moved over a conductor. The conductor or field is moved by mechanical energy.

DC Generators

A DC generator provides direct current (DC). The biggest difference between a generator and a motor is the wiring to the armature. In a motor, the armature receives current from a power source. This creates the magnetic field that opposes the magnetic fields in the motor's coils, which causes the armature to rotate. The armature in a DC generator is driven by the engine or other device. It is not magnetized, and the windings simply rotate through the stationary magnetic field of the field windings. This induces an AC voltage in the armature.

To provide DC voltage, it is necessary to reverse the polarity of the generator's output wires at the same time the voltage in the armature is reversed. This is accomplished by the commutator. The commutator has segments, and brushes ride over those segments, just like a brushed DC motor. There is always at least one positive brush and at least one negative brush. Wires deliver the DC output from the armature to an external electrical system **(Figure 3-28).**

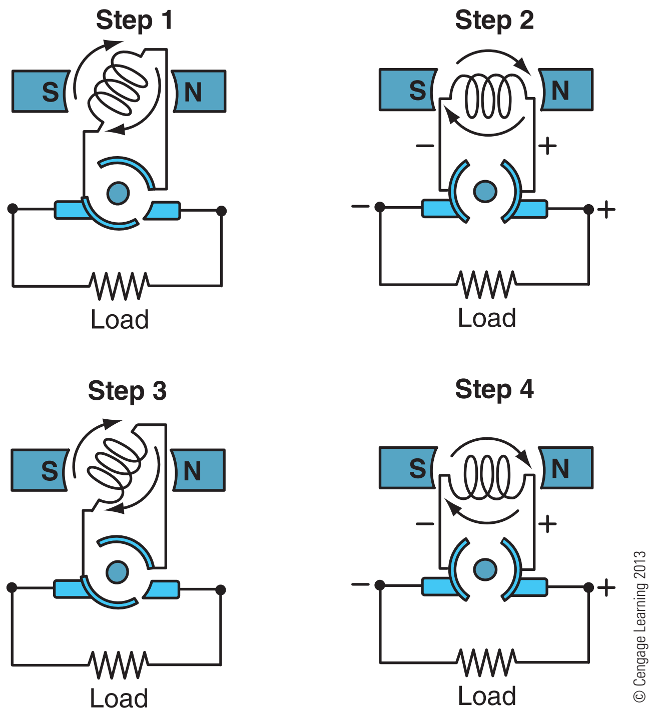

Figure 3-28 The basic operation of a simple DC generator.

The voltage output from a DC generator is pulsed **(Figure 3-29).** This is caused by the segmentation of the commutator.

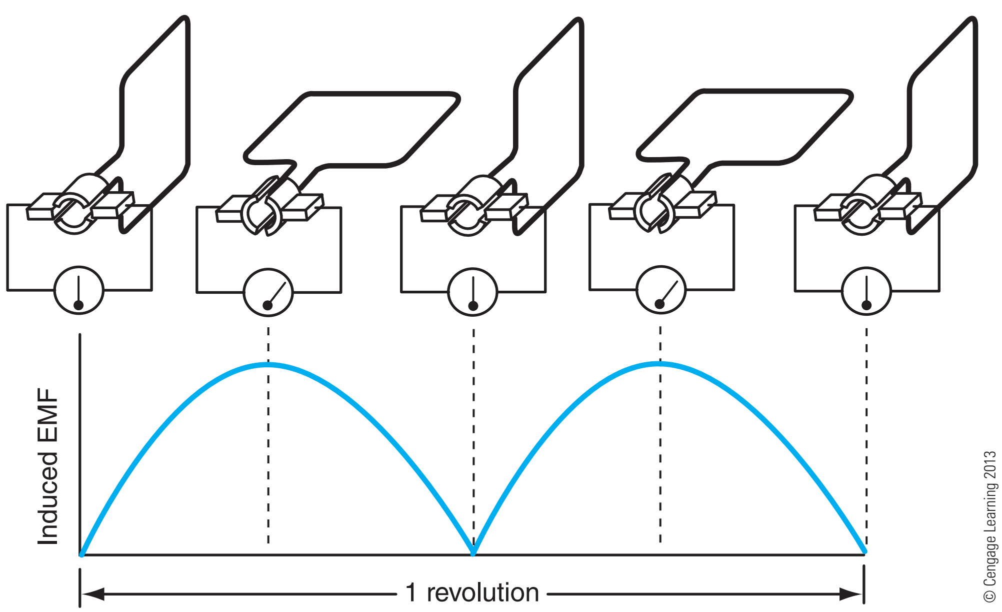

Figure 3-29 The output voltage from a DC generator is a pulsed voltage, not AC.

AC Generators

AC generators **(Figure 3-30)** use a design that is basically the reverse of a DC generator. In an AC generator, a spinning magnetic field rotates inside the stator. As the spinning north and south poles of the magnetic field pass the conductors in the stator, they induce a voltage that flows first in one direction and then in the opposite direction (AC voltage).

The rotor assembly may have electromagnets or permanent magnets. A small air gap separates the rotor and stator. The rotor's magnetic field induces a voltage in all of the stator windings at the same time. Therefore, the generation of AC can be quite high, if needed. The output can be controlled by controlling the current flow through the rotor. Of course, this cannot be done if the rotor is a permanent magnet. If the rotor is an electromagnet, it has slip rings. The slip rings are not segmented, and they provide an uninterrupted surface for the brushes. It is through the slip rings and brushes that the rotor is energized **(Figure 3-31).**

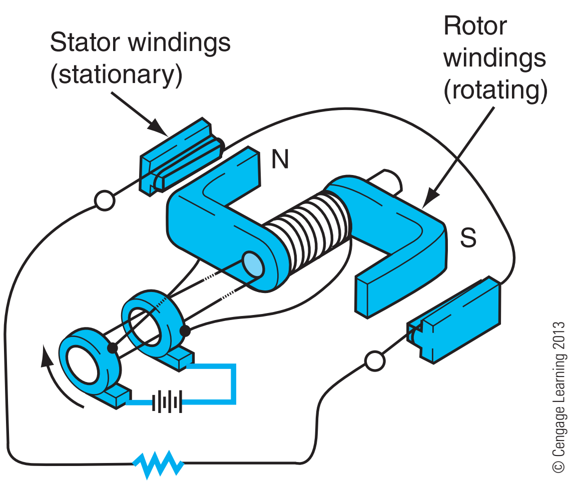

Figure 3-30 A simplified AC generator.

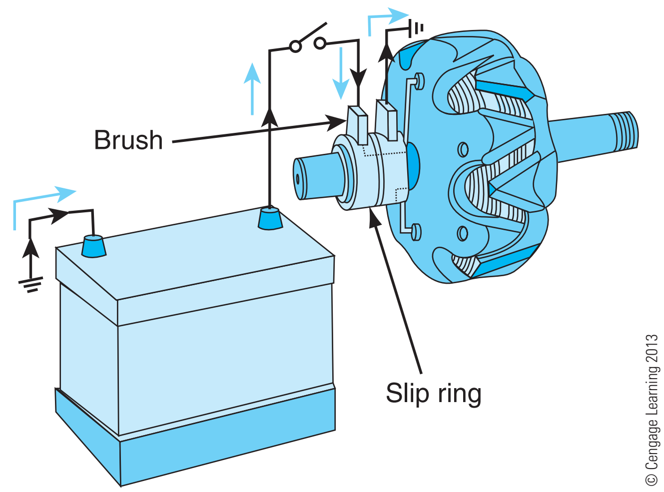

Figure 3-31 Current is carried to the rotor's windings through brushes in contact with the slip rings on the rotor shaft.

The stator is the stationary member of the AC generator. It is made up of a number of conductors, or wires, into which voltage is induced by the rotating magnetic field. Most AC generators use three windings to generate the required output. They are placed in slightly different positions so that their electrical pulses will be staggered in either a **delta configuration** **(Figure 3-32)** or a **wye configuration** **(Figure 3-33).** The delta winding received its name because its shape resembles the Greek letter delta. The wye winding resembles the letter Y. Usually, a wye winding is used in applications where high charging voltages at low engine speeds are required. AC generators with delta windings are capable of putting out higher amperages.

To store the generated AC voltage, some component must convert the AC to DC before it is sent to the batteries. The generated AC can be used to directly power AC equipment and then can be converted to DC for storage. The AC to DC conversion can be simply

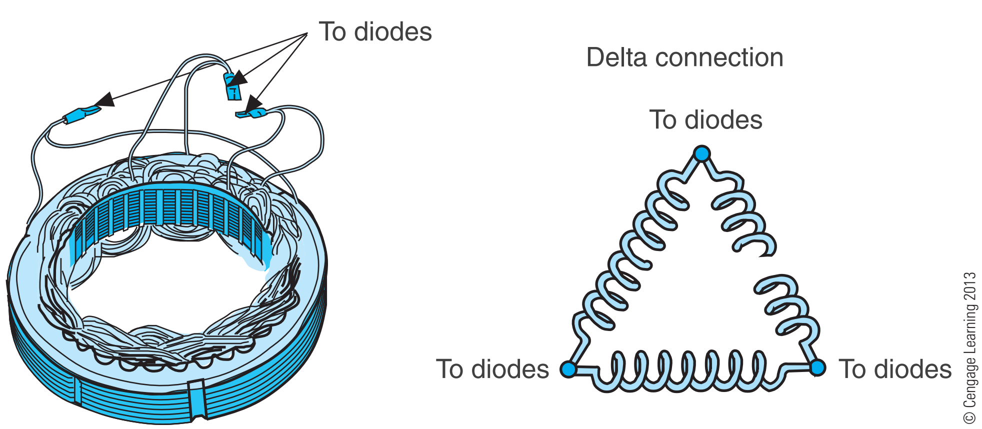

Figure 3-32 A delta-connected stator winding.

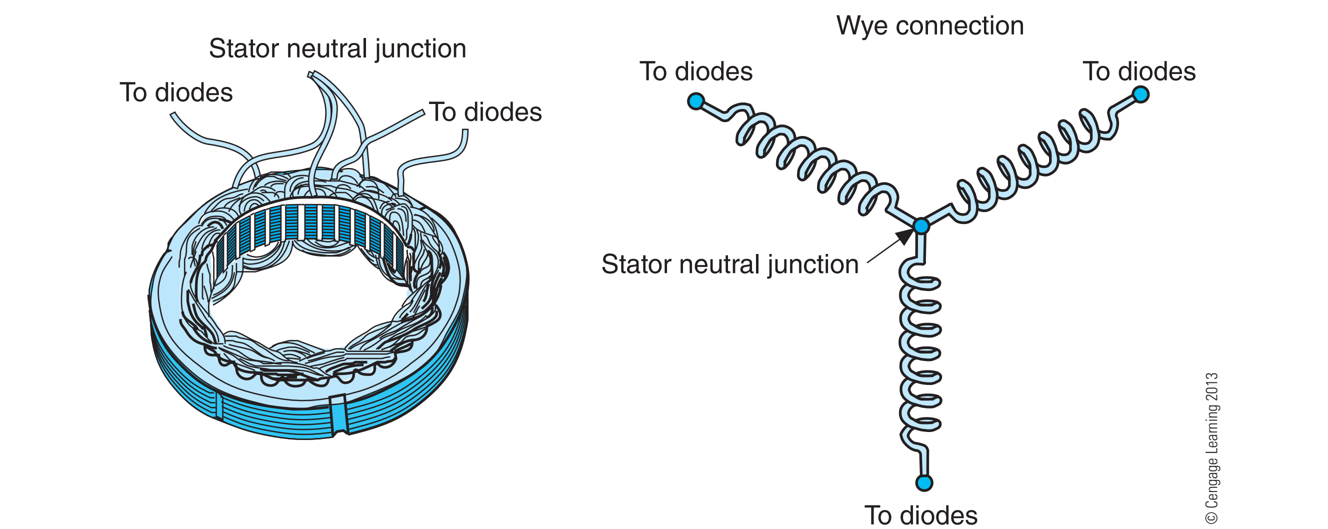

Figure 3-33 A wye-connected stator winding.

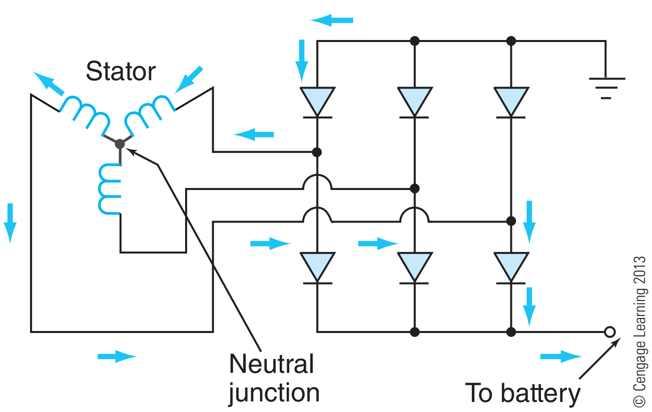

Figure 3-34 Diodes are connected between the output of the windings and the output of the AC generator.

done through an arrangement of diodes that are placed between the output of the windings and the output of the AC generator **(Figure 3-34).**

Alternating current produces a positive pulse and then a negative pulse. The resultant waveform is known as a **sine wave**. The complete waveform starts at zero, goes positive, and then drops back to zero before turning negative. These changes respond to one complete rotation or cycle of the rotor. Remember there are three overlapped stator windings. This produces three sets of sine waves 120 degrees apart. This voltage

A diode is an electronic device that allows current to flow only in one direction; therefore, if AC runs through a positive diode, the negative pulses are blocked off. If the diode is reversed, it blocks off current during the positive pulse and allows the negative pulse to flow. When only half of the AC current pulses (either the positive or the negative) are able to pass through the diodes, **half-wave rectification** has taken place. When all of the AC is rectified, **full-wave rectification** occurs.

A voltage regulator controls the voltage output of an AC generator. Regulation of voltage occurs by varying the amount of field current flowing through the rotor. The higher the field current, the higher the voltage output. The regulator receives an output signal from the generator, which is called the **sensing voltage**. If the sensing voltage is below the regulator setting, an increase in field current is allowed. Higher sensing voltage will result in a decrease in field current and voltage output.

Pulse width modulation can be used to control the generator's output by varying the amount of time the rotor is energized. When voltage regulation is controlled by a computer or electronic control module, the computer switches or pulses field current at a fixed frequency. By varying on-off times, the correct average field current is produced to provide correct AC generator output.

MOTOR/GENERATORS

The main difference between a generator and a motor is that a motor has two magnetic fields that

netic field and wires are moved through the field. Using electronics to control the current to and from the battery, engineers have developed a motor that also works as a generator. A motor/generator may be based on two sets of windings and brushes, a brushless design with a permanent magnet, or switched reluctance.

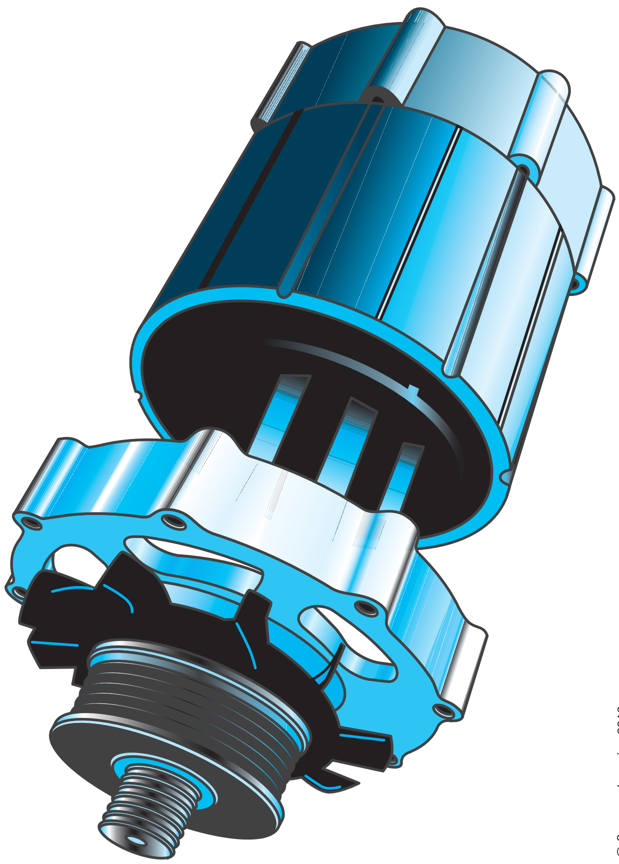

Figure 3-35 A motor/generator (alternator) assembly that is mounted external to the engine.

A motor/generator **(Figure 3-35)** can be mounted externally to the engine and connected to the crankshaft with a drive belt. In these applications, the unit can function as the engine's starter motor, as well as a generator driven by the engine. Some allow for some regenerative braking as well.

When a motor/generator is belt driven, a belt tensioner is mechanically or electrically controlled to allow the motor/generator to drive or be driven by the belt. One system has an electromagnetic clutch fitted to the crankshaft pulley. With the engine running, the clutch is engaged. This allows the unit to be a generator. When the vehicle is stopped, the crank pulley clutch disengages, and the unit is ready to act as the starting motor when the vehicle is ready to move again.

Motor/generators may also be mounted directly to the crankshaft

integrated into the flywheel, or contained inside the transmission. These designs work as a starter by spinning the crankshaft during starting and serves as a generator, charging both directly from the engine and during braking (regenerative braking). Many hybrid vehicles use this design. In some cases, the motor/generator may be part of a drive axle assembly. These designs can drive the axles as well as serve as generators during regenerative braking.

Motor/generators are capable of high charging outputs and allow for other features that make the vehicle more efficient:

- Stop-start—When the engine is not needed, such as when sitting at a stoplight, it is automatically turned off. The engine restarts as soon as the control module senses a need for engine power.
- Electrical assist—The motor/generator can add power to the engine during initial and hard acceleration or when the vehicle is operating under a heavy load.
- Regenerative braking—This feature captures some the energy during deceleration and braking and uses it to recharge the vehicle's batteries. Regenerative braking also helps the conventional brakes to slow down and stop the vehicle.

CONTROLLERS

A **controller** is used to manage the flow of electricity from the batteries and thereby to control the speed of the electric motor. A sensor located by or connected to the throttle pedal (also called gas pedal or the accelerator) sends the driver's input to the controller. The controller then sends the appropriate amount of voltage to the motor.

A simple controller is a variable resistor or potentiometer connected to the accelerator. When there is no pressure on the accelerator, resistance of the potentiometer is too high to allow voltage to the motor. When the accelerator is fully opened, the resistance is very low, and full battery voltage is delivered to the motor. The positions of the accelerator between closed and wide open allow corresponding amounts of voltage to the motor. This type of system does not provide for smooth control of the motor.

Using electronics, the same principle can be used but with more positive results. A sensor monitors the accelerator and sends information to a control unit. The control unit monitors that signal plus other inputs regarding the operating conditions of the vehicle. The

In this way, the voltage is pulsed, and more precise motor speed control is possible. Most controllers pulse the voltage more than 15,000 times per second. Pulsing the voltage causes the motor to vibrate at the frequency of the voltage. If the frequency is faster than 15,000 cycles per second, it cannot be heard.

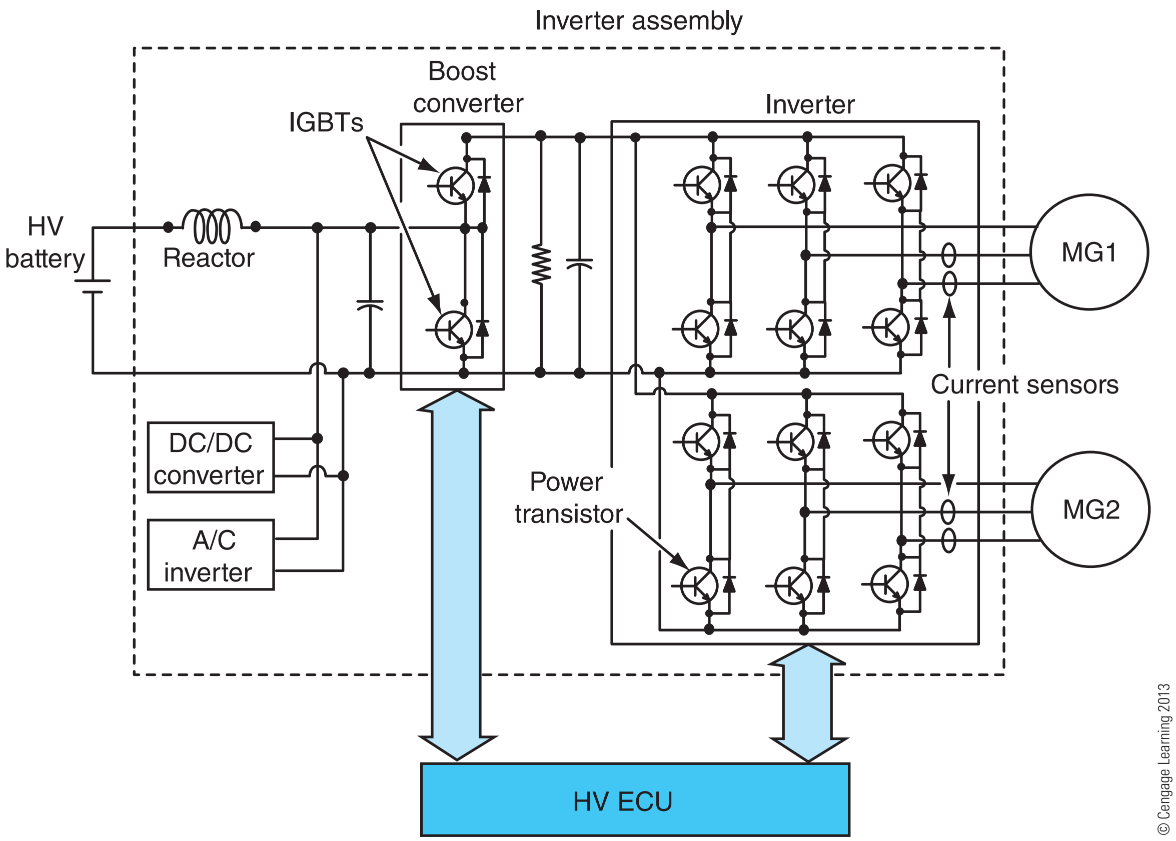

Figure 3-36 The motor control assembly for a Toyota hybrid vehicle.

A controller has an additional role when the electric drive motor is an AC-type motor. It is responsible for converting the DC voltage from the battery to a three-phase AC voltage for the motor. This is done by sets of power transistors. The transistors pulse the voltage and reverse it at a fixed frequency. The voltage may also be increased (boosted) before it is sent to the motor **(Figure 3-36).**

Inverters and Converters

An inverter may be part of the controller or it may be a separate unit. The **inverter** **(Figure 3-37)** converts the DC voltage from the batteries into three-phase AC voltage for the motor(s).

DC voltage from the battery is fed to the primary winding of a transformer in the inverter **(Figure 3-38).** The direction of the current is controlled by an electronic switch (generally a set of insulated gate bipolar transistors

primary winding and then is quickly stopped and reverses its direction. This change of direction induces an AC voltage in the transformer's secondary winding. The AC is then used to power the traction motors and other AC devices. The electronic switch responds to inputs from a variety of sensors, such as vehicle speed

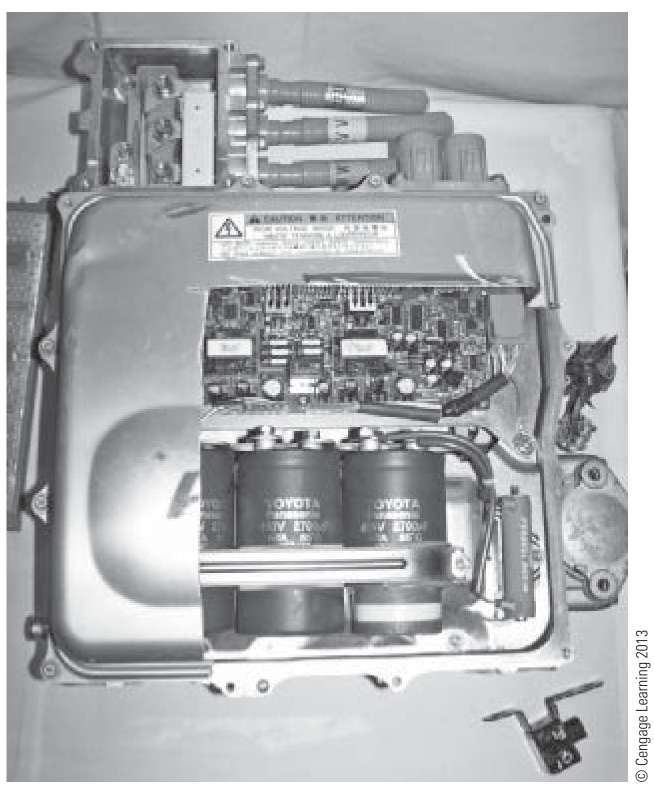

Figure 3-37 The inverter assembly for a Toyota hybrid vehicle.

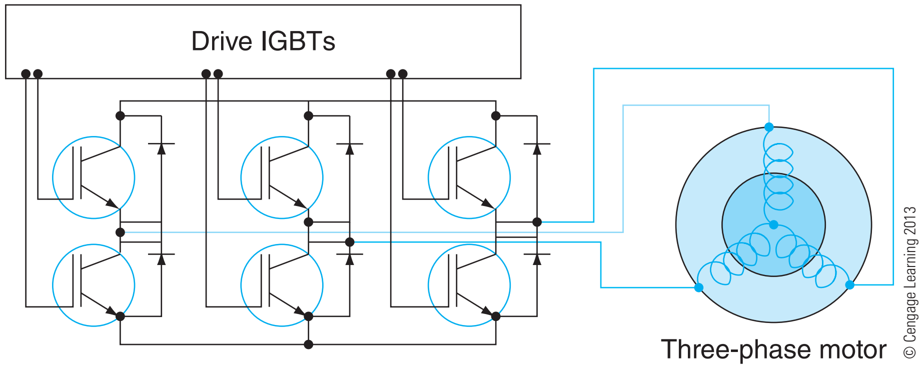

Figure 3-38 An electrical diagram of the connections made from the motor to the IGBTs in an inverter.

and throttle position. These inputs are used to determine the required amount of current and the frequency of the AC voltage.

When the conversion of AC to DC is required, current is sent through diodes that effectively change AC to DC by allowing only half of the AC's sine wave to flow past the diodes. The diodes are normally called rectifiers. Rectifiers are also found in AC generators.

Most inverter housings also contain a converter, although this could be contained in a separate housing. A **converter** changes the amount of voltage from a power source. There are two types of converters, one that increases voltage, called a step-up converter, and one that decreases the voltage, called a step-down converter.

A common application of a converter in electric drive vehicles is one that drops some of the high DC voltage to the low voltage required to power accessories such as sound systems, lights, blower fans, and the controller. A converter is also used to step down (reduce) high AC voltage to power accessories such as the air-conditioning compressor.

During the operation of the inverter and converter, a great amount of heat is generated. This heat must be controlled to protect their components, especially the transistors. To provide the necessary cooling and ventilation, inverter/converter housings have dedicated cooling systems that are independent of the engine's cooling system.

Review Questions

1. What is a synchronous motor?

2. If a permanent magnet is used in a DC motor, where is it most likely to be and why?

3. Describe the basic difference between a DC motor and a DC generator.

4. All of these statements describe how voltage can be generated, EXCEPT:

   A. By a change in the number of magnetic lines enclosed by a stationary loop or coil

   B. By a change in current flow through a conductor

   C. By a conductor moving or cutting across a stationary magnetic field

   D. By a moving magnetic field cutting across a stationary conductor

5.

   A. Stator windings

   B. Rotor

   C. Rotor windings

   D. Permanent magnet

6. *True or False:* The strength of the magnetic poles in an electromagnet decreases with an increase in the number of turns of wire and the current flowing through them.

7. What is three-phase AC, and why is it often used to power electric motors?

8. Describe the basic function of inverter and converter in an electric drive vehicle.

9. All of these factors influence the output speed of an AC motor, EXCEPT:

   A. The number of brushes on the commutator

   B. The number of windings and poles built into the motor

   C. The frequency of the AC supply voltage

   D. The load on the rotor's shaft

10. Briefly explain the differences between a brushed and a brushless DC motor.

CHAPTER 4 Battery Basics

Learning Objectives

After reading and studying this chapter, you should be able to:

- Explain the purpose of a battery.
- Describe how a battery works.
- Describe the basic construction of an electrochemical cell.
- Explain how electrochemical cells can be connected together to increase voltage and current.
- Explain the different methods used to recharge a battery.
- List and describe the various ways a battery may be rated.
- List and describe the various types of batteries, according to their chemistries, that may be used in automobiles.
- Explain why electric drive vehicles operate with high voltages.
- List the precautions that must be adhered to when working with or around high-voltage systems.
- Describe the construction and operation of a lead-acid battery.
- Describe the basic service procedures for maintaining a lead-acid battery.
- Explain how a lead-acid battery should be tested.
- Describe the safety precautions that should be followed when working with lead-acid batteries.
- Describe the construction and operation of a nickel-metal hydride battery.
- Describe the construction and operation of a nickel-cadmium battery.
- Describe the construction and operation of a lithium-ion battery.
- Describe the construction and operation of a lithium-ion polymer battery.
- Explain how a capacitor stores electrical energy.
- Describe the construction and operation of an ultra-capacitor.

Key Terms

absorbed glass mat (AGM)
ampere-hour (AH) rating
anode
batteries
capacitance
capacitor
cathode
cold cranking amps (CCA) rating

conductance test
cranking amps (CA) rating
cylindrical cell
deep cycling
electrochemical
electrolyte
element
farad (F)
fast charging
grids
high-voltage (HV) battery
lithium-ion (Li-Ion)
lithium-polymer (Li-Poly or LiPo) battery
load test
low-maintenance battery
maintenance-free battery
nickel-cadmium (NiCad)
nickel-metal hydride (NiMH)
open-circuit voltage
operating voltage
parasitic drain
primary batteries
prismatic cells
recombinant battery
reserve capacity (RC) rating
secondary batteries
slow charging
starting battery
super-capacitor
trickle charging
ultra-capacitor
valve-regulated lead-acid (VRLA) batteries
watt-hour rating

INTRODUCTION

The battery in an electric drive vehicle serves a different purpose than a battery in a conventional vehicle. In an internal combustion engine (ICE)-powered vehicle, the battery's primary purpose is to provide a short, powerful burst of power to start the engine. This type of battery is typically called a **starting battery**. In electric drive vehicles, however, the batteries provide continuous current to power electric motors for a long period of time.

A starting battery is also found in hybrids, in addition to a **high-voltage (HV) battery** **(Figure 4-1).** The starting battery is used to start the engine or to close the contractors to allow the HV battery to start the ICE and to power the electric motors. The HV system may also be used to power some accessories. In these vehicles, the starting battery is also used as the power source for normal accessories, such as lights.

Obviously, in a battery electric vehicle (BEV) and a fuel cell electric vehicle (FCEV), there is no need for a starting battery. These vehicles have drive or traction batteries constructed in the same way as those used in hybrids. The primary downfall of the BEV has been short driving range and long recharge times. Actually, the

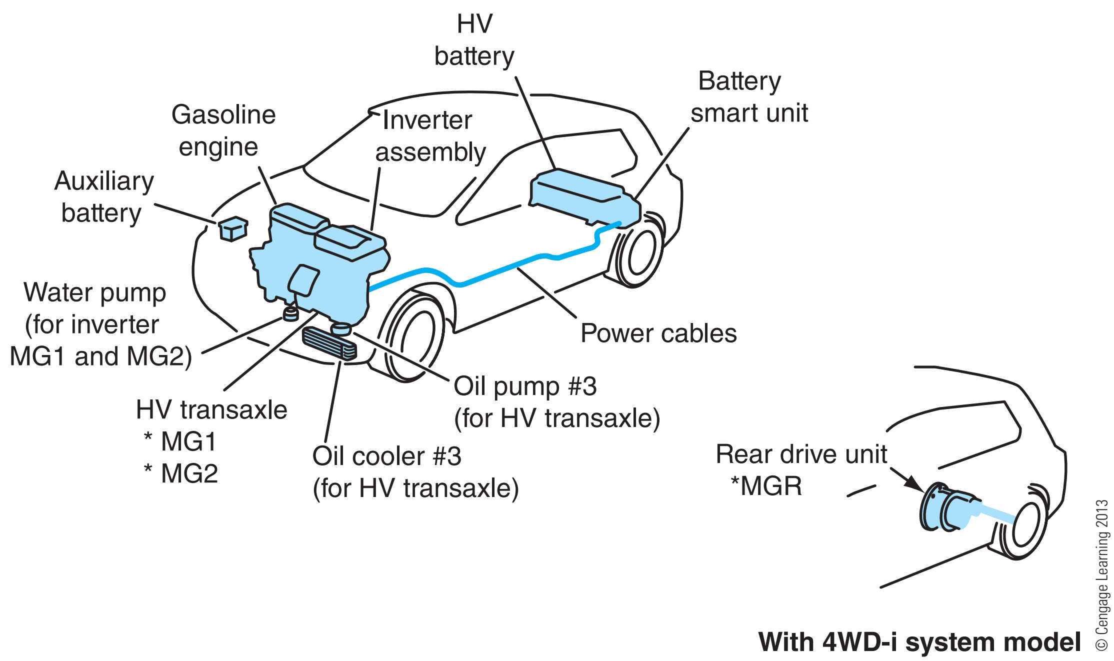

Figure 4-1 The layout of a hybrid vehicle showing the location of the auxiliary and HV (hybrid) batteries, as well as the other major components.

range limitations of BEVs were due to battery technology. Perhaps one day batteries will be developed to make BEVs a practical alternative to ICE-powered vehicles.

Electric drive vehicles not only need high-power, high-voltage batteries, they also need batteries that can be totally discharged and recharged often. This is a requirement called **deep cycling**, and a battery designed to do this is called a deep cycle battery. These batteries tend to have less instant power than a starting battery but can deliver electrical energy for longer periods of time, as well as go through many deep cycles.

Electric drive vehicles typically run on 100 to 600 volts. The batteries may be 6- or 12-volt batteries connected in series. If the electric motor requires 240 volts, the vehicle needs forty 6-volt batteries or twenty 12-volt batteries. In many cases, hundreds of individual battery cells, each about the size of a flashlight battery, are connected together to store and provide the needed power. Many different types of batteries are available and under development to exceed the needs of electric drive vehicles. In addition to batteries, some electric drive vehicles are equipped with ultra-capacitors, which also store and provide electrical energy. Each of these energy-storing devices will be discussed in this chapter.

BASIC BATTERY THEORY

Electrical current is caused by the movement of electrons from something negative to something positive. The strength of the attraction of the electrons (negative) to the protons (positive) determines the amount of voltage present. When a path is not present for the electrons to travel through, voltage is still present but there is no current flow. When there is a path, the electrons move and there is current. This is the basic operation of batteries.

Construction

A battery stores DC voltage and releases it when it is connected to a circuit. Inside the battery are two different types of electrodes or plates. One of the plates has an abundance of electrons (negative plate) and the other has a lack of electrons (positive plate). The electrons want to move to the positive plate and do so when a circuit connects the two plates. Batteries have two termina
and a negative connected to the negative plate.

The plates are surrounded by an **electrolyte**. Electrolytes are chemical solutions that react with the metals used to construct the plates. These chemical reactions cause a lack of electrons on the positive electrode and an excess on the negative electrode. When connected into a circuit, the electrons move out of the negative terminal and the chemical reactions begin. The reactions continue to provide electrons for current flow until the circuit is opened or the chemicals inside the battery become weak. At that time, either the battery has run out of electrons or all of the protons are matched with an electron. Recharging simply reverses the chemical reaction and restores the battery to its original chemical state.

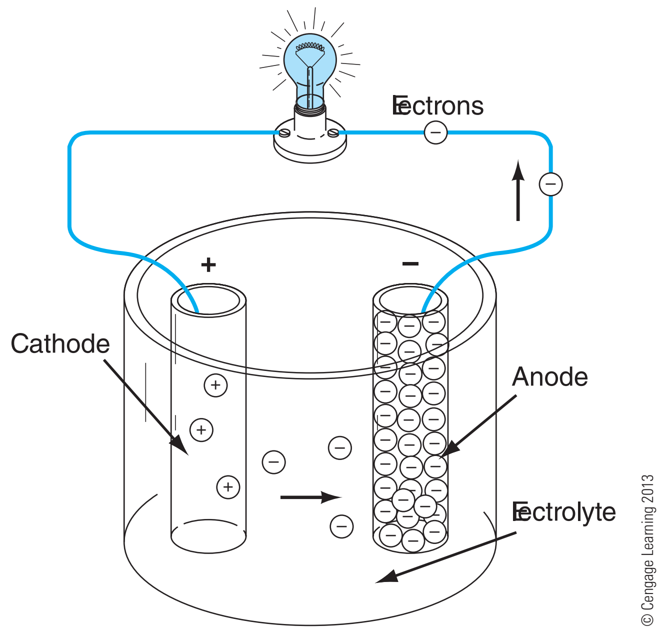

Figure 4-2 The basic components of an electrochemical battery cell. The positive electrode is the cathode and the negative one is the anode. Both are placed in an electrolyte.

Batteries are devices that convert chemical energy into electrical energy. Chemical reactions that produce electrons are called **electrochemical** reactions. Batteries are normally made up of electrochemical cells connected together. Each electrochemical cell has three major parts: an **anode** (negative electrode), a **cathode** (positive electrode), and electrolyte **(Figure 4-2).**

Effects of Temperature

Temperature affects the chemical reaction in batteries. For all battery designs, there is an ideal temperature range. Discharging or charging a battery outside its ideal temperature range shortens the life of the battery, reduces its ability to supply power, and can create an unsafe condition.

Battery Hardware

In order to connect the battery to the vehicle's electrical system, battery cables are used. They must safely handle the voltage and current demands of the vehicle.

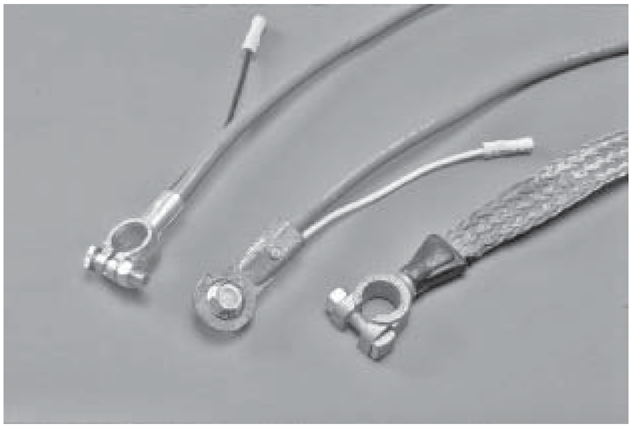

Figure 4-3 The main power cables in a hybrid vehicle.

Battery hold-downs are used to prevent damage to the battery, and heat shields are sometimes used to keep battery temperatures down. Most high-voltage battery packs are enclosed in a box that serves to secure the pack and to keep it cool.

Battery Cables. Battery cables must be able to carry the current required to meet all demands. The normal 12-volt cable size is 4 or 6 gauge. Various forms of clamps and terminals are used to assure a good electrical connection at each end of the cable. The positive cable is normally red and the negative cable is black.

High-voltage systems typically have their battery cables marked or colored in such a way that they can be easily identified. The high-voltage cables in all hybrid vehicles are colored orange and have markings on them. Sometimes the cables are enclosed in an orange casing, again to identify them. It is important to remember that some hybrids power other accessories with high voltage; these cables are orange just like the battery cables **(Figure 4-3).**

Battery Hold-Downs. All batteries must be held securely in the vehicle to prevent damage to the battery and to prevent the terminals from shorting to the vehicle. Battery hold-downs are made of metal or plastic.

The performance and durability of a battery, especially high-voltage battery packs, is heavily dependent on maintaining desired temperatures. High-voltage batteries are normally housed in a box or container and have a cooling fan and ductwork **(Figure 4-4)** or are connected

Most high-voltage battery packs have a control unit designed specifically to control the temperature of the battery **(Figure 4-5).** Some batteries work best when they are warm. For these, the battery box also has a heater. Remember, each battery design has its own optimal temperature range.

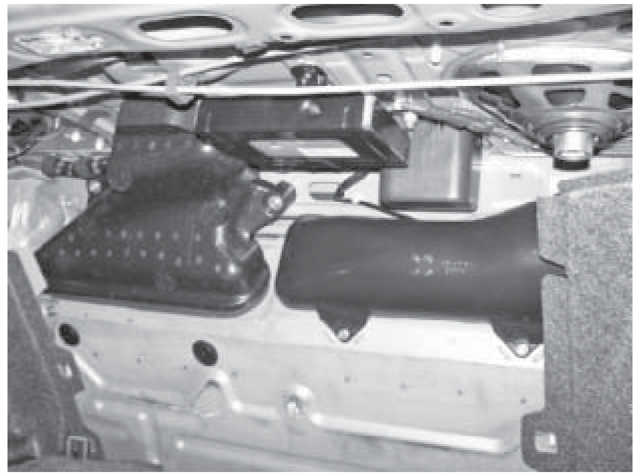

Figure 4-4 Vents to the battery pack that provide airflow to keep the batteries cool.

Heat Shields. Some batteries may have a heat shield made of plastic or another material to protect the starting battery from high underhood temperatures. Vehicles equipped for cold climates may have a battery blanket or heater to keep the battery warm during extremely cold weather.

Battery Arrangements

The voltage produced by an individual battery cell varies with the chemicals and materials used to construct the cell. Most cells produce between 1.2 and 3.0 volts. To provide higher voltages, the cells are connected in series. In addition, there is a limited amount of current available from an individual cell. Connecting the cells in parallel increases available current. Therefore, the cells in a battery may be connected in series, parallel, or both depending on the needs of the circuit.

Series Connections. Cells are connected in series to provide higher voltages. In this arrangement, the total voltage is the sum of the voltages in each cell. For example, a lead-acid cell, commonly used in starting batteries, produces about 2.1 volts. By connecting six cells together in series, the battery has a voltage of 12.6 volts **(Figure 4-6).** In an EV or HEV battery pack, hundreds of cells can be connected together to provide the required high voltages **(Figure 4-7).** Series connections

negative terminal of another and the positive terminal of that cell connected to the negative of another, and so on. Individual batteries can also be connected in series.

Parallel Connections. Cells are connected in parallel to increase the available current (amperage) of the

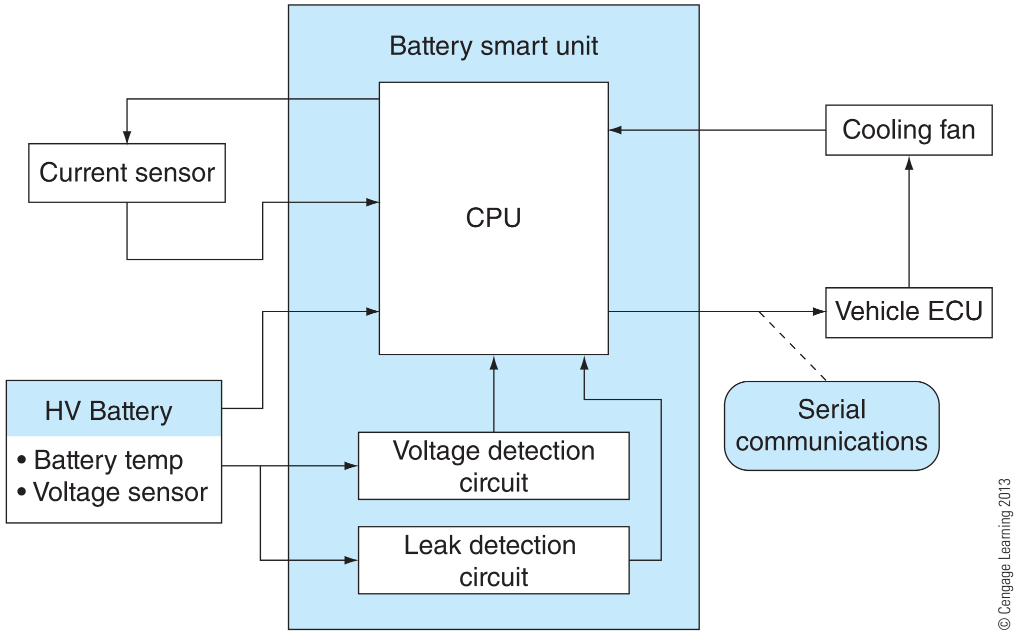

Figure 4-5 The basic components of a "battery smart unit."

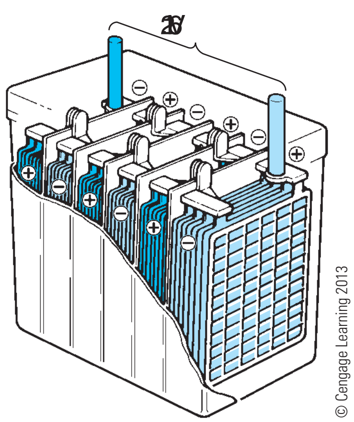

Figure 4-6 The six 2.1-volt cells are connected in series to provide 12.6 volts.

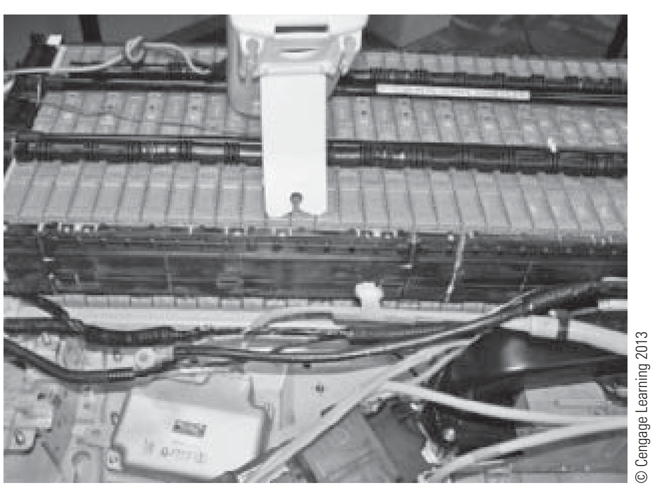

Figure 4-7 A number of individual cells connected together to provide high voltage.

pack of cells. The positive terminals are connected, and all the negative terminals are connected. The total amperage is the sum of amperages from each cell. The voltage is equal to the voltage of an individual cell.

Series-Parallel Connections. In this arrangement, groups of cells are wired in parallel and then those groups are connected in series. This arrangement provides for increases in voltage and amperage. Any number of cells can be connected in parallel, as long as each group of parallel cells that are wired in series has the same power output.

Charging

Charging a battery restores the chemical nature of the battery. To do this, a chemical reaction takes place inside the battery. Charging does little more than cause current flow in the electrochemical cells. Discharging allows for current flow outside the cell. To understand the charging process, remember that current flows from a higher potential (voltage) to a lower potential. If the voltage applied to the battery is higher than the voltage of the battery, current will flow into the battery. This means the charging voltage must be higher than the battery's voltage in order to charge it.

ments. It is very important to follow the correct procedure for the battery being charged. It is also important to prevent the battery from overheating during charging and to use the correct type of charger; these, too, vary with battery designs. Using the wrong charger can destroy the batteries or charger.

Chargers. Battery chargers are designed to supply a constant voltage, a constant current, or a mixture of the two. Constant-voltage chargers provide a specific amount of voltage to the battery. The current varies with the voltage of the battery. When the potential difference between the charger's voltage and the battery's voltage is great, the current is high. As the battery charges, its voltage increases and the charging current drops off. A constant-current charger varies the voltage applied to the battery in order to maintain a constant current.

Both of these techniques work fine as long as the temperature of the battery is maintained. Some chargers have a thermometer to monitor battery temperature. These chargers reduce the charging voltage and/or current in response to rising temperatures. It is important that high-voltage batteries be charged with the appropriate type of charger **(Figure 4-8).**

Many battery chargers are "smart" or "intelligent." These chargers are designed to charge a battery in three basic steps: bulk, absorption, and float. During bulk charging, current is sent to the battery at a maximum safe rate until the voltage reaches approximately 80 percent of its capacity. Once the battery reaches that voltage level, the charger begins the absorption step. During this time, charging voltage is held constant while the current changes according to the battery's voltage. Once the battery is fully charged, the charger switches to the float step. During this step, the charger supplies a constant voltage equal to slightly more than the voltage of the battery. The current flow is very low. This step is a maintenance charge and is intended to keep a battery charged while it is not being used.

Fast charging quickly charges a battery. This supplies large amounts of voltage and current. Although this charges the battery quickly, it also can overheat the battery if it is not closely monitored. This technique is best used when a battery is low on charge and will be installed into the vehicle in a short time. **Slow** or **trickle charging** applies low current to the battery and takes quite some time to fully charge it. However, it is unlikely that the battery will overheat, and the battery has a good chance to be completely charged. The chemicals used in the construction of the battery should always be considered before fast or slow charging a battery.

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Figure 4-8 A smart charger connected to the battery of a GM two-mode hybrid vehicle.

CAUTION *A battery should never be incinerated. Doing this can cause an explosion.*

Recycling Batteries

The materials used to make a battery can be used in the future through recycling. Batteries should not be discarded with regular trash, as they contain metals and chemicals that are hazardous to the environment.

In 1994, the Rechargeable Battery Recycling Corporation (RBRC) was established to promote recycling of rechargeable batteries in North America. RBRC is a nonprofit organization that collects batteries from consumers and businesses and sends them to recycling companies. Collected batteries are sorted by their chemical makeup. Then they are broken apart and their elements separated. The chemicals or materials are further separated and then collected.

Ninety-eight percent of all lead-acid batteries **(Figure 4-9)** are recycled. During the recycling process, the lead, plastic, and acid are separated. The electrolyte (sulfuric acid) can be reused or is discarded after it has been neutralized. The plastic casing is cut into small pieces, scrubbed, and melted to make new battery cases and other parts. The lead is also melted and poured into ingots to be used in new batteries.

BATTERY RATINGS

The voltage rating of a battery may be expressed as open-circuit or operating voltage. **Open-circuit voltage** is the voltage measured across the battery when there is no load on the battery. **Operating voltage** is

under a load.

The available current from a battery is expressed as the battery's capacity to provide a certain amount of current for a certain amount of time and at a certain temperature. Basically, a capacity rating expresses how much electrical energy a battery can store.

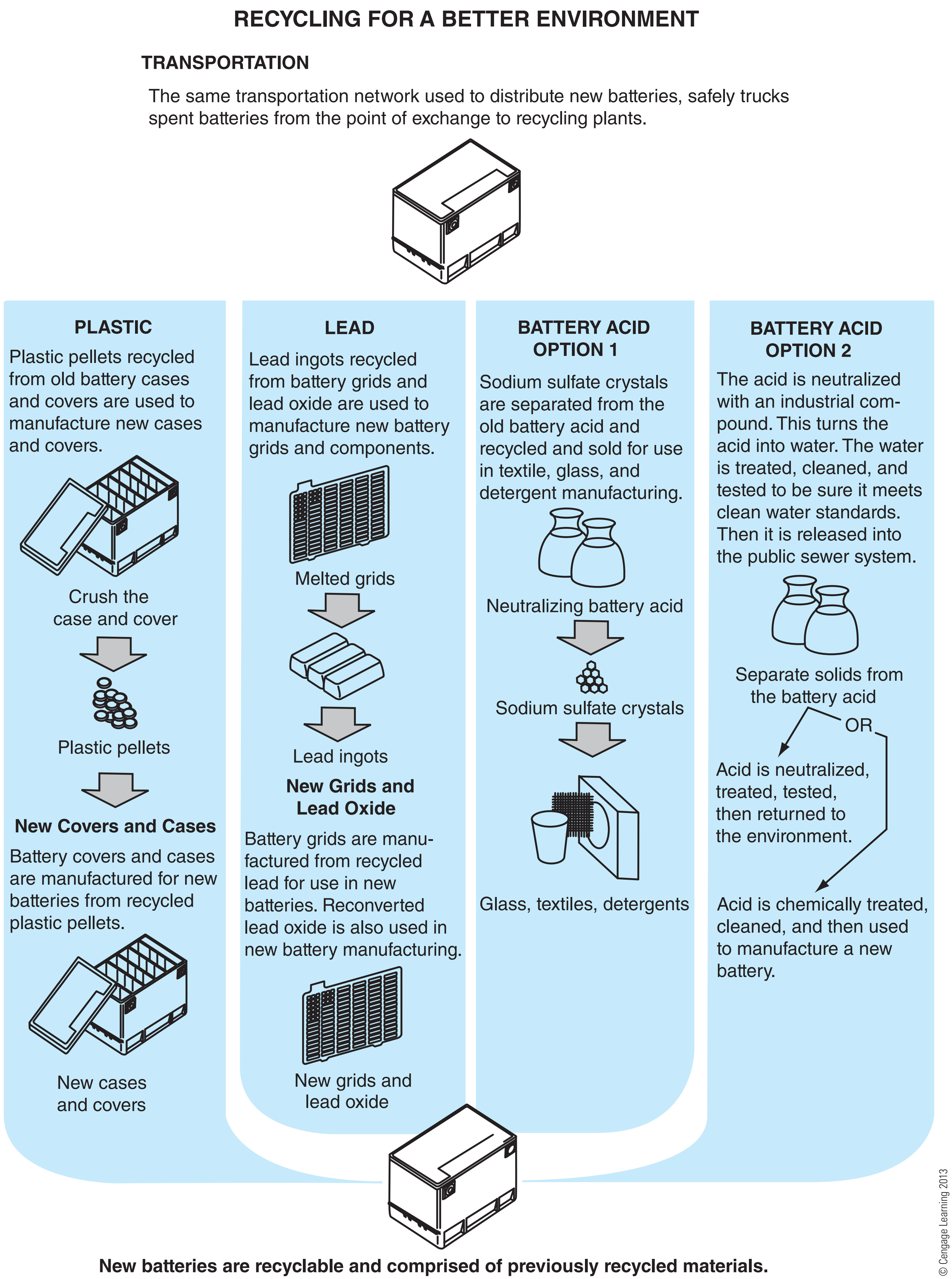

Figure 4-9 The recycling process for a lead-acid battery.

Ampere-Hour

A commonly used capacity rating is the ampere-hour rating. In the past, this was the common rating method for lead-acid batteries. However, these batteries are now rated in a different manner. Other battery designs are still rated in ampere-hours or milliamp-hours for cell phone applications.

The **ampere-hour (AH) rating** is the amount of steady current that a fully charged battery can supply for 20 hours at 80°F (26.7°C) without the cell's voltage dropping below a predetermined level. For example, if a 12-volt battery can be discharged for 20 hours at a rate of 4.0 amperes before its voltage drops to 10.5 volts, it is rated at 80 ampere-hours. A 100-AH battery will provide 1 amp for 100 hours, or 10 amps for 10 hours.

Watt-Hour Rating

Some battery manufacturers rate their batteries in watt-hours. The **watt-hour rating** is determined at 0°F (−17.7°C) because the battery's capacity changes with temperature. The rating is calculated by multiplying a battery's amp-hour rating by the battery's voltage. The watt-hour rating of a battery may be listed in units of kilowatts. If a battery can deliver 5 AH at 200 volts, it is rated at 1 kilowatt-hour.

Cold-Cranking Amps

The **cold cranking amps (CCA) rating** is the common method of rating most automotive starting batteries. It is determined by the load, in amperes, that a battery is able to deliver for 30 seconds at 0°F (−17.7°C) without its voltage dropping below a predetermined level. That voltage level for a 12-volt battery is 7.2 volts. The normal range for passenger car and light truck batteries is between 300 and 600 CCA; some batteries have a rating as high as 1,100 CCA.

Cranking Amps

The **cranking amps (CA) rating** is similar to CCA and is a measure of the current a battery can deliver at 32°F (0°C) for 30 seconds and maintain voltage at a predetermined level. Again, this level is 1.2 volts per cell (7.2 volts) for a 12-volt battery. This rating is commonly used in climates that are not subjected to extremely cold weather. Typically, the CCA rating of a battery is about 20 percent less than its CA rating.

Reserve Capacity

The **reserve capacity (RC) rating** is determined by the length of time, in minutes, that a fully charged starting battery at 80°F (26.7°C) can be discharged at 25 amperes before battery voltage drops below 10.5 volts. This rating gives an indication of how long the vehicle can be driven with the headlights on, if the charging system fails. A battery with a reserve capacity of 120 would be able to deliver 25 amps for 120 minutes before its voltage drops below 10.5 volts.

COMMON TYPES OF BATTERIES

In addition to their use in automobiles, batteries are used in many other applications. As a result, there are many different types and designs of batteries available. Most battery manufacturers divide batteries into two separate groups: primary and secondary **(Figure 4-10).**

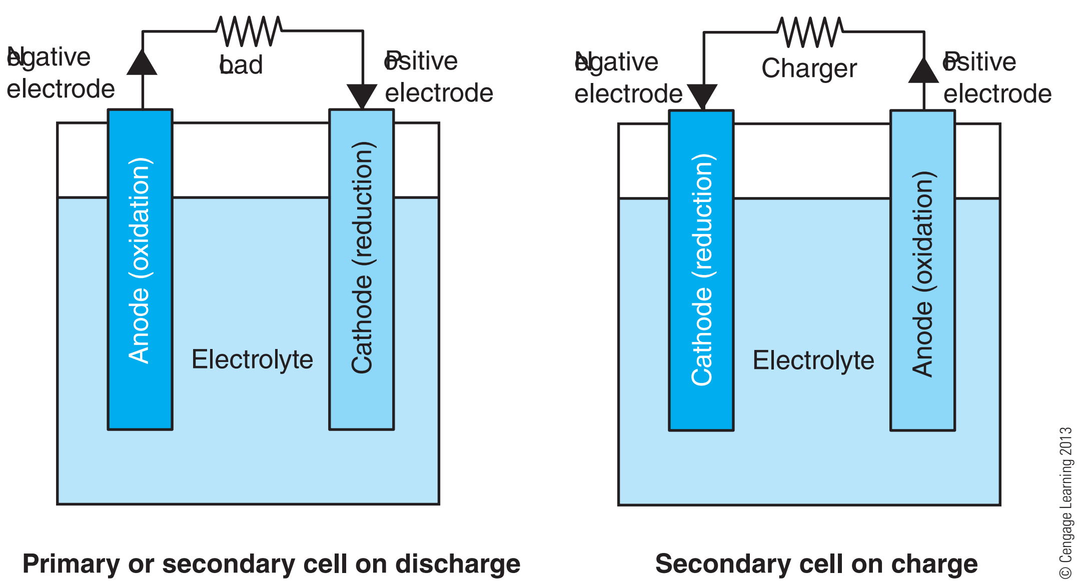

Figure 4-10 The discharge and charge cycles of primary and secondary batteries.

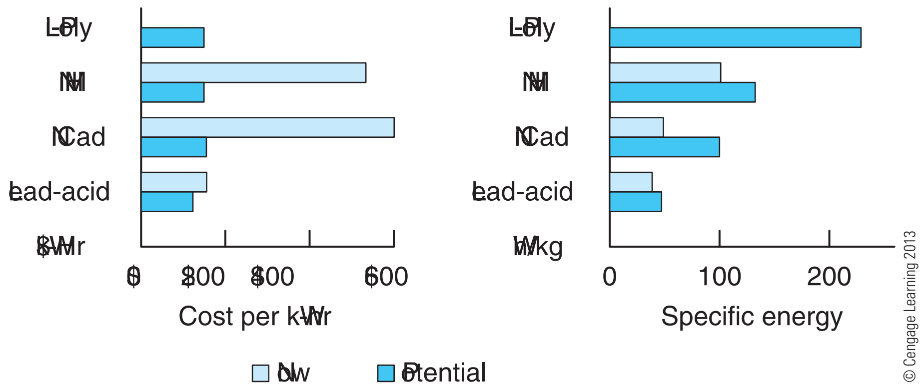

Figure 4-11 A comparison of the common types of automotive batteries.

Primary batteries are not rechargeable. These batteries are discarded once they become weak. **Secondary batteries** are rechargeable. The number of times they can be recharged is primarily dependent on the chemicals used in their construction.

Batteries differ in size, from small single cells to large battery packs, comprised of many cells. The primary difference between battery types is the chemicals used in the cells.

Battery Chemistry

The following battery types can be or are being used in electric drive vehicles. There are many other types available, but they are not relevant to the topic of this book. Some of the batteries in the list that follows will be discussed in more detail later in this chapter. **Figure 4-11** shows a simple comparison of the common types of automotive batteries.

Lead-Acid. Lead-acid batteries are the most commonly used starting batteries. This type of battery is rechargeable. In some electric vehicles, several lead-acid cells are connected in series to provide high voltage. There are many variations to the basic design, but all work and are constructed in the same way. The lead-acid cell has electrodes made of lead and lead oxide with an electrolyte that is a strong acid. The lead-acid battery is one of the oldest battery designs.

Nickel-Cadmium (NiCad). NiCad batteries are most used in portable radios, emergency medical equipment, professional

provide great power and are normally the battery of choice for power tools. The electrodes in a nickel-cadmium cell are nickel hydroxide and cadmium. The electrolyte is potassium hydroxide. NiCad batteries are economical and have a long service life. However, cadmium is an environmentally unfriendly metal, which is why NiCad batteries are being replaced by other designs.

Nickel-Metal Hydride (NiMH). Nickel-metal hydride batteries are very common; they are rapidly replacing nickel-cadmium batteries because they are more environmentally friendly. NiMH batteries also have more capacity than NiCads but have a lower current capacity under load. These batteries are commonly used in today's hybrid vehicles. The cells have electrodes made of a metal hydride and nickel hydroxide. The electrolyte is potassium hydroxide.

Sodium-Sulfur (NaS). The electrodes in a sodium-sulfur battery cell are composed of molten sodium (negative electrode) and liquid sulfur (positive electrode). The plates are separated by a solid ceramic electrolyte, made from aluminum. The battery must be kept at about 570°F (300°C) to discharge and recharge. This design of battery is very efficient and is currently being researched for possible use in electric drive vehicles.

Sodium-Nickel-Chloride. The electrodes in a sodium-nickel-chloride cell are made with nickel and iron powders and sodium chloride (table salt). The electrodes are separated by a ceramic electrolyte. Sodium-nickel-chloride batteries are also known as "ZEBRA" batteries **(Figure 4-12).** These batteries have nearly five times the energy density of a lead-acid battery and are totally recyclable. However, they must operate at high temperatures, and the required thermal manage-

batteries were designed to be used in electric drive vehicles, including automobiles and trains.

Lithium-Ion (Li-Ion). The electrodes in lithium-ion cells are made of carbon (graphite) and a metal oxide. The electrodes are submersed in lithium salt.

Figure 4-12 The sodium-nickel-chloride battery, made from nickel and iron powders, sodium chloride, and a ceramic electrolyte, is also known as the "ZEBRA" battery.

Overheating these cells may produce pure lithium in the cells. This metal is very reactive and can explode when hot. To prevent overheating, Li-Ion cells have built-in protective electronics and/or fuses to prevent reverse polarity and overcharging. Li-Ion batteries have very good power-to-weight ratios, which is why many electric drive vehicles are fitted with them. They are also found in laptop computers, video cameras, and cell phones.

Lithium-Polymer (Li-Poly). The lithium-polymer battery is nearly identical to a lithium-ion battery. In fact, it evolved from the Li-Ion design. Like the Li-Ion, the electrodes are made of carbon (graphite) and a metal oxide. However, the lithium salt electrolyte is held in a thin, solid, plastic-like polymer rather than as a liquid. The solid polymer electrolyte is not flammable; therefore these batteries are less hazardous if they are mistreated. These batteries can be shaped to fit the application and are currently being used in some electric drive vehicles.

Zinc-Air. The zinc-air cell **(Figure 4-13)** is commonly used in hearing aids, but has been tested and modified for possible use in electric drive vehicles. The interesting characteristic of this battery is that oxygen from the outside air is used as the cathode. The anode is a replaceable cassette made of zinc particles in an electrolyte solution of potassium hydroxide. Within the cell, a chemical reaction produces electrical energy, and the cells are not electrically rechargeable. They can, however, be recharged by replacing the anode cassette. This type of battery is lightweight and has very high energy density.

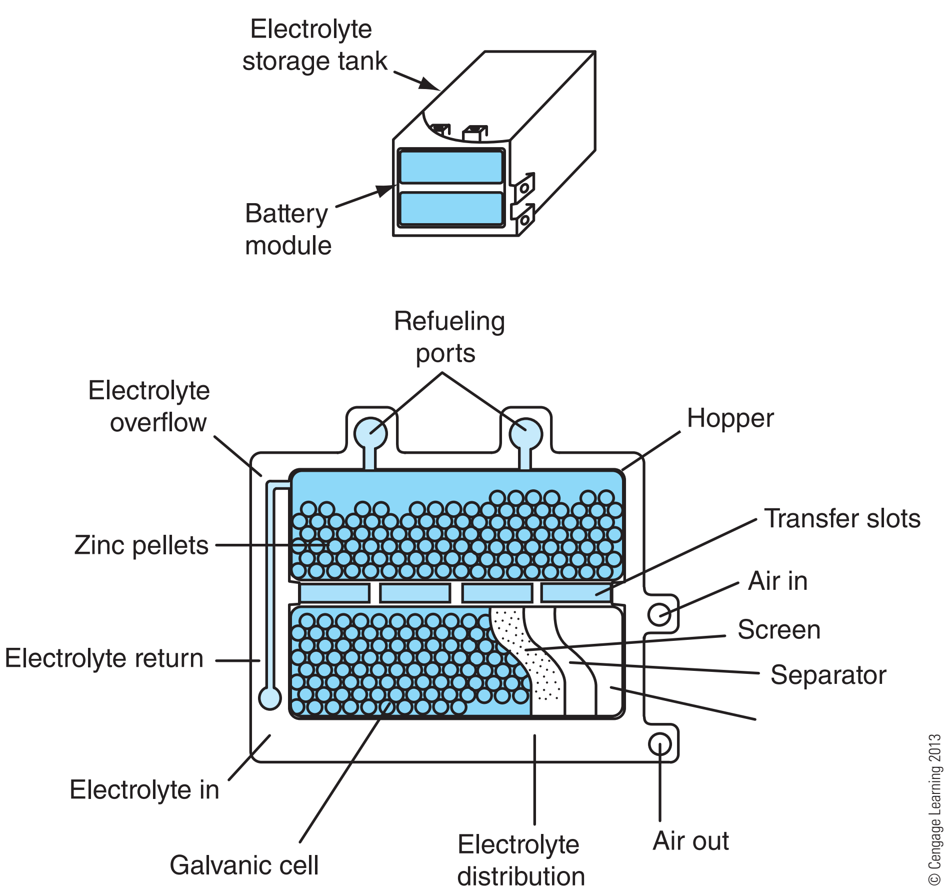

Figure 4-13 Details of a zinc-air battery unit cell (end view).

Nickel-Zinc. Nickel-zinc battery cells are also being researched and tested for possible use in electric drive vehicles. These batteries have a high specific energy and power capability, good deep cycle capability, can operate within a wide range of temperatures, are made of abundant low-cost materials, and are environmentally friendly. The nickel-zinc battery is an alkaline rechargeable system. These cells use a nickel/nickel oxide electrode as the cathode and the zinc/zinc oxide electrode as the anode. The electrolyte is normally potassium hydroxide.

Ultra-Capacitors. An ultra-capacitor is not a battery; however, it can function much like one. This device stores and releases electrical energy electrostatically, rather than electrochemically. Ultra-capacitors have the ability to quickly discharge high voltages and then be quickly recharged. These characteristics make them ideal for adding electrical energy to motors when a vehicle needs extra power for acceleration or to overcome heavy loads. Ultra-capacitors are also very good at absorbing the energy from regenerative braking. Some current hybrid vehicles use ultra-capacitors for both purposes.

HIGH-VOLTAGE BATTERIES

Electric drive vehicles require high voltages. These high-voltage batteries are assemblies of many cells and are called battery packs. The cells are either cylindrical or prismatic **(Figure 4-14).** In a **cylindrical cell**, the electrodes are rolled together and fit into a metal cylinder. A separator soaked in the electrolyte is sandwiched between the plates. Battery packs comprised of this cell design require a large housing. Also, when several cylinders are assembled together, there is much wasted space between the cylinders. **Prismatic cells** do not have this problem. They have flat electrodes placed into a box with separators between them. Prismatic cells tend to be more expensive to produce than cylindrical cells.

Applications

To understand the need for high-voltage systems, let us take a quick look at some history. In 1954, General Motors equipped its Cadillacs with a 12-volt system. Prior to that, vehicles had 6-volt systems. The electrical demands of accessories, such as power windows and seats, put a severe strain on the 6-volt battery and charging system. With the introduction of 12-volt systems, there was half as much strain and current drain on the charging system as before. This means the charging system had to work less hard and there was an ample amount of electrical power for the accessories.

The increase in voltage also allowed wire sizes to decrease, which means less vehicle weight. Wire sizes decreased because the amperage required to power things was reduced. To explain this, consider an accessory that required 20 amps to operate when it was in a 6-volt system. This means it needed 120 watts to operate. When the voltage was increased to 12 volts, the system only drew 10 amperes. Required wire size is dictated by current.

Today we are faced with the same situation. The use of computers and the need to keep their memories fresh has put a drain on the battery. Plus, the number of electrical accessories found on today's vehicles has and will continue to grow. The 12-volt system is becoming overburdened by these.

Today's vehicles are very sensitive to voltage change. In fact, the overall efficiency of a vehicle

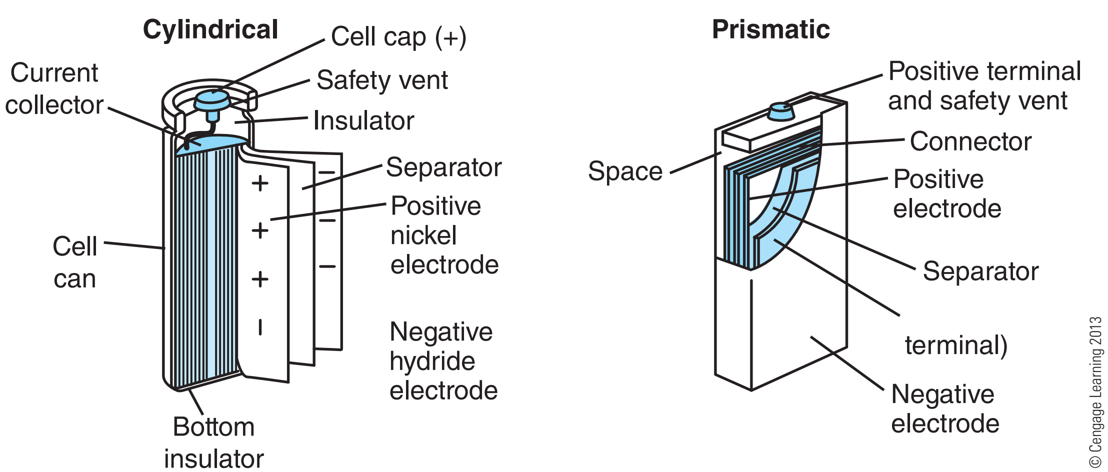

Figure 4-14 The basic construction of cylindrical and prismatic cells.

depends on a constant voltage. The demands of new technology make it difficult to maintain a constant voltage, and engineers have determined system voltage must be increased to meet those demands and maintain vehicle efficiencies. As our vehicles evolve, emission, fuel economy, comfort, convenience, and safety features will require more electrical power than they do now. This increased demand is the result of converting purely mechanical systems into electromechanical systems, such as steering, suspension, and braking systems, as well as new safety and communication systems. It is has been estimated that the continuous electrical power demand in a few years will be 3,000 W to 7,000 W. The current 12-volt systems are rated at 800 W to 1,500 W.

These demands can be met by increasing the amperage capacity of the battery and charging system or by increasing system voltage. Larger-capacity batteries and generators are only a band-aid to the problem. Because the generator is driven by engine power, more power from the engine will be required to keep the higher-capacity battery charged. Therefore, overall efficiency will decrease. By moving to a higher system voltage, the battery may need to be larger but system amperage will be lower, and, therefore, the wire size will be smaller. Perhaps the weight gain at the battery will be offset by the decreased weight of the wiring.

There are initiatives to move from a 12-volt to a 42-volt system. But why 42 volts? The starting battery in today's vehicles is rated at 12 volts but stores about 14 volts. Also, the charging system puts out 14 to 15 volts while the engine is running. Because the primary source of electrical power when the engine is running is the charging system, it is fair to say an automobile's electrical system is a 14-volt system. This is the logic used by engineers in planning for 42-volt systems. Forty-two volts represent three 12-volt batteries.

Forty-two-volt systems are based on a single 36-volt battery but have dual voltage systems **(Figure 4-15).** Part of the vehicle is powered by 12 to 14 volts and the rest by 36 to 42 volts. The battery has two positive connectors, one for each voltage, or the voltage is divided by a converter. The split-voltage system provides 42 volts for high-voltage applications such as the starter/generator, power steering, air conditioning, traction control, brake, and engine cooling systems. The lights, power door locks, radios, navigation systems, and cell phones.

Again, the same logic is followed when designing electric drive vehicles. High voltage is needed to prevent the need for extremely large cables and wiring. Also, keeping the required amperage low is easier on the batteries. The voltage used by electric vehicles varies, as does the chemistry of the battery.

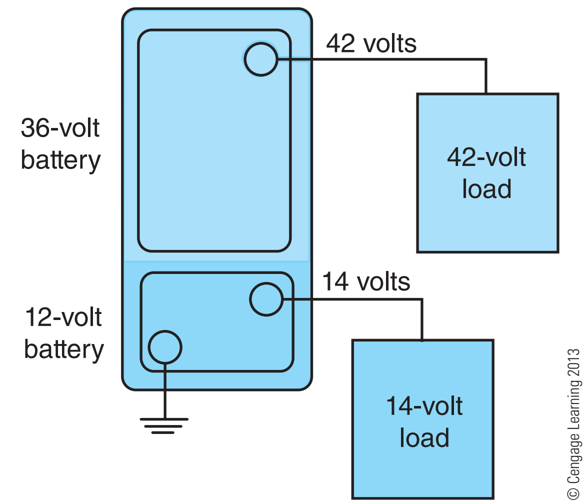

Figure 4-15 A split voltage arrangement providing 14 and 42 volts from a 36-volt battery.

The first generation of General Motors' EV1, a BEV, used twenty-six 12-volt lead-acid batteries. The individual batteries were connected in series. The battery pack provided 312 volts and weighed 1,310 pounds (595 kg). The driving range between battery recharges was 55 to 95 miles (88 to 153 km). The next, and last, generation EV1 used NiMH batteries and had a slightly longer range.

Vehicles equipped with a starter/generator can be considered mild hybrids, and many rely on a 42-volt system. Functions such as stop-start, regenerative braking, and electrical assist are common to full and mild hybrid vehicles.

Only full hybrids have the ability to move in an electric-only mode. A full hybrid vehicle has a much higher-voltage system than a mild hybrid; therefore, the motor is capable of providing much more power, more frequently, and for longer periods of time. Hybrid vehicles may also have a separate starting battery for the ICE **(Figure 4-16).** The starting battery also is the power source for the lights and other accessories.

The battery pack in a hybrid vehicle is typically made up of several cylindrical cells **(Figure 4-17)** or prismatic cells **(Figure 4-18).** These battery packs are often called HV batteries.

Safety Issues

High-voltage circuits are identifiable by size and color. The cables have thicker insulation and are colored orange. The connectors are also colored orange. On some vehicles, the high-voltage cables are enclosed

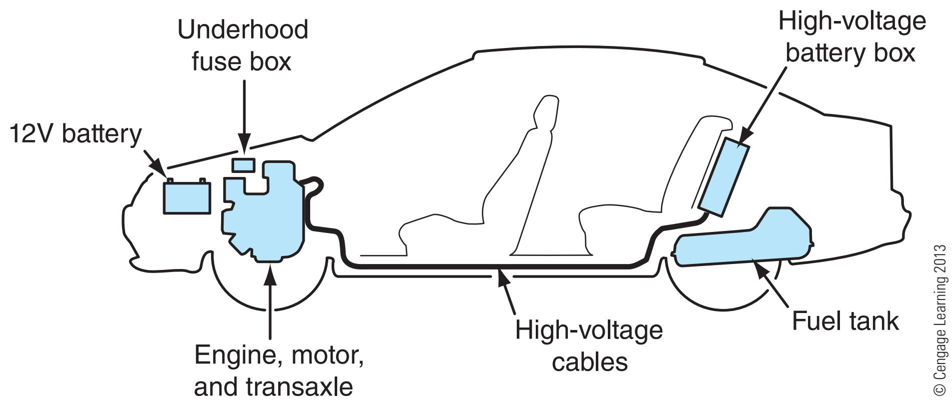

Figure 4-16 Location of the batteries in a Honda Civic Hybrid.

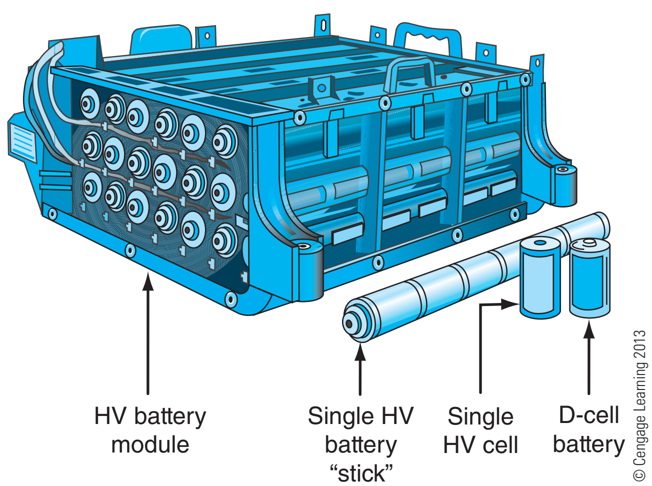

Figure 4-17 A high-voltage battery module made of several cylindrical battery cells.

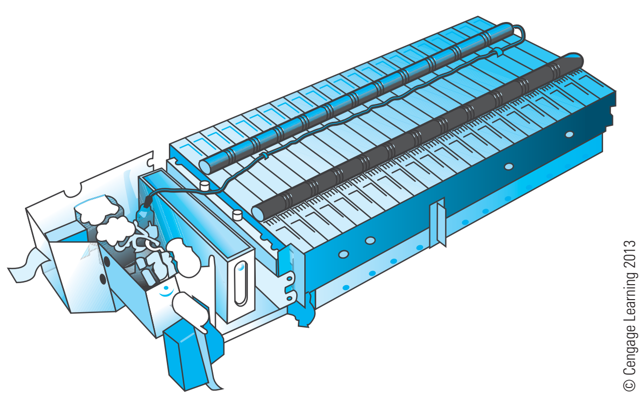

Figure 4-18 The battery pack of a Toyota Prius, which uses prismatic cells.

in an orange shielding or casing; again the orange indicates high voltage. In addition, the high-voltage battery pack and other high-voltage components have "High Voltage" caution labels. It is important to remember that high voltage is also used to power some vehicle accessories **(Figure 4-19).**

With these high voltages come special precautions:

- Always precisely follow the correct procedures. If a repair or service is done incorrectly, an electrical shock, fire, or explosion can result.
- Avoid all orange-colored cables, connectors, and wires unless you have disconnected the high-voltage power source and know what you are doing.
- Always follow the manufacturer's procedures for disconnecting the power source before working on the high-voltage system **(Figure 4-20).**
- Systems may have a high-voltage capacitor that must discharge after the high-voltage system has been isolated. Make sure to wait the prescribed amount of time (about 10 minutes) before working on or around the high-voltage system.
- Wear insulating gloves (Class 0–1000V) when working on or around the high-voltage system. Make sure the gloves have no tears, holes, or cracks and that they are dry.
- After removing a high-voltage cable, cover the terminal with vinyl electrical tape.
- Always use insulated tools.
- Alert other technicians that you are working on the high-voltage systems with a warning sign such as "high voltage work: do not touch."

on its own if it is left in the idle stop mode. Make sure the READY light in the instrument panel is OFF.

- Do not carry any metal objects, such as a mechanical pencil or a measuring tape, that could fall and cause a short circuit.

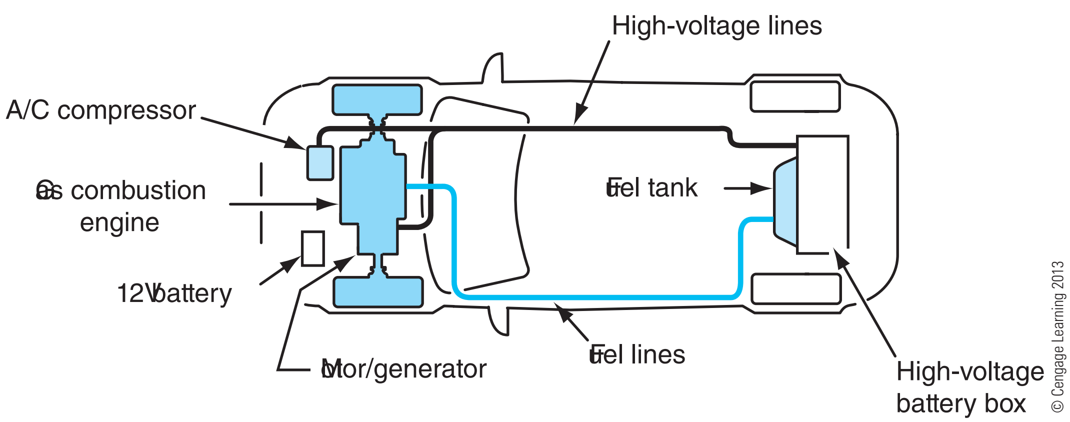

Figure 4-19 The A/C compressor is powered by the high-voltage system on the hybrid.

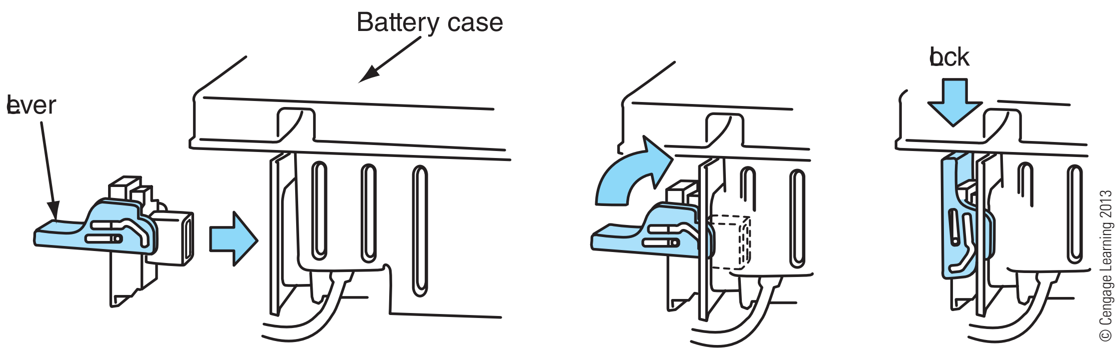

Figure 4-20 Removal of the service plug on a Toyota Hybrid to disconnect the high-voltage circuits.

LEAD-ACID BATTERIES

Most nonelectric-drive vehicles have lead-acid batteries; in fact some electric drives use this design in addition to the high-voltage battery. The wet cell, gel cell, absorbed glass mat (AGM), and valve regulated are versions of a lead-acid battery. The wet cell comes in two styles: serviceable and maintenance-free.

A lead-acid battery consists of grids, positive plates, negative plates, separators, elements, an electrolyte, a container, cell covers, vent plugs, and cell containers **(Figure 4-21).** The **grids** form the basic framework of the battery plates. Grids are the lead alloy framework that supports the active material of the plate. Plates are typically flat, rectangular (prismatic) components that are either positive or negative, depending

The positive plate has a grid filled with lead peroxide as its active material. Lead peroxide (PbO_2) is a dark brown, crystalline material. The material pasted onto the grids of the negative plates is sponge lead (Pb). Both plates are very porous and allow the liquid electrolyte to penetrate freely.

Basic Construction

Each battery contains a number of elements. An **element** is a group of positive and negative plates. The plates are formed into a plate group, which holds a number of plates of the same polarity. The like-charged plates are welded to a lead alloy post or plate strap. The plate groups are then alternated within the battery—positive, negative, positive, negative, and so on. There is usually one extra set of negative plates to balance the charge. To prevent the different plate groups from touching each other, separators are inserted between them. Separators are porous plastic, electrically insulating sheets that allow for a transfer of ions between plates.

When the element is placed inside the battery case

volt battery has six cells connected in series. Each cell has an open-circuit voltage of approximately 2.1 volts; therefore, the total open-circuit voltage of the battery is 12.6 volts.

The lead peroxide and sponge lead are the active materials in the battery. However, these materials are not

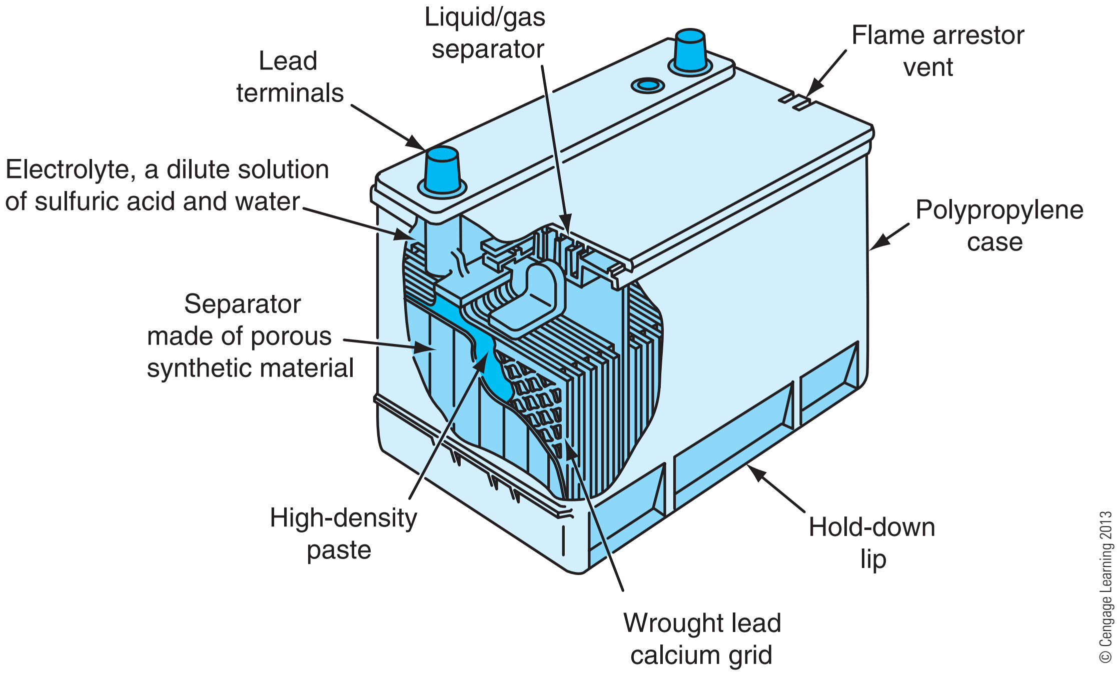

Figure 4-21 The construction of a typical lead-acid battery.

active until they are immersed in electrolyte. The electrolyte is a solution of sulfuric acid and water. The sulfuric acid supplies sulfate, which chemically reacts with both the lead and lead peroxide to release electrical energy. In addition, the sulfuric acid is the carrier for the electrons as they move inside the battery.

To achieve the required chemical reaction, the electrolyte must be the correct mixture of water and sulfuric acid. At 12.6 volts, the desired solution is 65 percent water and 35 percent sulfuric acid. Available voltage decreases when the percentage of acid in the solution decreases.

Casing Design. The container or shell of the battery is usually a one-piece, molded assembly of polypropylene, hard rubber, or plastic. The top of the battery is encased by a cell cover. The cover may be a one-piece design, or the cells might have individual covers. The cover must have vent holes to allow hydrogen and oxygen gases to escape. These gases are formed during charging and discharging. Vent caps are used on some batteries to close the openings in the cell cover and allow for the topping off of the cells with electrolyte or water.

Terminals. The battery has two external terminals: a positive (+) and a negative (−). These terminals are either two tapered posts, "L" terminals, threaded studs on top of the case, or two internally threaded connectors on the side **(Figure 4-22).** The terminals have either a positive (+) or a negative (−) marking, depending on which end of the series they represent.

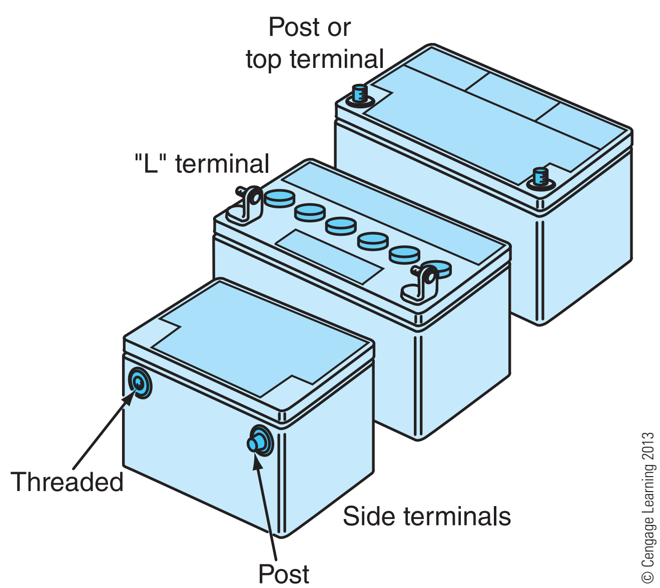

Figure 4-22 Various terminals for lead-acid batteries.

CAUTION *When lifting a battery, excessive pressure on the end walls could cause acid to spew through the vent caps, resulting in personal injury. Lift with a battery carrier or with your hands on opposite corners.*

Discharging and Charging

When a battery discharges **(Figure 4-23),** lead in the lead peroxide of the positive plate combines with the sulfate radical (SO_4) to form lead sulfate ($PbSO_4$). A similar reaction takes place at the negative plate. In this plate, lead (Pb) of the negative active material combines with sulfate radical (SO_4) to also form lead sulfate ($PbSO_4$), a neutral and inactive material. Thus, lead sulfate forms at both types of plates as the battery discharges.

As the chemical reaction occurs, the oxygen from the lead peroxide and the hydrogen from the sulfuric acid combine to form water (H_2O). As discharging takes place, the electrolyte becomes weaker and the positive and negative plates become like one another.

The recharging process **(Figure 4-24)** is the reverse of the discharging process. Electricity from an outside source, such as the vehicle's generator or a battery charger, is forced into the battery. The lead sulfate ($PbSO_4$) on both plates separates into lead (Pb) and sulfate (SO_4). As the sulfate (SO_4) leaves both plates, it combines with hydrogen in the electrolyte to form sulfuric acid (H_2SO_4). At the same time, the oxygen (O_2) in the electrolyte combines with the lead (Pb) at the positive plate to form lead peroxide (PbO_2). As a result, the negative plate returns to its original form of lead (Pb), and the positive plate reverts to lead peroxide (PbO_2).

An unsealed battery gradually loses water due to its conversion into hydrogen and oxygen; these gases escape into the atmosphere through the vent caps.

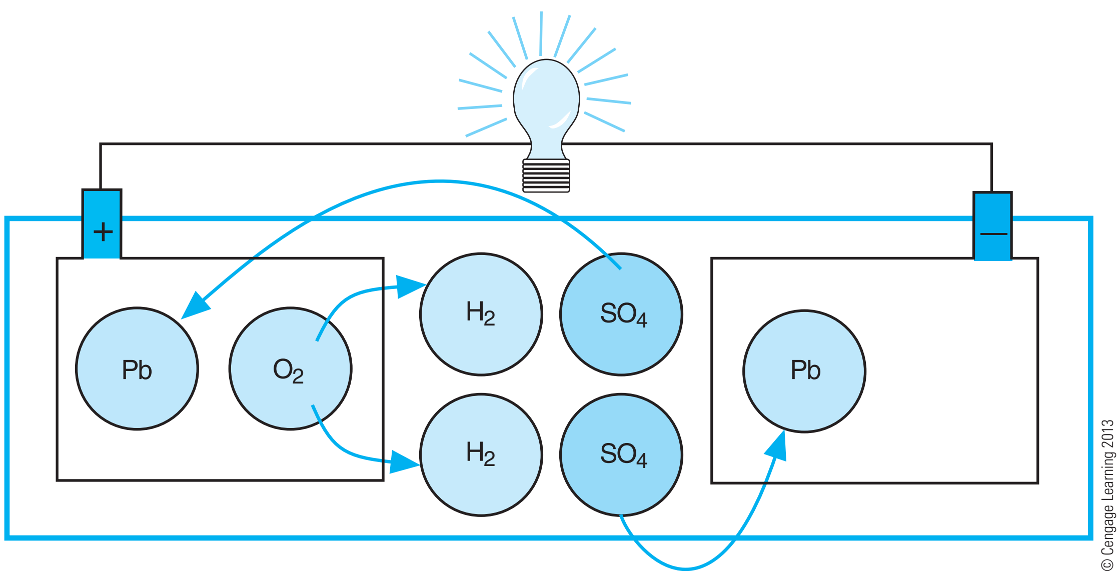

Figure 4-23 The chemical reaction during discharge of a lead-acid battery.

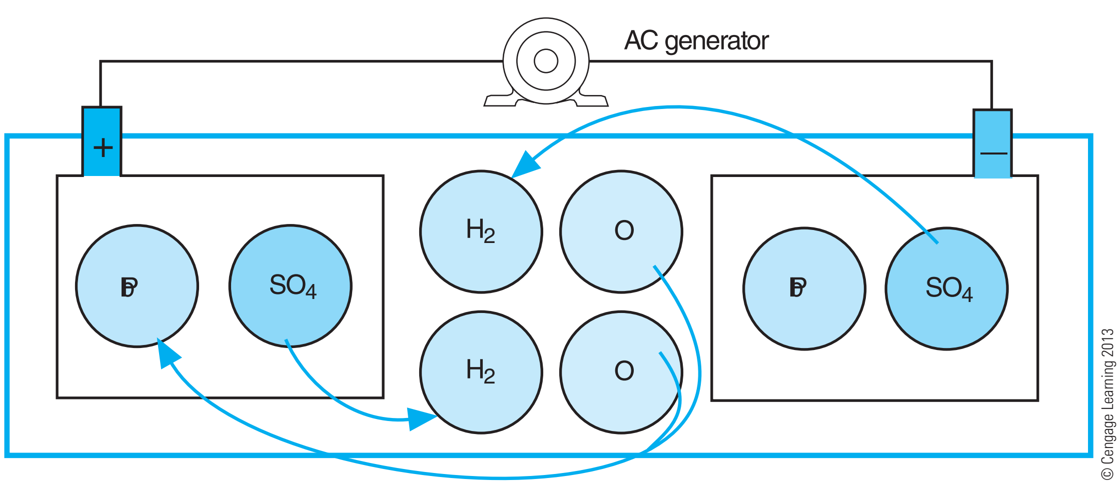

Figure 4-24 The chemical reaction during the recharging of a lead-acid battery.

If the lost water is not replaced, the level of the electrolyte falls below the tops of the plates. This results in a high concentration of sulfuric acid in the electrolyte and permits the exposed material of the plates to dry and harden, which can result in premature failure of the battery.

Temperature. Batteries do not work well when they are cold. At 0°F (−17.8°C), a battery is only capable of working at 40 percent of its capacity. There is also the possibility of the battery freezing when it is very cold and its charge is low. When the battery is allowed to get too hot, the electrolyte can evaporate. Batteries used in hot climates should have their electrolyte levels checked frequently.

Maintenance-Free and Low-Maintenance Batteries. Most automotive batteries installed today are either low-maintenance or maintenance-free. A **low-maintenance battery** is a heavy-duty lead-acid battery. Many of the components have thicker construction, and different, more durable materials are used. Similar in construction but made with different plate material, a **maintenance-free battery** experiences little gassing during discharge and charge cycles. Therefore, maintenance-free batteries do not have external holes or caps **(Figure 4-25).** They are equipped with small gas vents that prevent gas-pressure buildup in the case. Water is never added to maintenance-free batteries.

Recombination Batteries. A recombination or **recombinant battery** is a completely sealed maintenance-free battery that uses an electrolyte in a gel form. In a gel cell battery, gassing is minimized and vents are not needed. During charging, the negative plates in a recombination battery never reach a fully charged condition and therefore cause little or no release of hydrogen. Oxygen is released at the positive plates, but it passes through the separators and recombines with the negative plates. Because the oxygen released by the electrolyte is forced to recombine with the negative plate, these batteries are called recombination batteries.

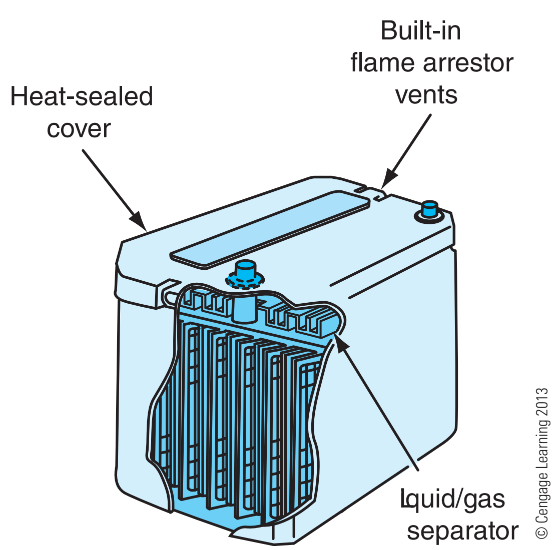

Figure 4-25 The construction of a maintenance-free battery.

Absorbed Glass Mat Batteries. The electrolyte in **absorbed glass mat (AGM)** batteries is held in moistened fiberglass matting instead of existing as a liquid or gel. The matting is sandwiched between the battery's lead plates, where it doubles as a vibration dampener. AGM batteries are recombinant batteries.

Rolls of high-purity lead plates are tightly compressed into six cells **(Figure 4-26).** The plates are separated by acid-permeated vitreous separators. Vitreous separators absorb acid in the same way a paper towel absorbs water. Each of the cells is enclosed in its own cylinder within the battery case, forming a sealed, closed system that resembles a six-pack of soda. During normal use, hydrogen and oxygen within the battery are captured and recombined to form water within the electrolyte. This eliminates the need to ever add water to the battery.

Most AGM batteries have spiral rolled plates and fiberglass mats are virtually impervious to vibration and impact. AGM batteries will never leak, they have short recharging times, and they have low internal resistance, which provides increased output.

Valve-Regulated Batteries. **Valve-regulated lead-acid (VRLA) batteries** are similar to AGM batteries. They are recombinant batteries. The oxygen produced on the positive plates of this lead-acid battery is absorbed by the negative plate. That, in turn, decreases the amount of hydrogen produced at the negative plate. The combination of hydrogen and oxygen produces water, which is returned to the electrolyte. Therefore, this battery never needs to have water added to its electrolyte mixture.

One plate in a VRLA is comprised of a lead-tin-calcium alloy with porous lead dioxide; the other is lead as the active material. The electrolyte is sulfuric acid that is absorbed into plate separators made of a glass-fiber fabric. The battery is equipped with a valve that opens to relieve any excessive pressure that builds up in the battery. At all other times, the valve is closed and the battery is totally sealed.

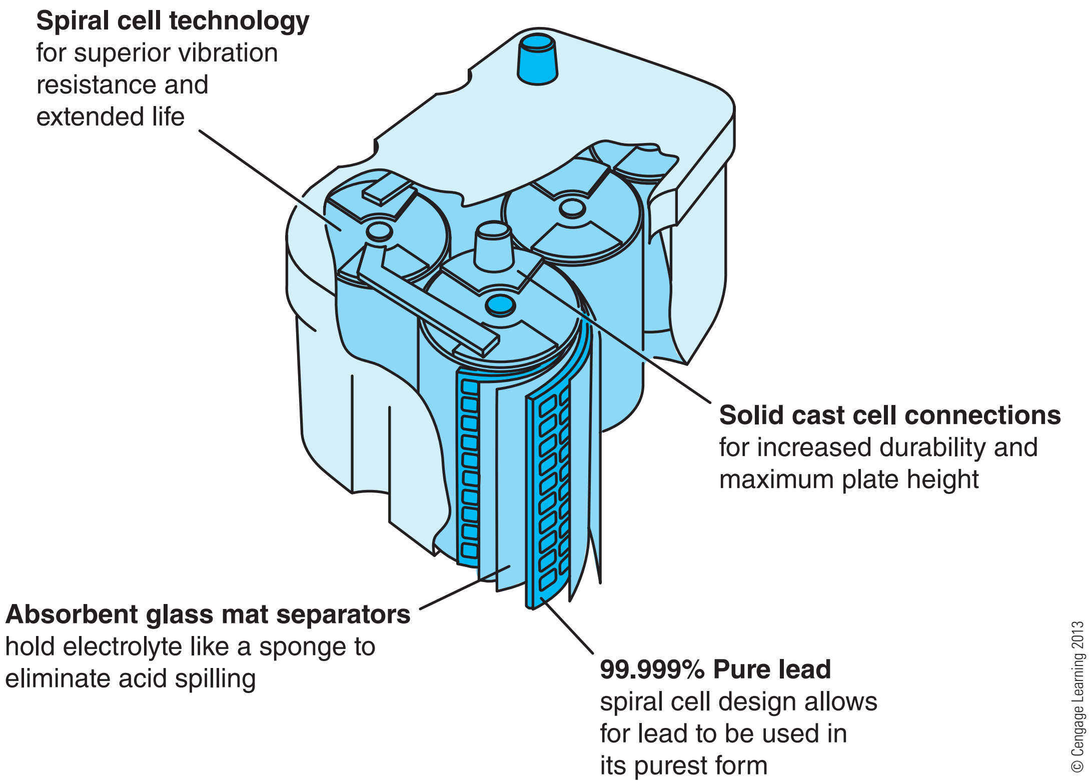

Figure 4-26 An absorbed glass mat battery.

Service

As the charge/discharge process takes place, the water in the electrolyte releases hydrogen into the air, and the electrolyte becomes a stronger acid. This destroys the plates and causes the battery to quickly lose its efficiency. Therefore, most lead-acid batteries need to have their electrolyte fluid levels checked at periodic intervals. When refilling the electrolyte, only use mineral-free or distilled water.

A lead-acid battery should also be kept clean. Deposits on the outside of the battery case and around the battery terminals can cause current to flow to between the battery posts, which will constantly discharge the battery. The battery and its hold-downs and tray should be periodically cleaned with a couple of tablespoons of baking soda mixed with a pint of water. Cable connections and terminals should also be kept clean and their connections tight.

Many of today's vehicles suffer from a problem called

a battery with the key off. This drain is not necessarily caused by a problem (although it certainly could be) but is typically caused by systems that operate when the engine is not running. Remember, the starting battery in most vehicles is designed to provide starting current, and all other current drains are covered by the charging system. When the battery is faced with drains while the engine is not running, the battery's potential output is decreased and may not be able to maintain the systems running in the vehicle. A constant low or dead battery caused by excessive parasitic drain can shorten the life of a battery.

Testing

Testing a lead-acid battery should begin with a thorough inspection of the battery and its terminals **(Figure 4-27).** The following items should be checked:

1. Check the age of the battery by looking at the date code on the battery.
2. Check the condition of the case. A damaged battery should be replaced.
3. If the battery is not sealed, check the electrolyte levels in all cells. If the level is low, use distilled water to bring the level up to one-half

   charge the battery before conducting any test on the battery.
4. Check the condition of the battery terminals and cables. Clean any corrosion from the cable ends and terminals. Make sure the cable ends are tightly fastened to the terminals.

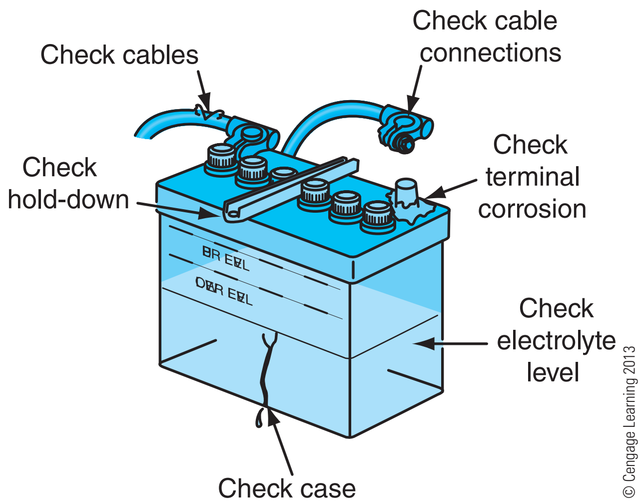

Figure 4-27 Inspect the battery and its cable connections and hold-downs.

5. Make sure the battery hold-downs are holding the battery securely in place.
6. If the battery has a built-in hydrometer, check its color. If the dot is green, the battery has a 65 percent charge. If the dot appears to be dark, the battery needs to be charged before testing. If the indicator appears to be clear, a low electrolyte level is indicated.

Prior to conducting any battery test, make sure the battery is fully charged. Also, remove the surface charge of the battery by turning on the headlights with the engine off. Keep the lights on for at least three minutes. Turn the headlights off and then with a voltmeter, measure the voltage across the battery terminals. This is called open terminal or circuit voltage. A fully charged lead-acid 12-volt battery should have a terminal voltage of 12.6 volts. However, sealed AGM and gel-cell batteries will have a slightly higher voltage (12.8–12.9 volts). If the voltage reading is 10.5 volts or lower and the battery is charged, this indicates that at least one cell is shorted.

Volt/Ampere Tester. A volt/ampere tester (VAT) is used to test batteries, starting systems, and charging systems **(Figure 4-28).** The tester contains a voltmeter, ammeter, and carbon pile. The carbon pile is a variable resistor. When the tester is attached to the battery and turned on, the carbon pile will draw current out of the battery. The ammeter will read the amount of current draw. The maximum current draw from the battery, with acceptable voltage, is compared to the rating of the battery to see if the battery is okay. A VAT will also measure the current draw of the starter and current output from the charging system.

This test is commonly referred to as a **load test**. The load put on the battery during the test simulates the current draw of a starting motor. The amount of current draw is determined by the rating of the battery. Normally the load is equal to one-half of the CCA rating of the battery. For example, a battery rated at 600 CCA would load test with 300 amperes for 15 seconds. If the battery's voltage fell below 9.6 volts during the test, the battery should be replaced. Ampere-hour ratings can also be used to determine the test load. Normally the load is set to three times the ampere-hour rating and the voltage is observed for 15 seconds.

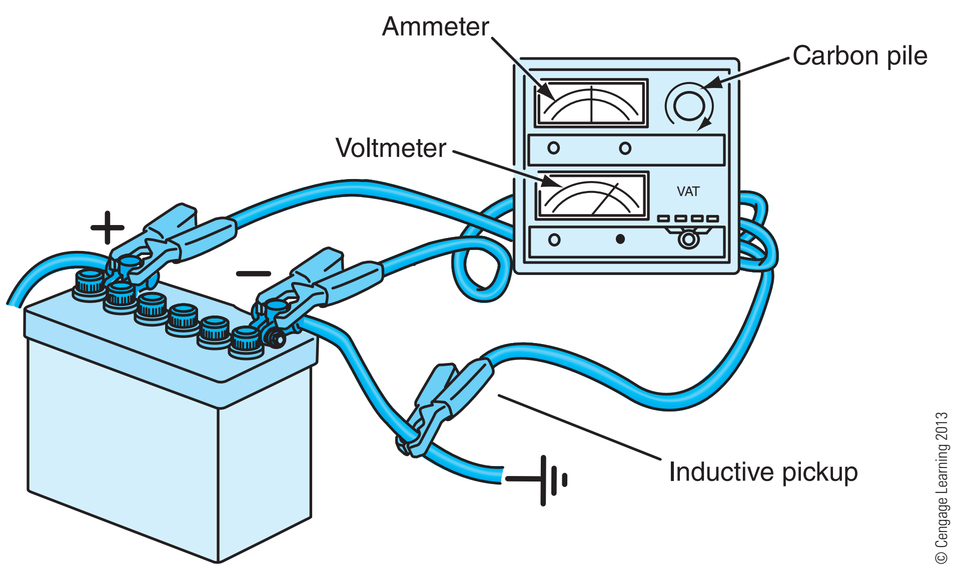

Figure 4-28 The typical connections for a VAT tester.

Battery Capacitance Test. Many manufacturers recommend that a capacitance or **conductance test** be performed on batteries. Conductance describes a battery's ability to conduct current. It is a measurement of the plate surface available in a battery for chemical reaction. Measuring conductance provides a reliable indication of a battery's condition and is correlated to battery capacity. Conductance can be used to detect cell defects, shorts, normal aging, and open circuits, which can cause the battery to fail.

A fully charged new battery will have a high conductance reading, anywhere from 110 percent to 140 percent of its CCA rating. As a battery ages, the plate surface can sulfate or shed active material, which will lower its capacity and conductance.

When a battery has lost a significant percentage of its cranking ability, the conductance reading will fall well below its rating and the test decision will be to replace the battery. Because conductance measurements can track the life of the battery, they are also effective for predicting end of life before the battery fails.

To measure conductance, the tester creates a small signal that is sent through the battery, and then measures a portion of the AC current response. The tester displays the service condition of the battery. The tester will indicate that the battery is good, needs to be recharged and tested again, has failed, or will fail shortly.

Battery Safety

The potential dangers caused by the sulfuric acid in the electrolyte and the explosive gases generated during battery charging require that battery service and troubleshooting are conducted under absolutely safe working conditions. Always wear safety glasses or goggles (preferably a face shield) and protective clothing when working around and with batteries, no matter how small the job.

Sulfuric acid can also cause severe skin burns. If electrolyte contacts your skin or eyes, flush the area with water for several minutes. When eye contact occurs, force your eyelid open. Always have a bottle of neutralizing eyewash on hand and flush the affected areas with it. Do not rub your eyes or skin. Receive prompt
skin or eyes. Call a doctor immediately.

When a battery is charging or discharging, it gives off quantities of highly explosive hydrogen gas. Some hydrogen gas is present in the battery at all times. Any flame or spark can ignite this gas, causing the battery to explode violently, propelling the vent caps at a high velocity, and spraying acid in a wide area. To prevent this dangerous situation, take these precautions:

- Never smoke near the top of a battery and never use a lighter or match as a flashlight.
- Remove wristwatches and rings before servicing any part of the electrical system. This helps to prevent the possibility of electrical arcing and burns.
- Even sealed, maintenance-free batteries have vents and can produce dangerous quantities of hydrogen if severely overcharged.
- When removing a battery from a vehicle, always disconnect the battery ground cable first **(Figure 4-29).** When installing a battery, connect the ground cable last.
- Always disconnect the battery's ground cable when working on the electrical system or engine. This prevents sparks from short circuits and prevents accidental starting of the engine.
- Always operate charging equipment in well-ventilated areas.
- A battery that has been overworked should be allowed to cool down, and air should be allowed to circulate around it before attempting to jump-start the vehicle.
- Never connect or disconnect charger leads when the charger is turned on. This generates a dangerous spark.
- Never lay metal tools or other objects on the battery, because a short circuit across the terminals can result.
- Always disconnect the battery ground cable before fast charging the battery on the vehicle. Improper connection to the battery can reverse the current flow and damage the generator.

Figure 4-29 When working on a battery or when disconnecting it, always disconnect the negative cable first.

- Always operate charging equipment in well-ventilated areas.
- Never attempt to use a fast charger as a boost to start the engine.
- Never try to charge a battery that has ice in the cells. Passing current through a frozen battery can cause it to rupture or explode. If ice or slush is visible or the electrolyte level cannot be seen, allow the battery to thaw at room temperature before servicing. If there is any doubt, allow the battery to warm to room temperature before servicing.
- As batteries get old, especially in warm climates and with lead-calcium cells, the grids start to grow. The chemistry is rather involved, but the point is that plates can grow to the point where they touch, causing a shorted cell.

NICKEL-BASED BATTERIES

Two designs of nickel-based rechargeable batteries are commonly used: the **nickel-metal hydride (NiMH)** and **nickel-cadmium (NiCad)**. Except for the materials used as the anode, a NiMH cell is constructed in the same way as a NiCad cell. Both designs are found in the same types of equipment such as laptop computers, digital cameras, and electric vehicles. The cell voltage from both designs is 1.2 volts, which makes them potentially interchangeable. Most of today's hybrid vehicles use NiMH batteries.

NiMH batteries have replaced NiCad batteries in many applications because of their higher energy densities (more energy is available for a given amount of space) and because they use environmentally friendly metals. Cadmium is harmful to the environment.

NiCad batteries also suffer from "memory effect." This problem occurs when a battery is not fully discharged and then recharged. If the battery is consistently being recharged after it is only partially discharged, 50 percent, for example, the battery will eventually only accept and hold a 50 percent charge. NiMH batteries tend not to be affected by the memory effect.

Nickel-Metal Hydride Cells

NiMH cells are available in the cylindrical and prismatic designs. The prismatic design requires less storage space but has less energy density than the cylindrical design. NiMH cells are currently the battery of choice for hybrids **(Figure 4-30)** because of their capacity.

These cells are still being studied and developed to overcome some of their weaknesses and limitations. They have a relatively short service life; however, most batteries used in HEVs have an eight-year warranty. Service life is reduced by subjecting the battery to many deep cycles of charging and discharging.

Chemical Reactions. Nickel-metal hydride batteries have a positive plate that contains nickel hydroxide. The negative plate is made of hydrogen-absorbing metal alloys. The plates are separated by a sheet of fine fibers saturated with an aqueous and alkaline electrolyte—potassium hydroxide. The components of the cell are

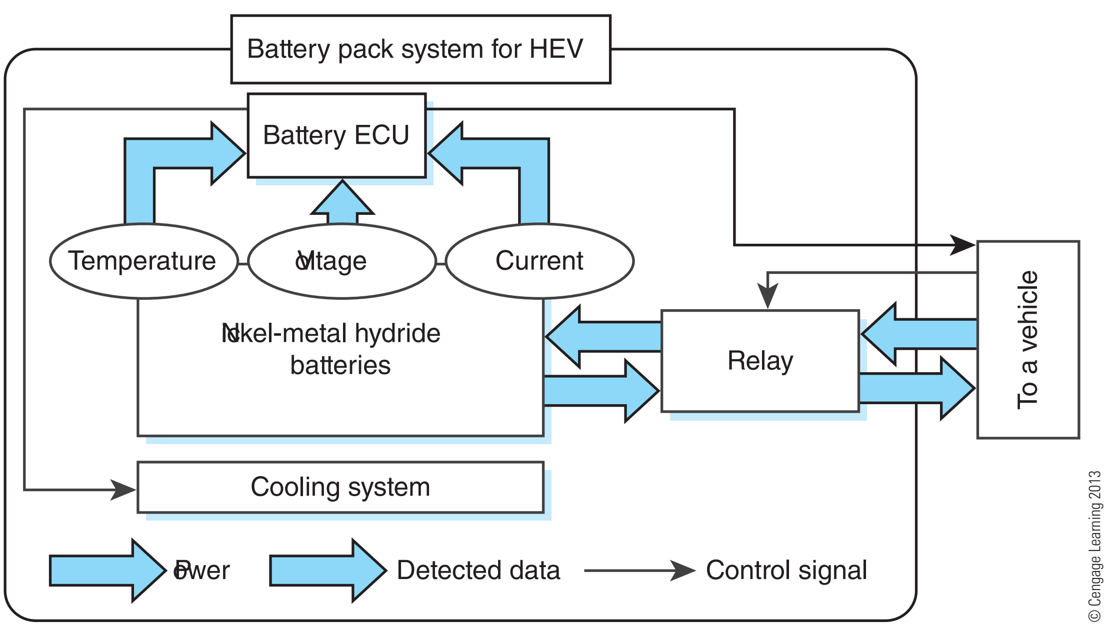

Figure 4-30 A diagram showing how a NiMH battery fits into the operation of a hybrid vehicle.

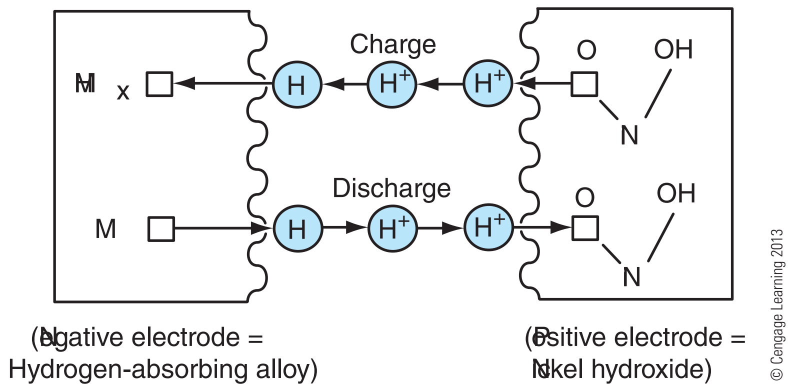

Figure 4-31 The chemical action inside a NiMH cell when it is supplying electrical energy.

typically placed in a metal housing and the unit is sealed. There is a safety vent that allows high pressures to escape, if needed.

The most commonly used hydrogen-absorbing alloys are compounds of titanium, vanadium, zirconium, nickel, cobalt, manganese, and aluminum. An alloy formed by the combination of two or three of these metals has the ability to absorb and store hydrogen. The amount of hydrogen that can be stored is many times greater than the actual volume of the alloy.

When a NiMH cell discharges, hydrogen moves from the negative to the positive plate **(Figure 4-31).** The electrolyte has no active role in the chemical reaction; therefore, the electrolyte level is not changed by the reaction. When the cell is recharged, hydrogen moves from the positive to the negative electrode.

Applications. NiMH batteries are commonly found in electric drive vehicles and have been found to offer great service. However, they are very heavy and have low energy density.

In most HEVs, the control unit monitors the temperature and state of charge. In many cases, NiMH battery failure has not been caused by the battery itself; rather, corrosion on the connectors has been the problem. Also, there have been some failures related to nonuse. If a battery pack has not been cycled for a month or two, the cells begin to degrade. Some manufacturers have placed a warning label stating that if the NiMH-equipped vehicle will be unused for more than a month, the battery may be damaged.

Nickel-Cadmium Cells

NiCad (also referred to as NiCd) cells are commonly used in many appliances and may have a future in electric drive vehicles. They have a number of advantages over NiMH cells, one of which is the fact that they can withstand many deep cycles—about three times as many as NiMH cells. NiCad batteries can be produced at relatively low costs and have a long shelf and service life. NiCad batteries are especially good performers when high energy boosts are required. Most NiCad batteries are of the cylindrical design.

On the downside, NiCad batteries have toxic metals, suffer from the memory effect, have low energy densities, and require charging after they have been unused for a while.

Chemical Reactions. NiCad batteries **(Figure 4-32)** use a nickel hydroxide positive electrode. This plate is made of a fiber mesh. The anode or negative plate is also made of fiber. The plate is covered with cadmium. An alkaline electrolyte, aqueous potassium hydroxide (KOH), serves as a conductor of ions and has only a slight role in the chemical reaction. During discharge, ions leave the anode and move to the cathode. During charging, the opposite occurs.

LITHIUM-BASED BATTERIES

Lithium-based batteries are very similar in construction to nickel-based batteries and cells. They have high energy density, do not suffer much from memory effect, and are environmentally friendlier. There are two major types of lithium-based cells: lithium-ion and lithium-polymer.

Lithium is the lightest known metal and provides the highest energy density of all known metals. Lithium is considered an alkali metal and is used for many purposes, including as the base for many medicines. Lith-

is highly flammable. Lithium metal is also corrosive.

Lithium-Ion Battery

Battery cells do not use lithium metal due to safety issues; instead they use lithium compounds. The term

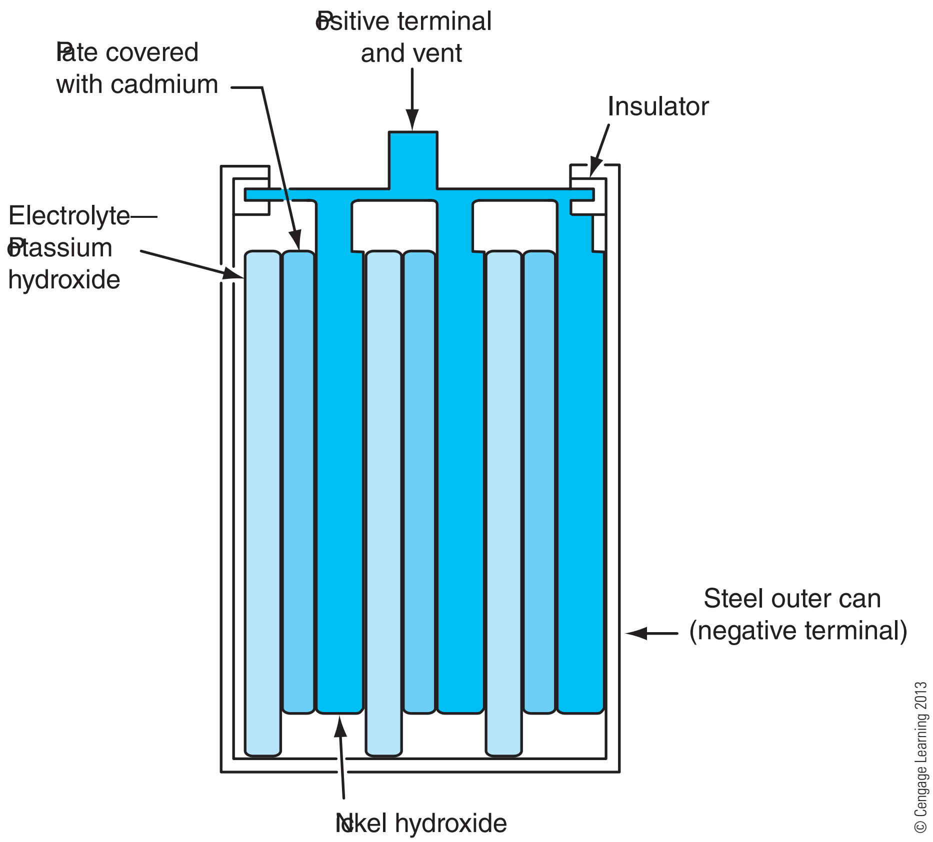

Figure 4-32 Construction of a typical NiCad cell.

lithium-ion (Li-Ion) applies to all batteries that use lithium regardless of the materials mixed with the lithium. These compounds are the focus of much research. Recently, a manganese lithium-ion battery has been developed that may last twice as long as a NiMH battery.

Li-Ion cells have a voltage output of 3.6 volts. The compounds used in the cell determine the energy density of the cell. However, the higher-density designs are more dangerous than many other batteries. Safety issues also surface when connecting Li-Ion cells, in series or in parallel, to form a battery pack. Not all lithium-ion cells are designed to be used in a battery pack; only cells that meet tight voltage and capacity tolerances should be used. If the connected cells do not have the same output and capacity, the battery pack can be overcharged and cause a fire.

Lithium-ion batteries are expensive to produce. This

Because lithium metal is very reactive and can explode, the cycling of the battery must be monitored. A protection circuit limits the peak voltage of each cell during charging and prevents the voltage from dropping too low during discharge. The temperature of the battery pack is also monitored, and charge and discharge activity is controlled to prevent high temperatures. The circuit also contains electronics and/or fuses to prevent polarity reversal.

Chemical Reactions. As with other cells, ions move from the anode to the cathode when the cell is providing electrical energy, and during recharging, the ions are moved back from the cathode to the anode **(Figure 4-33).** The anode is made of graphite, a form of carbon. The cathode is mostly comprised of graphite and a lithium alloy oxide. The construction of the cathode is one of the areas that researchers are working on to produce a safer and stronger Li-Ion battery.

The electrolyte is also the target of much research. The basic electrolyte is a lithium salt mixed in a liquid. Polyethylene membranes are used to separate the plates inside the cells and, in effect, separate the ions

small pores that allow the ions to move within the cell.

Charging. Li-Ion cells have a nominal voltage of 3.6 volts and a typical charging voltage of 4.2 volts. The cells should be charged with a constant voltage, and the charging current should change in response to the

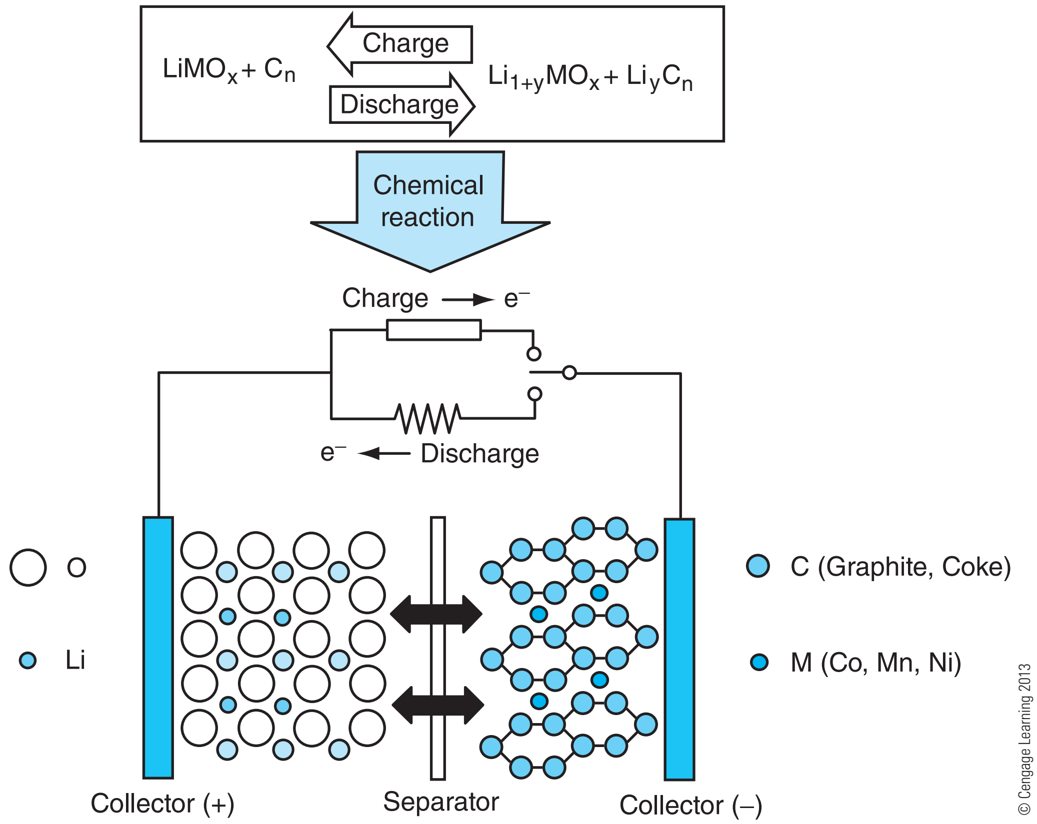

Figure 4-33 The chemical action inside a Li-Ion cell when it is supplying electrical energy and when it is being charged.

voltage of the cell. In other words, as the cell's voltage increases, the charging current should decrease. Lithium-ion batteries should not be fast charged.

Due to the explosive nature of lithium, certain precautions must be followed to safely discharge and charge Li-Ion batteries:

- Never connect cells in parallel and/or series if they do not have identical output voltages.
- Never charge or discharge the battery if it is not connected to its protection circuit.
- If the protection circuit does not have a temperature sensor, carefully monitor the battery's temperature while charging and discharging.
- Never charge a Li-Ion battery that is physically damaged.

Lithium-Polymer Batteries

The

was developed through the continuous research on the Li-Ion battery. The electrolyte used in Li-Poly cells is not a liquid; rather, the lithium salt is held in a solid polymer composite (such as polyacrylonitrile). The polymer electrolyte is not flammable, and these batteries are less hazardous than Li-Ion batteries.

The dry polymer electrolyte does not conduct electricity. Instead, it allows ions to move between the anode and cathode. The polymer electrolyte also serves as the separator between the plates. The dry electrode has very high resistance and therefore cannot provide bursts of current for heavy loads. The voltage of a Li-Poly cell is about 4.23 volts when fully charged. The cells must be protected to prevent overcharging. However, these cells are more resistant to overcharging than Li-Ion cells, and there is much less of a chance for electrolyte leakage.

Li-Poly cells are expensive to manufacture and have a much higher cost-to-energy ratio than lithium-ion cells. However, since Li-Poly cells do not use a metal case, they are lighter and can be packaged in many ways. As a result, Li-Poly cells have a much higher energy density than Li-Ion, NiMH, and NiCad batteries.

In some Li-Poly cells, a gelled electrolyte has been

lithium-ion-polymer cells.

ULTRA-CAPACITORS

Ultra- or super-capacitors are used in many current hybrid vehicles and in some experimental fuel cell

electric vehicles. Before discussing what an ultracapacitor is or how it works, we must take a look at conventional capacitors.

Capacitors

A **capacitor** is used to store and release electrical energy. Capacitors can be used to smooth out current fluctuations, store and release a high voltage, or block DC voltage.

Although a battery and a capacitor store electrical energy, the battery stores the energy chemically. A capacitor stores energy in an electrostatic field created between a pair of electrodes **(Figure 4-34).**

A capacitor can release all of its charged energy in an instant, whereas a battery slowly releases its charge. A capacitor is quick to discharge and quick to charge. A battery needs some time to discharge and charge, but it can provide continuous power. A capacitor only provides power in bursts.

Capacitors have a positive and a negative terminal. Each terminal is connected to a thin electrode or plate (usually made of metal). The plates are placed in parallel to each other and are separated by a dielectric. The dielectric can be paper, plastic, glass, or anything that does not conduct electricity. Placing a dielectric between the plates allows the plates to be close to each other without allowing them to touch.

When voltage is applied to a capacitor, the two electrodes receive equal but opposite charges **(Figure 4-35).** The plate in the capacitor that is connected to the negative terminal of the battery, or other power source, accepts electrons and stores them on its surface. The other plate loses electrons to the power source. This action charges the capacitor. Once the capacitor is charged, it has the same voltage as the power source.

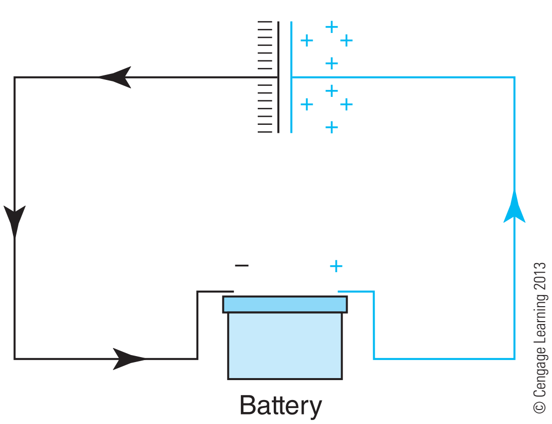

Figure 4-34 A capacitor stores energy in an electrostatic field created between a pair of electrodes.

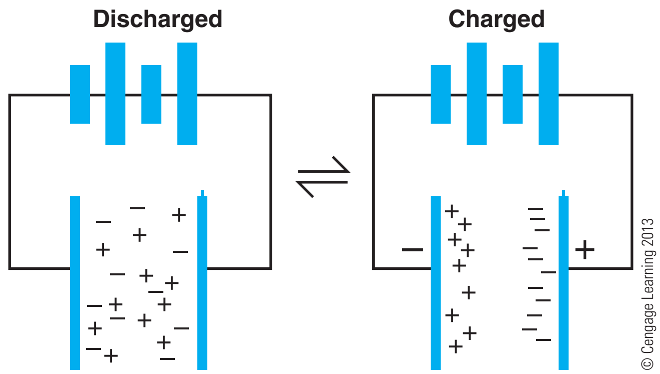

Figure 4-35 When voltage is applied to a capacitor, the two electrodes receive equal but opposite charges.

This energy is stored until the two terminals are connected together.

The ability of a capacitor to store an electric charge is called **capacitance**. The standard measure of capacitance is the **farad (F)**. A 1-farad capacitor can store 1 coulomb of charge at 1 volt. A coulomb is 6.25 *billion billion* electrons. One ampere equals the flow of 1 coulomb of electrons per second, so a 1-farad capacitor can hold 1 ampere-second of electrons at 1 volt. Most capacitors have a capacitance rating of much less than a farad, and their values are given as:

- microfarads: μF (1 μF = 10^{-6} F)
- nanofarads: nF (1 nF = 10^{-9} F)
- picofarads: pF (1 pF = 10^{-12} F)

Three major factors determine the capacitance of a capacitor: the insulating qualities of the dielectric, the surface area of the electrodes, and the distance between the electrodes. The amount of capacitance is directly proportional to the surface areas of the plates and the nonconductiveness of the dielectric, and is inversely proportional to the distance between the plates.

Capacitors have a major role in today's electric drive vehicles. They are used to protect the high-voltage battery from unwanted voltage spikes that could damage the battery. Some vehicles have a "backup control"

12 volts just in case the regenerative braking stops working. The backup unit allows the electrically controlled brake system to operate long enough to stop the vehicle. When the capacitors in the backup control are totally discharged, the brake system reverts to a completely hydraulic system.

Ultra-Capacitors

Ultra (or super)-capacitors are capacitors with a large electrode surface area and a very small distance between the electrodes. These features give them very high capacitance, which is why they are called ultra- or super-capacitors. Some ultra-capacitors are rated at 5,000 farads.

Ultra-capacitors use an electrolyte rather than a dielectric and store electrical energy at the boundary between the electrodes and the electrolyte. Although an ultra-capacitor is an electrochemical device, no chemical reactions are involved in the storing of electrical energy. As a result, they have no negative impact on the environment.

Ultra-capacitors are maintenance-free devices. They can withstand an infinite number of charge/discharge cycles without degrading and have a long service life. They also are very good at capturing the large amounts of energy from regenerative braking, and they can deliver power for acceleration and heavy loads quickly. Also, because they charge very quickly, they have energy available shortly after they have been discharged.

Ultra-capacitors, however, cannot store as much total energy as batteries and they are expensive to manufacture. To provide the required high voltages for electric vehicles, several capacitors must be connected in series. Each cell of an ultra-capacitor can only store between 2 and 5 volts. Up to 500 cells are required to meet the needs of a typical electric drive vehicle.

Construction. A regular capacitor is made of conductive foils and a dry separator. An ultra-capacitor has two special electrodes and some electrolyte, much like a battery cell **(Figure 4-36).** The electrodes are typically made of carbon but can be made from a metal oxide or conducting polymers. The carbon surface of the electrodes is very coarse, with thousands of microscopic peaks and valleys. These irregularities increase the electrodes' surface area. In fact, an ounce (28.35 grams) of carbon provides nearly 13,500 square feet (1,250 sq. m) of surface area.

The plates are immersed in an electrolyte. The electrolyte is typically boric acid or sodium borate mixed in water and ethylene glycol to reduce the chances of evaporation. When voltage is applied across the capacitor, the electrolyte becomes polarized. The charge of the positive electrode attracts the negative ions in the electrolyte and the charge of the negative electrode attracts the positive ions. When the positively charged ions form a layer on the surface of the negative electrode, electrons within the electrode, but beneath the surface, move to match up with them. The same occurs on the positive electrode, and these two layers of separated charges form a strong static charge.

A porous, dielectric separator is placed between the two electrodes to prevent the charges from moving between them. This separator is ultra-thin; in fact, it is about half the size of the ions in the electrolyte. This small separator and the immense amount of surface area is what allow an ultra-capacitor to have high capacitance. However, the thin insulator is also the

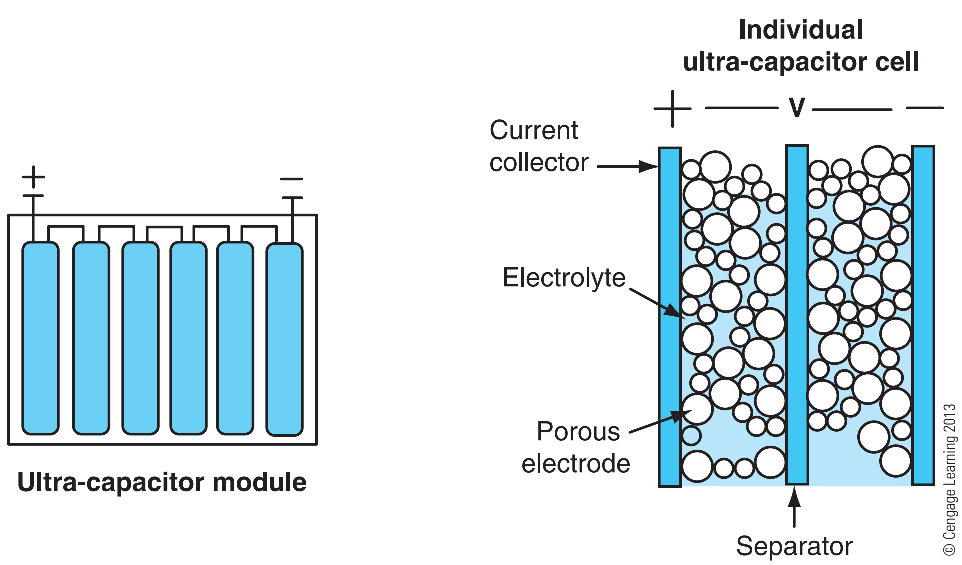

Figure 4-36 An ultra-capacitor cell.

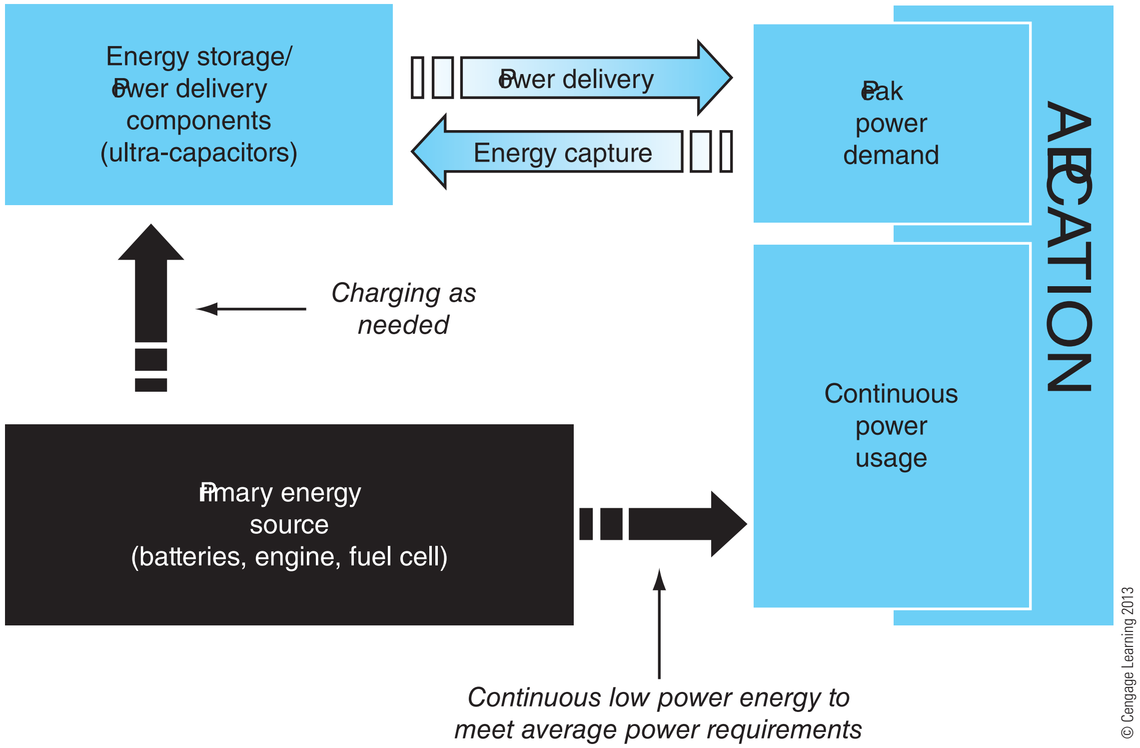

Figure 4-37 A diagram showing how an ultra-capacitor fits into the powertrain of a hybrid vehicle.

reason cell voltage must be kept low. High voltages would easily cause arcing across the plates.

Applications. The capacitors can store energy captured during deceleration and braking and can release that energy to the traction motor while it is assisting the engine during acceleration **(Figure 4-37).** The Toyota Prius was the first automobile to use a bank of large capacitors. In a Prius, the energy in the capacitors is used to start the inverter immediately after a stop/start sequence. The capacitors also prevent current fluctuations to the inverter. Other full hybrid vehicles also have ultra-capacitors in their power platform.

Mild hybrids, those with regenerative braking, a starter/generator, and the stop/start feature, can also benefit from the use of ultra-capacitors. These systems are 42-volt systems. In city driving when the vehicle stops, the engine shuts down. When it is time to accelerate, the engine starts again. In very heavy traffic, this

of time. The cycling is very hard on batteries. An ultra-capacitor can be used to provide the power needed to start the engine. Recharged by regenerative braking and/or the generator, the ultra-capacitor can be quickly charged and is capable of providing enough energy for two engine restarts after it is charged. Supplying only 42 volts, the ultra-capacitor pack is much less expensive than those required in a full hybrid.

A bank of ultra-capacitors can also improve the performance of pure electric vehicles and fuel cell electric vehicles. Ultra-capacitors can allow a battery to be discharged and charged at a continuous rate. This would allow the use of simpler battery designs, ones that do not need to provide bursts of power or absorb bursts of energy from braking.

Charging. An ultra-capacitor is normally placed in parallel with a battery pack and is recharged by regenerative braking. An ultra-capacitor can also be charged with a battery charger. A typical ultra-capacitor needs about 10 seconds to be fully recharged. The charging process is much the same as that of a battery—the initial charge takes little time and current should be limited during the final stages of charging. The ultra-capacitor is fully charged when it reaches the voltage

as much energy as needed and, therefore, there is no possibility of overcharging. Once they are charged, they will not accept further charging. Ultra-capacitors can be recharged and discharged an unlimited number of times.

Review Questions

1. Describe the difference between a cylindrical and prismatic battery cell.

2. How can you identify the high-voltage system in most hybrid vehicles?

3. List five reasons ultra-capacitors are and can be effectively used in electric drive vehicles.

4. List the factors that determine the capacitance of a capacitor.

5. Which of the following cells are NOT considered environmentally friendly?

   A. NiCad

   B. NiMH

   C. Li-Ion

   D. Ultra-capacitors

6. Which of the following statements about NiMH cells is true?

   A. The cylindrical design requires less storage space but has less energy density than the prismatic design.

   B. They have a relatively long service life.

   C. Service life can be extended by frequent deep cycles.

   D. They do not respond well to overcharging; they should be trickle charged.

7. Which of the following statements about battery ratings is true?

   A. The ampere-hour rating is defined as the amount of steady current that a fully charged battery can supply for 1 hour at 80°F (26.7°C) without the cell voltage falling below a predetermined voltage.

   B. The cold cranking amps rating represents the number of amps that a fully charged battery can deliver at 0°F (−17.7°C) for 30 seconds while maintaining a voltage above 9.6 volts for a 12V battery.

   C. The cranking amp rating expresses the number of amperes a battery can deliver at 32°F (0°C) for 30 seconds and maintain at least 1.2 volts per cell.

   D. The reserve capacity rating expresses the number of amperes a fully charged battery at 80°F can supply before the battery's voltage falls below 10.5 volts.

8. *True or False:* In a lithium-polymer battery, the electrolyte is not flammable, and these batteries are less hazardous than Li-Ion batteries.

9. Which of the following statements about NiMH cells is NOT true?

   A. When a NiMH cell discharges, hydrogen moves from the negative to the positive plate.

   B. Nickel-metal hydride batteries have a negative plate that contains nickel hydroxide.

   C. The alkaline electrolyte has no active role in the chemical reaction.

   D. The plates are separated by a sheet of fine fibers saturated with potassium hydroxide.

10. *True or False:* All electrochemical batteries have three major parts: an anode, a cathode, and an electrolyte.

CHAPTER

5 The Basics of a Battery-Operated Electric Vehicle

Learning Objectives

After reading and studying this chapter, you should be able to:

- Describe the basic differences between a battery-operated electric vehicle and an internal combustion engine vehicle.
- List some of the advantages of driving an electric vehicle.
- List some of the disadvantages of driving an electric vehicle.
- Describe the various types of emissions that result from the use of fossil-fueled motor vehicles.
- Describe the major systems that make up a BEV.
- Compare motor specifications with ICE specifications.
- Describe the purpose and function of a battery control system.
- Explain the advantages and disadvantages of having an AC motor rather than a DC motor in an electric vehicle.
- Describe the purpose of a motor controller.
- Describe the purpose of an inverter and a converter.
- Explain how regenerative braking works.
- Describe the different methods used to recharge the batteries in a BEV.
- Explain the differences between conductive and inductive battery charging.
- Describe the differences in the operation of accessories and auxiliary systems in a BEV and an ICEV.
- Describe some of the unique things about driving an electric vehicle.
- Explain how most electric vehicles' problems are diagnosed.
- Describe some precautions that should be followed when troubleshooting and repairing an

Key Terms

conductive charging
Data Link Connector (DLC)
diagnostic trouble codes (DTCs)
electro-hydraulic brake systems
electro-hydraulic steering systems
flywheel energy storage
flywheel power storage
heat pump
inductive charging
malfunction indicator light (MIL)
Monroney label
pulse width modulation (PWM)

INTRODUCTION

Today, there are only a few pure battery electric vehicles (BEVs) manufactured by the major automobile companies. However, nearly all are planning to release new BEVs in the near future. Although there were quite a few BEVs in the 1990s, none were sold in large numbers because of their high price and limited driving range. **Table 5-1** compares one example of an early EV and the gasoline-powered version of the same vehicle. The disadvantages of those EVs are quite apparent when comparing the two. Today's technologies allow the BEVs to have longer ranges than in the past; unfortunately the cost of the vehicles is still high.

Here is a list of the BEVs currently available:

- Chevrolet Volt
- Ford Focus BEV
- Mitsubishi i-MiEV
- Nissan Leaf
- Smart ED
- Tesla Roadster

The Chevrolet Volt is a BEV for a small part of its range. Once the battery is low on charge, it becomes a series hybrid vehicle. This car is referred to as an extended range electric vehicle.

The following BEVs will probably be available in the near future:

- BMW Active E
- BYD e6
- CODA Sedan
- Honda Fit EV
- Mini E
- RAV 4 Second Gen
- Tesla Model S
- Toyota FT-EV
- Volvo C30 Electric

TABLE 5-1: COMPARISON OF GASOLINE AND ELECTRIC VERSIONS OF THE RAV4 SUV MANUFACTURED BY TOYOTA

Condition	Gasoline	Electric
Driving refueling or recharge		
Top speed in mph	109 mph	79 mph
Acceleration time from 0 to 60 mph	10.5 sec	18 sec
Approximate price	$24,000	$40,000

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Some features of an EV are well accepted by the public: reduced air pollution and reduced fuel cost. Nevertheless, hybrid electric vehicles have been selling quite well and BEV sales are, so far, rather slow. HEVs have long driving ranges, are affordable, and are very fuel efficient. Some predict that even a decade from now, BEVs will account for less than 1 percent of all U.S. sales.

ADVANTAGES

There are three basic types of electric drive vehicles: battery electrical vehicles, hybrid electric vehicles (HEVs), and fuel cell electric vehicles (FCEVs). BEVs use the electrical energy stored in batteries to power the drive or traction motors **(Figure 5-1).** BEVs have zero emissions, but are unable to travel far between battery recharges, and their batteries may need replacement after many discharge-charge cycles. HEVs can travel far between fuel fill-ups, and there is no need to stop and recharge the batteries, as they are charged by internal combustion engine (ICE)-driven generators and by regenerative braking. The engine in a hybrid still requires fossil fuels and has undesirable emissions. However, HEVs have emissions levels much lower than pure ICE vehicles. Fuel cell vehicles use an expensive in-vehicle fuel cell to generate the electrical energy required to power the vehicle's traction motors. FCEVs are zero-emission vehicles, but they rely

dispensing hydrogen, although fuel reformers can be used to extract hydrogen from other fuels.

With a BEV, there is the convenience of being able to "fill up" at home, eliminating the need to go a service station. There are also some remote charge stations available in a few states. The cost to refuel is

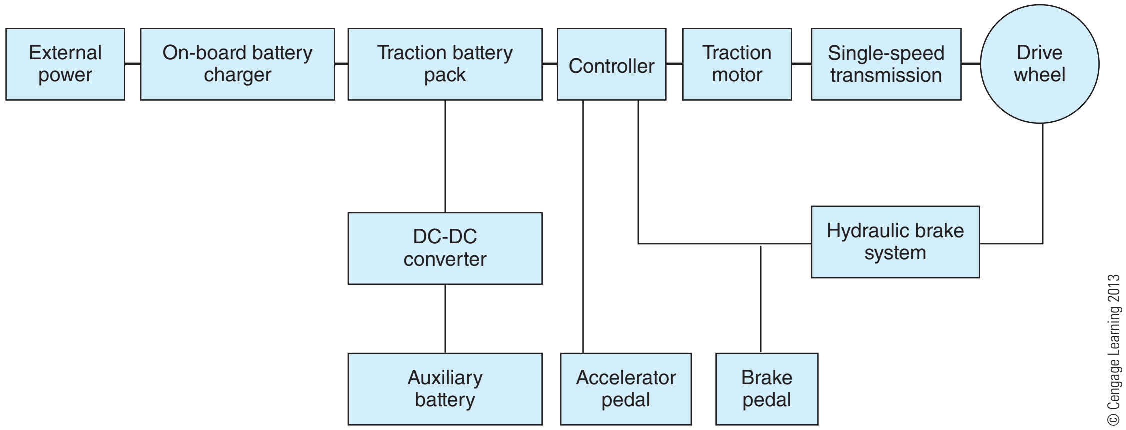

Figure 5-1 Major components of a battery-operated electric vehicle.

very low; typically a recharge costs less than $4.00. Electrical sources, such as solar and wind generation systems, have zero emissions and can further reduce the cost and further decrease the dependency on natural resources to generate electricity. **Figure 5-2** shows how some major energy companies produce their electricity and the average amount of CO_2 that is released while providing one kilowatt-hour of energy. Please note these statistics are based on available data from 2010.

Because of their limited range, BEVs are ideal for commuting or traveling within a limited area. Studies have shown that 80 percent of commuters travel fewer than 40 miles per day; this is well within the range of most BEVs.

Cost

The initial cost of a BEV tends to be higher than that of a comparable ICE vehicle. This is due to the limited availability of BEVs and the cost of the battery packs. Current estimates put the cost of a typical battery for an EV at $10,000 to $15,000. New batteries developed to extend the range of a BEV are, unfortunately, more expensive. However, as more BEVs are produced and sold, their cost should decrease. The initial cost of an EV in the United States is reduced by federal tax breaks that lower the cost by $7,500, and some states offer further subsidies.

The true cost of driving a BEV depends on the cost of electricity per kilowatt-hour (kWh) and the efficiency

Energy Company	Coal	Natural Gas	Oil and Diesel	Nuclear	Hydro-electric	Geo-thermal	Solar	Wind Power	Wood/ Biomass	Pounds of CO_2
AEP	73%	16%	0%	8%	2%	0%	0%	2%	0%	1.63
AES	30%	60%	0%	0%	0%	0%	0%	0%	10%	1.22
Constellation Energy	32%	15%	7%	43%	3%	0.5%	0.1%	0%	0.4%	0.92
Dominion Resources	31%	21%	14%	20%	13%	0%	0%	0%	0.5%	1.11
Duke Energy	48%	9%	9%	24%	9%	0%	0%	0%	0%	1.23
Edison	40%	18%	6%	29%	5%	0%	0%	2%	0%	1.09
Exelon Corp										
FPL Group	4%	55%	32%	9%	0%	0%	0%	0%	0%	1.22
PG&E	0%	0%	2%	36%	62%	0%	0%	0%	0%	0.05
Southern Co	21%	40%	32%	4%	3%	0%	0%	0%	0%	1.42

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Figure 5-2 How different electricity providers produce their power.

TABLE 5-2: A COMPARISON OF THE MAJOR COMPONENTS OF AN ICEV AND A BEV

Major Components of an ICE	Purpose of the Component	Major Components of an EV
Gasoline tank	Stores the energy to run the vehicle	Battery
Gasoline pump	Replaces the energy to run the vehicle	Battery charger
Gasoline engine	Provides the force to move the vehicle	Electric motor
Fuel injection system	Controls acceleration and speed	Controller
Generator/alternator	Converts AC to DC to charge the battery and run the accessories	Inverter and DC/DC converter
Not needed	Converts DC to AC to power traction motor	Inverter
Emissions	Reduces pollutants from the exhaust	Not needed

of the vehicle. Actual operating costs are reduced by making the cars lighter, more aerodynamic, and with less rolling resistance.

BEV vs. ICEV

To move and operate, all vehicles must have a way to store energy, a way to control the input and output of energy, and a way to change the energy into a rotary motion to rotate the drive wheels (see **Table 5-2**). In an electric vehicle, the battery serves the same purpose as the fuel tank in an internal combustion engine vehicle (ICEV), storing energy until it is needed. To regulate the speed and acceleration of the vehicle, an ICEV uses a fuel injection system to control the flow of energy. In a BEV, the flow of energy is regulated by a controller. The controller provides electrical energy to the motor at the required rate. Like in an ICEV, the rate is adjusted according to the position of the accelerator pedal. In both types of vehicles, the power output is used to rotate the drive wheels.

An EV can look like a conventional car without an exhaust pipe or have a very distinctive look **(Figure 5-3).** Internally, however, a BEV is quite a bit different. In many EVs, there is no transmission because the rotary motion of the motor can be applied directly to the differential gears. A motor is capable of providing enough torque throughout its speed range to move the vehicle without torque multiplication from transmission gears. The motor can be positioned to provide front-wheel or rear-wheel

An engine loses much energy through heat **(Figure 5-4).** Much of the energy produced during combustion merely heats up the engine or goes out of the exhaust, rather than serving as energy to power the vehicle. Also, some of the energy from the engine is used to drive accessories; this also decreases the

Figure 5-3 An electric vehicle strictly designed for city driving.

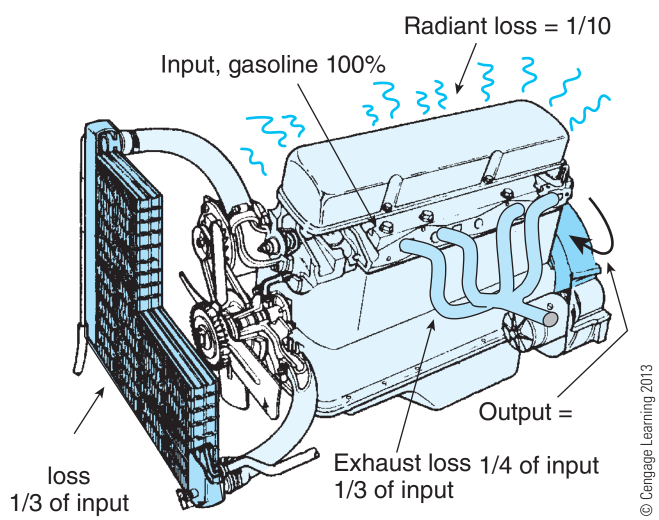

Figure 5-4 In an ICE, much of the energy produced during combustion merely heats up the engine or goes out of the exhaust, rather than serving as energy to power the vehicle.

efficiency of the engine. BEVs generate much less heat and, therefore, much less energy is wasted. BEVs can also reclaim or capture energy through regenerative braking. In BEVs, most accessories are driven by power from the battery and not by the motor, further increasing efficiency.

The power source for an EV has few moving parts. The armature or rotor of the motor is the only moving part in the powerplant system. An engine has hundreds of moving parts, each requiring clean lubrication and each subject to wear. The rotor in a motor is normally mounted on sealed bearings and requires little, if any, additional lubrication throughout its life. The controller and battery charger are electronic units with no moving parts, and they require little or no maintenance. The batteries are sealed and maintenance-free. In summary, an EV requires less periodic maintenance and is more reliable than an ICE.

Torque

An ICE does not develop peak torque until it has reached a particular rpm. Then once the peak torque is reached, it starts to decrease quickly. This is why ICEs are coupled to multispeed transmissions. The various available gear ratios allow the engine to run at speeds where it is most effective for the conditions.

With an electric motor, instant torque is available at any speed. The entire rotational force of the motor is available the instant the accelerator pedal is pressed. Peak torque stays constant to nearly 6,000 rpm, and then it begins to slowly decrease **(Figure 5-5).**

The wide torque band, especially the available torque at low speeds, eliminates the need for multispeed transmissions. There is no need for a reverse gear, either, since switching the polarity of the stator will cause the rotor to turn in reverse. The absence of a typical transmission saves weight and makes the powertrain much less complex.

Emissions

BEVs produce zero emissions. The only emissions related to a BEV are those released when coal, oil, or natural gas are used in power plants to generate the electrical energy required to recharge the batteries. The use of hydroelectric, wind, sunlight, or other renewable sources to generate electricity would eliminate all emissions associated with EVs. It is impossible to have zero emissions from an ICE. Other than operating cost advantages, zero emissions is a primary justification for having a BEV. There are many chemicals and substances related to the emissions of an ICE, none of which are emitted by an electric vehicle:

- Carbon monoxide (CO) is a by-product of combustion and is a deadly gas.
- Sulfur dioxides (SO_x) are produced by combustion of coal, fuel oil, and gasoline, because these fuels contain sulfur. SO_x combined with water vapor in the air become a major contributor to acid rain.
- An ICE releases hydrocarbons (HCs) through its exhaust and its fuel storage system. HCs are best thought of as unburned fuel. These fumes contribute to the formation of ozone, and HCs can cause cancer or irritate mucous membranes.
- Nitrogen oxides (NO_x) are released from an ICE's exhaust and the burning of coal, oil, or

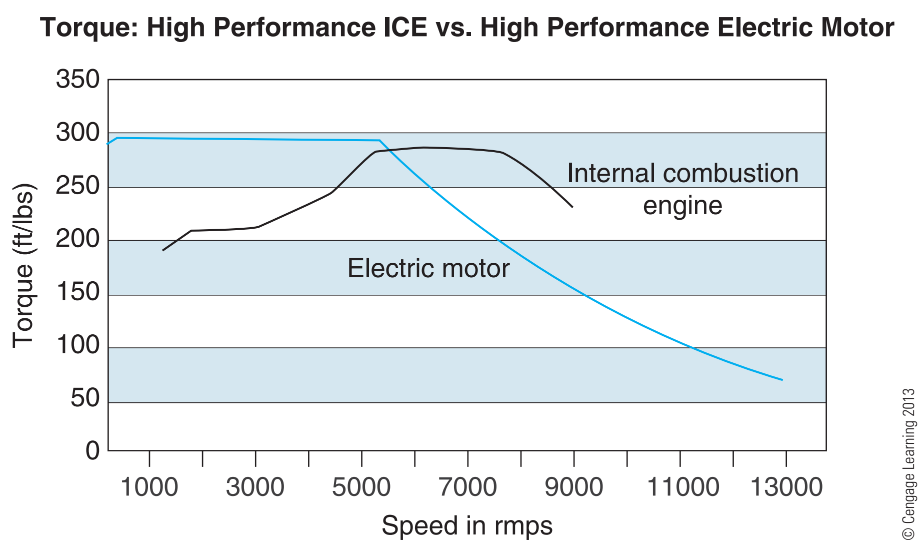

Figure 5-5 A comparison of the amount of torque produced by an ICE and an electric motor.

natural gas. When nitrous oxides combine with the oxygen in the air, a poisonous gas is formed that can damage lung tissue.

- Volatile organic compounds (VOCs) contribute to ozone and smog formation. VOCs are emitted by ICE exhaust, gasoline/oil storage and transfer, chemical manufacturing, dry cleaners, paint shops, and other facilities using solvents.
- Ozone (O_3) is a toxic gas and is seen as a white haze (smog) over many cities. Ground-level ozone is formed by a chemical reaction between VOCs and NO_x, in the presence of sunlight.
- Carbon dioxide (CO_2) is a product of combustion. Some CO_2 is needed because vegetation needs it to survive. However, a high concentration of CO_2 traps heat and warms the atmosphere, which causes the ‘‘greenhouse effect’’ and global warming.

DISADVANTAGES

Although there are many advantages to using an electric vehicle for transportation, there are some major disadvantages. Perhaps the biggest disadvantage is the very limited range with current battery technologies. The driving range between recharges with the batteries currently available is between 50 and 150 miles. Although some new battery designs have extended this range, long travel in an electric vehicle is still not practical.

Long recharge times are also a problem with current battery technologies. Recharging the batteries takes much longer than filling the fuel tank at a service station. In addition to the recharge times, there is a problem of where they can be recharged. If the owner is at home, the charger can be connected to the electrical system of the house. If the vehicle is on the road, some sort of electrical hookup must be made. Most EV manufacturers offer special home charging stations that shorten the required charge time.

An example of using new battery technologies is the Tesla Roadster. This is an EV sports car that has an EPA estimated range of 244 miles. Tesla Motors refers to its battery pack as the Energy Storage System (ESS). The ESS contains 6,831 lithium-ion cells arranged into 11 ‘‘sheets’’ connected in series; each sheet
‘‘brick’’ contains 69 cells connected in parallel. The cells are similar to those commonly used in batteries for laptop computers. A full recharge of the battery requires 3½ hours with Tesla’s special charger.

It is important to understand that a battery’s size and the amount of power it stores do not directly determine the range of an EV. Remember, the smallest, lightest, and most aerodynamic electric vehicles will provide the longest range, with the same battery.

Perhaps the biggest concern for consumers is the price of an EV. Typically the overall cost of an EV is nearly twice the cost of a comparable ICE vehicle. The higher price is due to the cost of the batteries and development costs of the vehicle. Although some of the difference in price can be offset by lower fuel costs, it will take quite a few years of savings to offset the initial price difference. Some estimate that it would take more than 10 years of driving 15,000 miles each year to offset a \$10,000 difference in the original purchase cost.

Another challenge facing BEV owners is the availability and access to skilled service technicians to service and maintain their vehicles. Training for current technicians must be readily available, and there must be programs developed in schools to prepare individuals for this technology before BEVs are practical.

FLYWHEEL ENERGY STORAGE

Another technology for storing electrical energy is being studied: the use of **flywheel energy storage**, also called **flywheel power storage** **(Figure 5-6).** This system has promise for the future of electric vehicles. Flywheel power storage systems have storage capacities comparable to batteries but with faster discharge rates. Temperature does not affect the efficiency of the flywheel and the amount of energy it can store is only dependent on the speed the flywheel can spin at, without self-destructing. There is also no limit as to how many charge and discharge cycles it can experience. A typical flywheel storage system is composed of a large, heavy flywheel suspended by magnetic bearings and connected to a combination electric motor/generator. The flywheel is placed inside a sealed vacuum chamber to reduce friction. Kinetic energy is stored as the flywheel spins with the motor. The momentum of the flywheel keeps it rotating when the motor stops. The rotating flywheel then spins the generator to produce electrical energy.

MONRONEY LABEL

The **Monroney label** must be displayed on all new automobiles. The label displays certain official information about the car. This label or sticker is named after a U.S. senator from Oklahoma, Almer Stillwell Monroney. He sponsored the Automobile Information

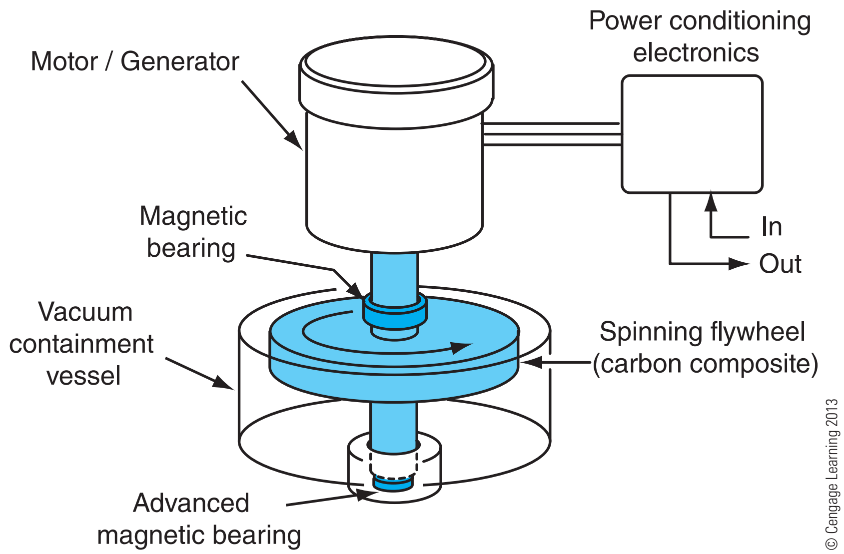

Figure 5-6 Basic construction of a flywheel energy storage system.

Disclosure Act of 1958, which mandated that information about new cars must be made available to consumers. The sticker must be affixed to the side window or windshield of every new car sold in the United States and should only be removed by the consumer. Until recently the label contained the following information:

- The manufacturer's suggested retail price (MSRP)
- Optional equipment and their cost
- Basic engine and transmission specifications
- Standard equipment and warranty details
- EPA city and highway fuel economy ratings
- National Highway Traffic Safety Administration (NHTSA) crash test ratings

In 2011, the NHTSA and EPA issued a rule setting new requirements for what should be displayed on a Monroney label for all new passenger cars and trucks beginning with the model year 2013 **(Figure 5-7).** Manufacturers could voluntarily adopt it for 2012 vehicles. The new design includes specific labels for alternative fuel and alternative propulsion vehicles, such as electric, plug-in hybrids, flexible-fuel, hydrogen fuel cell, and natural gas vehicles. It also shows a comparison of alternative fuel and advanced technology vehicles with conventional ICE vehicles using miles per gallon of gasoline equivalent (MPGe).

MPGe ratings give an estimate of how much fuel or electricity

ratings are based on the EPA's formula, in which 33.7 kilowatt-hours of electricity is equivalent to 1 gallon of gasoline, and the energy consumption of the vehicle during EPA's standard drive cycle tests. **Table 5-3** shows how MPGe ratings compare to conventional MPG ratings.

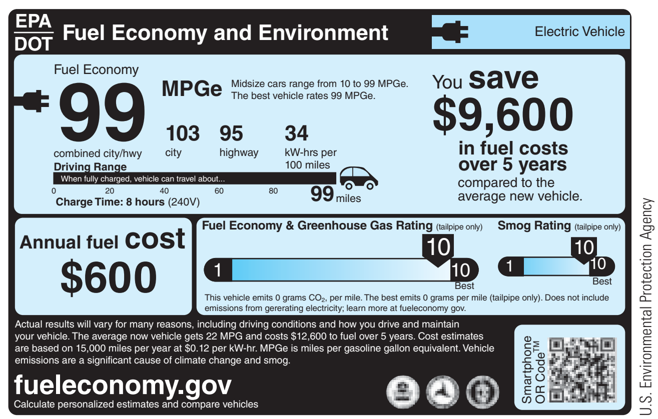

Figure 5-7 The new Monroney sticker for electric vehicles.

The new Monroney includes the following, in addition to the information found on the old design:

- MPG (city and highway, and combined); MPGe (city and highway, and combined); gallons per 100 miles; and kWh per 100 miles
- A comparison of tailpipe emissions of carbon dioxide between this vehicle and other vehicles
- Smog emissions ratings
- Estimates of how much consumers will save or

  to the average new vehicle
- The driving range while running in all-electric mode and charging time for plug-in hybrids and electric cars
- A QR Code for retrieving additional information with a smartphone

TABLE 5-3: MPGe RATINGS VS. MPG RATINGS						
Vehicle	**Operating Mode**	**Combined Fuel Economy**	**City Fuel Economy**	**Highway Fuel Economy**	**Fuel Cost for 25 Miles**	**Annual Fuel Cost**
2011 Nissan Leaf	All-electric	99 MPGe *34 kWh/ 100 miles*	106 MPGe *32 kWh/ 100 miles*	92 MPGe *37 kWh/ 100 miles*	$0.94	$561
2011 Chevrolet Volt	Electric only	93 MPGe *36 kWh/ 100 miles*	95 MPGe *35.7 kWh/ 100 miles*	90 MPGe *37.4 kWh/ 100 miles*	$0.99	$594
	Gasoline only	37 MPG	35 MPG	40 MPG	$2.72	$1,632
2011 Toyota Prius	Gasoline-electric hybrid	50 MPG	51 MPG	48 MPG	$1.90	$1,137

MAJOR PARTS

The basic systems in a BEV are a high-voltage battery pack, battery management system, the propulsion system, 12-volt system, converter and/or inverter, and the driver's displays and controls **(Figure 5-8).**

The battery pack consists of several battery cells connected together to provide the required voltage and current for the system. The battery management system monitors and controls the discharge and recharge activity of the batteries. It can also serve many other functions, such as causing the motor to turn into a generator for regenerative braking. The battery management system may include an on-board charging system that uses an outside source of 110 or 220 volts to recharge the batteries while the vehicle is not in use.

The propulsion system is made up of two primary components: the traction motor that provides the power to rotate the drive wheels and the controller that controls the power output of the motor. Two types of electric motors are used in electric vehicles: a direct current (DC) motor and an alternating current (AC) motor. The 12-volt system supplies the electrical power for the vehicle's accessories, such as the radio and lights. An inverter and converter are required to convert

use a DC motor do not need an inverter; BEVs with AC motors need the inverter to change the DC from the batteries into AC for the motor. A converter is used to reduce the system's high voltage in order to charge the 12-volt battery and to provide power to the low-voltage systems.

Component Specifications

Common automotive specifications include ratings of horsepower (HP) and gallons of gasoline, but in electric vehicles, different specifications are used **(Table 5-4).** Power is stated in kilowatts. A kilowatt (kW) is the international unit to measure power (not only electrical); a kilowatt is 1,000 watts. One kW equals 1.34 horsepower, and 746 watts equals 1 horsepower. Stored electrical energy is stated in kilowatt-hours. A kilowatt-hour (kWh) is a unit of electrical energy or work, equal to what is accomplished by 1 kilowatt acting for one hour.

Because 1 horsepower equals 746 watts and 200 HP equals approximately 149,200 watts or 149 kW, a 149-kW motor may seem like a reasonable substitute for a 200-HP ICE. This, however, is not true! The power of an ICE is always specified at the maximum horsepower it can produce at a specific speed (engine rpm). It is important to realize that the only time the engine produces this power is when it is at that speed. There is less available horsepower below and above that engine speed. The available torque from the engine also changes with engine speed; typically the maximum torque is available at an engine speed lower than the speed at which maximum horsepower is

accelerate and pull loads. When the vehicle is maintaining highway speeds, only 10 to 20 horsepower are needed to maintain the cruising speed.

Electric motors are rated at maximum continuous (not on-demand) power output. An electric motor rated at 40 kW (approximately 54 HP) can provide a peak

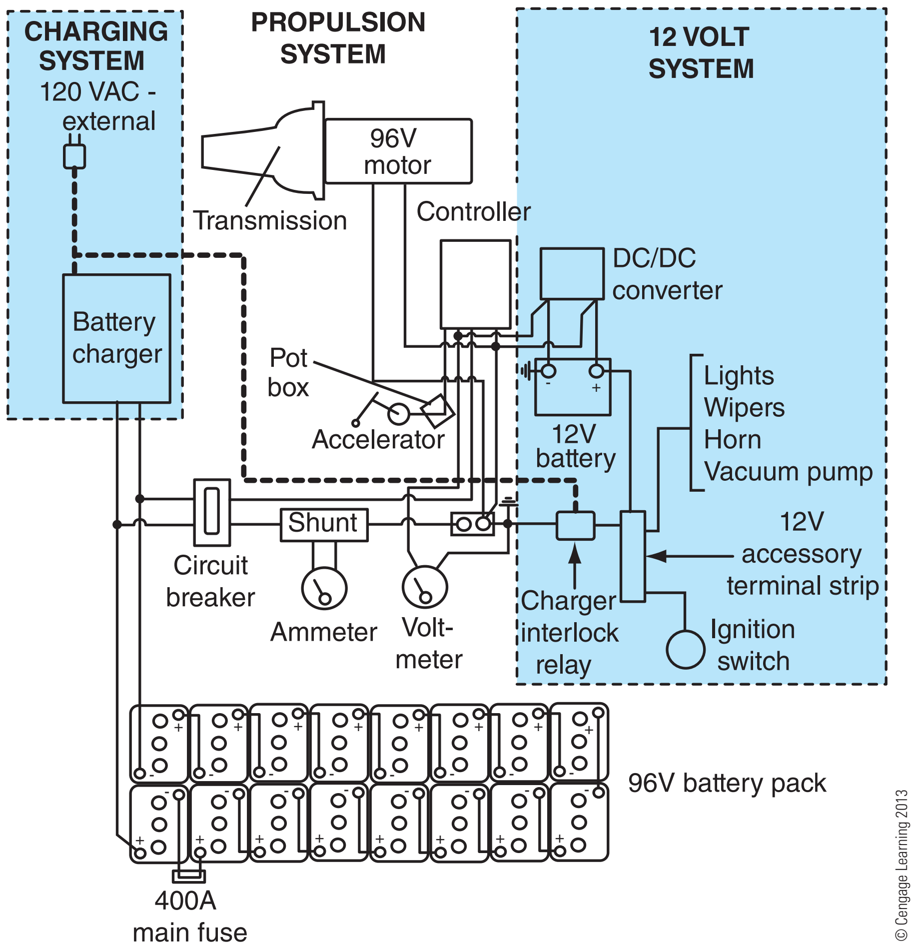

Figure 5-8 A basic wiring diagram of an electric vehicle.

TABLE 5-4: COMPARISON OF HYPOTHETICAL ICEV AND BEV SPECIFICATIONS

Specification	ICEV	BEV
Engine or motor power output	150 horsepower (HP)	150 kilowatts (kW) = 200 HP
Torque @ rpm	110 ft.-lb @ 4,500 rpm	165 ft.-lb @ 0 to 5,000 rpm
Energy storage	20-gallon gas tank	20 kilowatt-hour (kWh) battery
Low-voltage electrical system	12 volts	12 volts (for accessories)
High-voltage electrical system	(none)	300 volts (for propulsion)
Transmission	5-speed automatic	(none)

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power output of at least 200 kW, which is five times its rating. This available power can be used for acceleration

able to provide the same performance as a 200-HP ICE in the same vehicle. In addition, an electric motor develops its maximum torque instantly.

Propulsion of a BEV is provided by traction motors. The motors are either AC or DC motors specifically designed for this use. The motors can be liquid- or air-cooled and are normally lubricated for life. Most production BEVs use AC motors, and many conversion

cost. DC motors can be powered directly by the batteries, whereas AC motors require converters and inverters to change the DC voltage stored in the batteries into the AC required by the motors **(Figure 5-9).**

DC electric motors are quite reliable, but the brushes and commutators present some durability

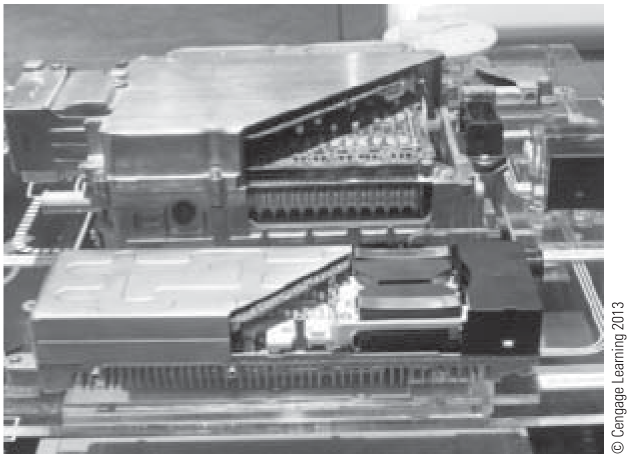

Figure 5-9 A cutaway of an inverter.

concerns. The carbon brushes spark and wear out, and the spring tension on the brushes must be kept within specifications. Excessive spring tension causes excessive friction and wear of the brushes and commutator. When the spring tension is too low, sparking occurs between the brush and the commutator, causing damage to both, and the brushes can bounce, which breaks the circuit. Both of these problems can result in overheating the motor and a decrease in reliability. Although brushless DC motors do not have this problem, most cannot provide enough power to move a vehicle.

DC motors are typically more expensive than comparable AC motors. In addition, the available torque from a DC motor is at its peak when the rotor or armature is not turning. The available torque decreases from that peak as armature speed increases. DC motors also tend to run hotter; therefore, they need proper cooling. DC motors also do not provide for regenerative braking unless they are separately excited (Sep-Ex) DC motors fitted with a special controller that allows for efficient switching of the motor to a generator and back to a motor.

AC motors are lighter than comparable DC motors. They are also very reliable. Because they have only one moving part, the shaft, they should last the life of the vehicle with little or no maintenance. In an AC motor, there is no commutator to distort or burn and no brushes to wear or spark.

AC systems typically operate at higher voltage and lower

output. In an AC induction motor, the torque output is constant through a wide range of speeds. This provides even acceleration and often allows driving without the need of a transmission and different speed gears. There is no need for additional controllers or electronics to have regenerative braking.

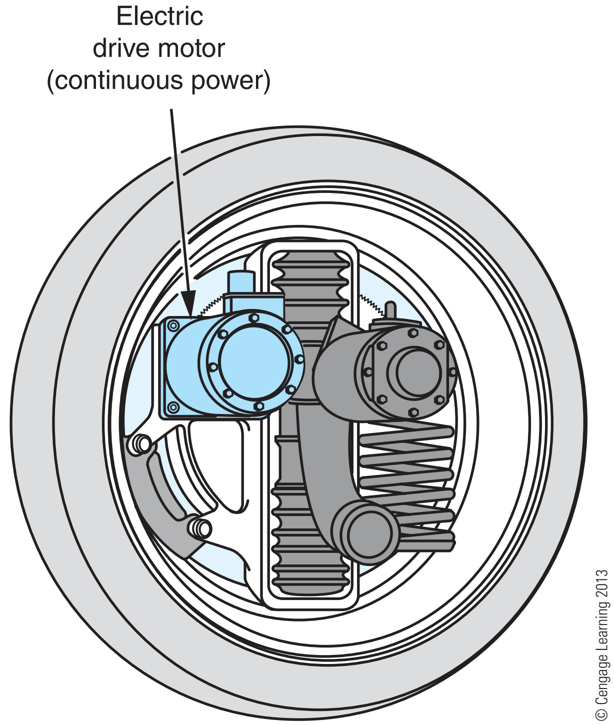

Figure 5-10 A wheel motor assembly.

The primary disadvantage of an AC motor is, again, the cost of the electronic systems required to convert (invert) the battery's DC to AC for the motor. However, most electronic equipment is becoming less expensive (as well as better), and this disadvantage has less merit than it did a few years ago and will be less of a consideration in the future. Manufacturers used AC motors simply because of their efficiency and lighter weight.

In-Wheel Motors. Continued research with BEVs has led to the use of different battery types, as well as different motor types. Mitsubishi has been developing a four-wheel-drive performance electric car, the Lancer Evolution MIEV. This car combines in-wheel motors with lithium-ion battery technology. The AC motors have a hollow donut construction that puts the rotor outside the stator **(Figure 5-10).** This is the opposite of conventional motor designs; however, it is less complex, provides substantial weight savings, and overcomes steering problems associated with normal wheel-mounted motors. The Lancer Evolution MIEV produces 67 HP and 382 ft.-lb of torque, and has a curb weight of 3,505 pounds.

Controller

A controller for a BEV is a device used to control the voltage and current to the traction motor in response

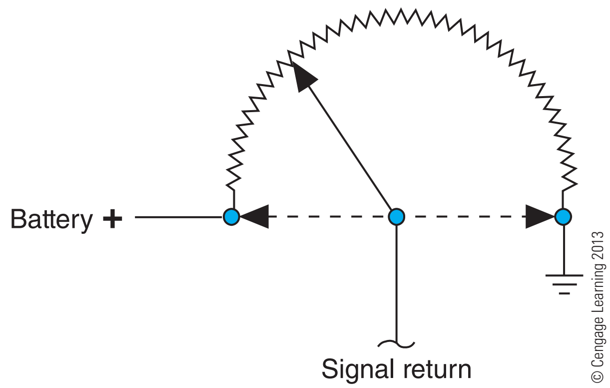

Figure 5-11 In electric vehicles with DC motors, a simple variable-resistor-type (potentiometer) controller was used to regulate the acceleration and speed of the vehicle.

to the driver's input on the accelerator (throttle) pedal. The controller also responds to movement of the brake pedal when the vehicle has regenerative braking; at the same time it stops power to the motor. The controller may also reverse the current flow to the motor when the reverse gear is selected.

In electric vehicles with DC motors, a simple variable-resistor-type **(Figure 5-11)** controller can be used to regulate the speed of the motor. With this type of controller, full current and power are drawn from the battery all of the time. At slow speeds, when full power is not needed, a high resistance in the resistor reduces current flow to the motor. With this type of system, a large percentage of the energy from the battery is wasted as an energy loss (heat) at the resistor. The only time all of the available power is used is at high speeds.

Modern controllers adjust motor speed through **pulse width modulation (PWM)**. Pulse width is the length of time, in milliseconds, that a component is energized. Controllers rely on transistors to rapidly interrupt the flow of electricity to the motor. High electrical power (during high speed, acceleration, and/or heavy loads) is available when the intervals during which the current is stopped are short. During slow-speed driving, little power is needed, and the intervals of no current flow are longer **(Figure 5-12).**

Inverter/Converter

An AC power inverter converts the traction battery's DC voltage into three-phase AC voltage to power the traction motor. The increase in current in the three-phase windings creates more torque, and speed is increased by increasing the frequency of the voltage. The output voltage varies according to the demands of

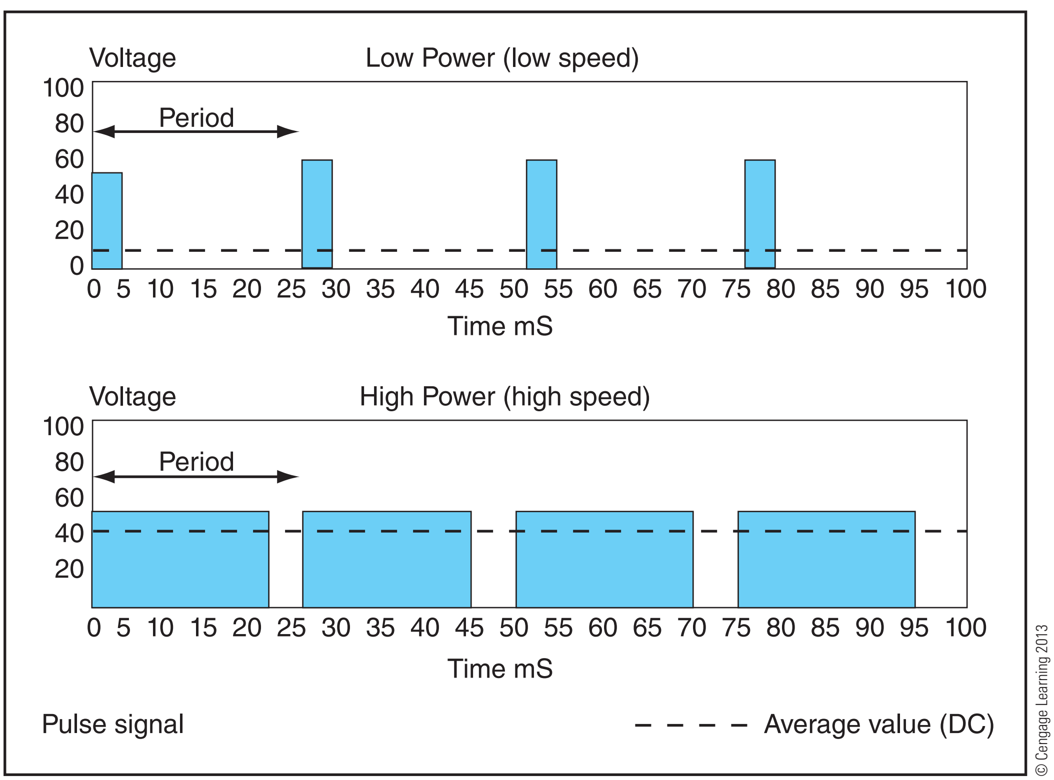

Figure 5-12 An explanation of pulse width modulation at low and high speeds.

the driver and the vehicle. Normally the power inverter is controlled by an electronic control module. The output from a typical inverter is constantly being calculated using input signals from the accelerator pedal, the motor's shaft speed sensor, the motor's direction sensor, and the brake pedal. The inverter is essential to the operation of the motor and, if it fails, the motor cannot run. Electric vehicles that use DC motors do not need an inverter.

The inverter is liquid-cooled, and the heat from the inverter can be used to supplement the passenger compartment's heater to save energy. This is done automatically whenever the controls are set for heat.

In DC systems, the voltage and current from the battery pack merely need to be controlled. The actual current flow to the motor is regulated by the controller and the subsequent CEMF in the motor. Remember, a DC motor draws a maximum amount of current and produces its maximum torque when it has zero speed. If a DC converter fails, it is possible for a motor to receive maximum current, and the vehicle can suddenly move with the highest possible torque from the motor. This could be very dangerous and is one of the primary reasons major manufacturers use AC systems in their vehicles.

A DC/DC converter reduces the voltage from the main battery pack to provide power for the 12-volt accessories, such as the head and taillights, wipers, radio, windows, power steering pump, and so on. The DC/DC converter also keeps the 12-volt auxiliary battery charged. The auxiliary battery may be used as an emergency power source if the main converter fails. Instantaneous power demands can be provided by an ultra-capacitor wired in parallel to the converter's output. The ultra-capacitor takes care of power demands for a fraction of a second.

Regenerative Braking

The controllers on most vehicles also have a system for regenerative braking. Regenerative braking is one of the most important differences between ICEVs and EVs. In ICEVs, the energy flow in the propulsion system is in only one direction: from the gas tank to the drive wheels. In EVs, the energy flow can be in both directions: from the battery to the wheels during acceleration

battery during braking or coasting. This reverse flow of electricity causes the effect known as regenerative braking, which slows the vehicle and partially recharges the battery. This is possible because electric motors can also act as generators. **Figure 5-13** shows the operation of the regenerative braking system.

During the regenerative braking, some of the vehicle's kinetic energy that is normally absorbed by the brakes and turned into heat is converted to electricity by the traction motor. The energy then passes back through the controller to the battery, where it is stored, ready to be used again. The controller regulates how fast this energy is converted, and thus regulates how fast the braking occurs. The controller gets its signal from the brake pedal, telling it how much regenerative braking to apply and how much hydraulic braking will be used.

Regenerative braking increases an EV's range potential, especially when the vehicle's speed is changing, like in city traffic where the brakes are used frequently. By using regenerative braking, the driving range of a BEV can be increased by 25 percent (compared to relying only on the batteries). Regenerative braking not only increases the range, but it also decreases brake wear and reduces maintenance costs.

Some vehicles are equipped with a switch or lever that allows the driver to activate the regenerative braking system during coasting or deceleration without depressing the brake pedal. Doing this slows down the vehicle and adds some charge to the battery. Regenerative braking is generally found on more expensive electric vehicles and all hybrid-electric vehicles (HEVs). It is not currently used on most small, simple, low-priced EVs such as golf cars.

Regenerative braking works better when the generator can spin quickly. It works poorly at low speed; therefore, the controller must calculate the amount of regenerative braking based on the speed of the vehicle and the pressure applied to the brake pedal. The controller must also apply the regenerative braking smoothly so the vehicle does not jerk when it is engaged.

In most BEVs, the basic brake system is very similar to the hydraulic system used in conventional vehicles. Regenerative braking systems are not a physical part of the brake system. The hydraulic brake system is directly activated by the brake pedal, and most EVs have antilock brakes. To provide regenerative braking, a motor controller responds to signals from the brake pedal, accelerator, and/or hydraulic pressure sensors **(Figure 5-14)** and changes the motor to a generator. The torque required to turn the gen-

BATTERY CHARGING

Refueling a BEV simply means charging the batteries. Recharging involves connecting a battery charger to a source of electricity and connecting the charger to

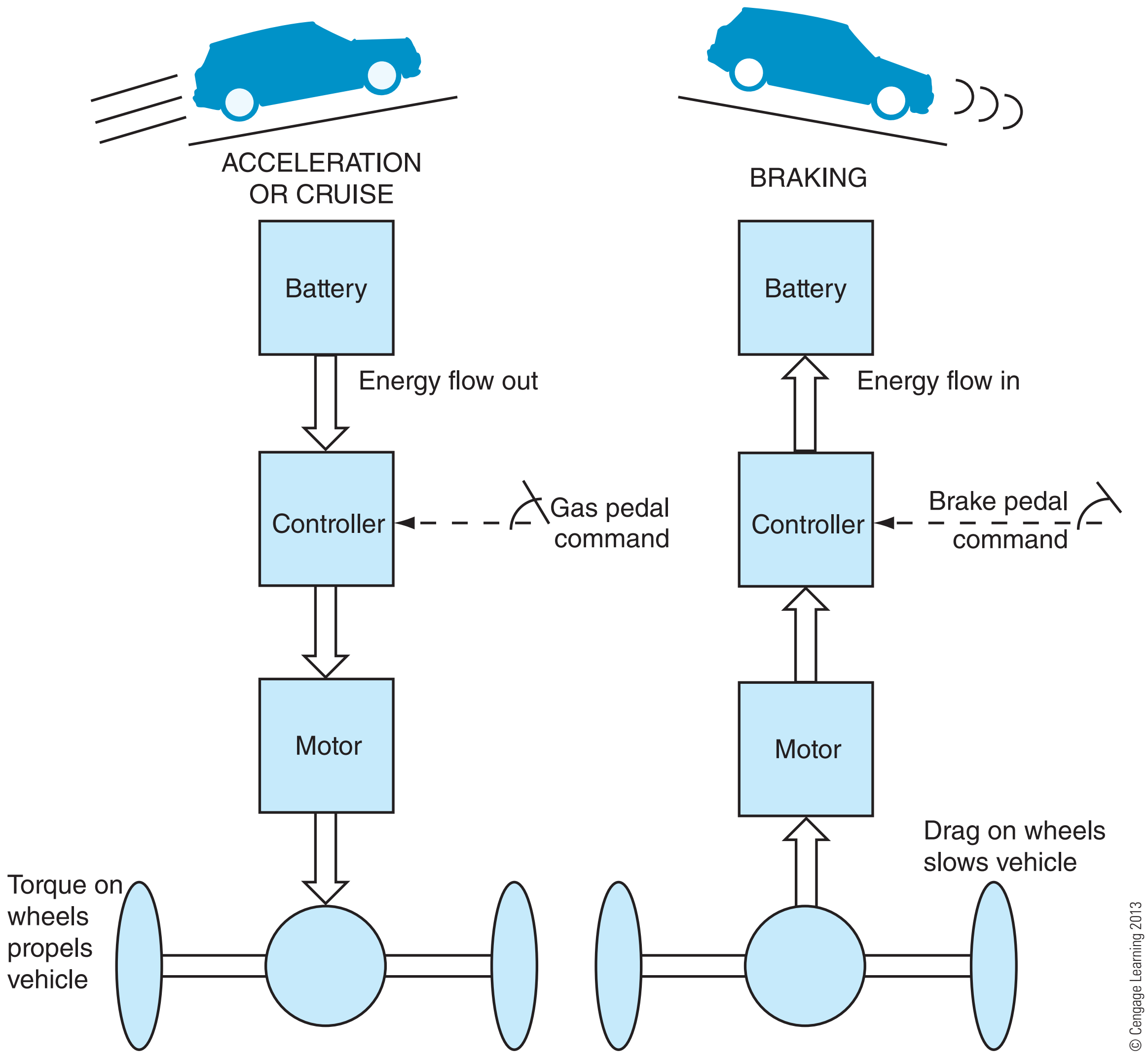

Figure 5-13 Regenerative braking energy flow.

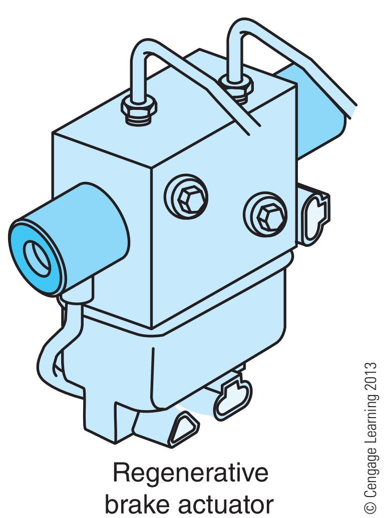

Figure 5-14 This unit senses pressure on the brake pedal and sends a signal to the controller to activate regenerative braking.

the battery pack. Battery chargers **(Figure 5-15)** may be internal or on-board (in the vehicle) or external or off-board (at a fixed location). There are advantages and disadvantages to both. An on-board charger allows the batteries to be recharged wherever there is an electrical outlet. The disadvantage of on-board chargers is their added weight and bulk. To minimize this, manufacturers normally equip the vehicles with low-power chargers that require long charge times. Off-board chargers, however, force the driver to charge the

decrease the time required to charge the batteries. Some manufactured BEVs with off-board chargers also have a convenience charger. These on-board chargers plug into standard 110-volt outlets and allow the driver to recharge batteries wherever there is electricity available.

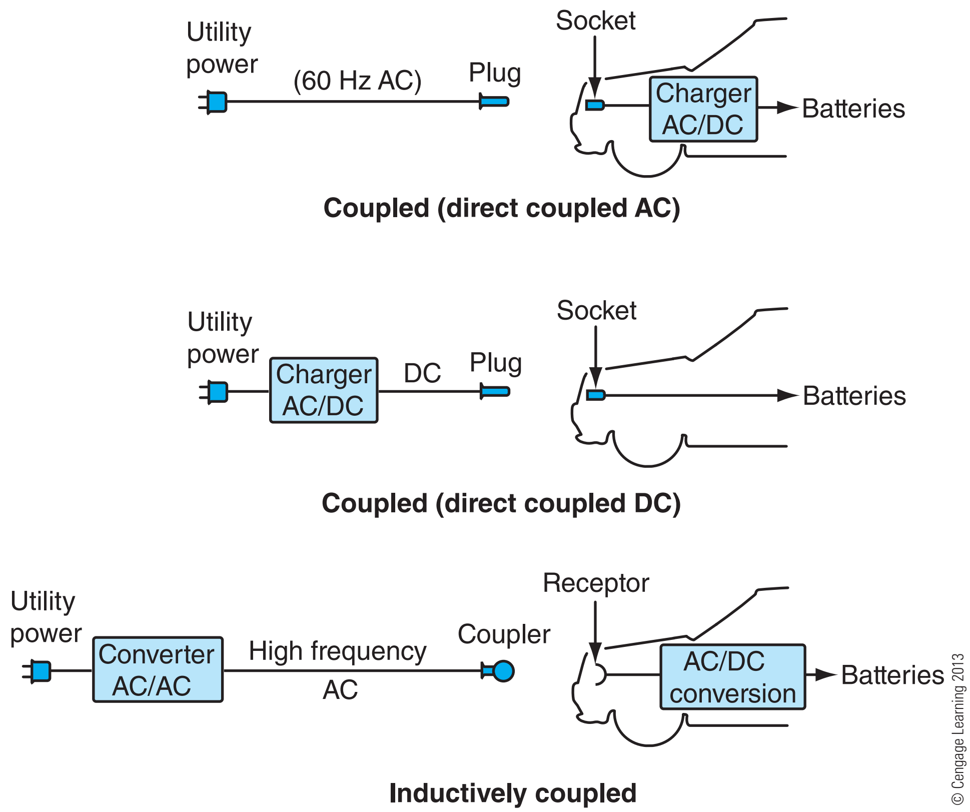

Figure 5-15 EV battery chargers may be internal (on-board) or external (off-board).

It normally takes several hours to recharge the battery pack. The required time varies with the size and type of battery pack and battery charger. New designs of chargers have been able to recharge a battery pack in less than 20 minutes. These chargers use sophisticated electronics to monitor the cells and regulate the charging voltage and current. Being able to quickly charge the batteries would certainly make an electric vehicle more practical.

The connections between the battery charger and the power outlet can be an ordinary plug (as used for golf cars) or a specialized connector to improve safety (as used for electric automobiles). These specialized connections contain ground-fault interrupters that break the circuit if any electrical current leakage to ground is detected, such as when charging the vehicle when it is wet. A block diagram of the golf car and electric automobile charging systems are shown in **Figure 5-16.**

There are two basic ways a BEV is connected to an external source of electricity for charging. One is the traditional

coupling is plugged into a receptacle on the vehicle, where it connects into the wiring for the batteries. The other end of the coupling is connected to a 110-volt or 220-volt outlet or a battery charger **(Figure 5-17).** The other type of coupling is called an inductive coupling. This coupling uses a paddle that fits into a socket on the vehicle. Rather than transferring the power by a direct wire connection, power is transferred by induction. This is actually a magnetic coupling between the windings of two separate coils, one in the paddle and the other mounted in the vehicle. Because there is no exposed metal on the insulated magnetic coils, this is a very safe connection.

Charge Levels

Battery chargers are classified by the level of power they can provide to the battery pack:

- Level 1—Level 1 chargers use the standard household three-prong electrical plug. They are usually portable and have ratings of up to 120 VAC and 15 amps.
- Level 2—Typically an on-board charger with ratings of up to 240 VAC and 60 amps.

  greater than 240 VAC and 60 amps.

Fast chargers are rated as Level 3 chargers. However, not all Level 3 chargers are fast chargers. A charger can be considered a fast charger if it is capable of charging an average battery pack in 30 minutes or less.

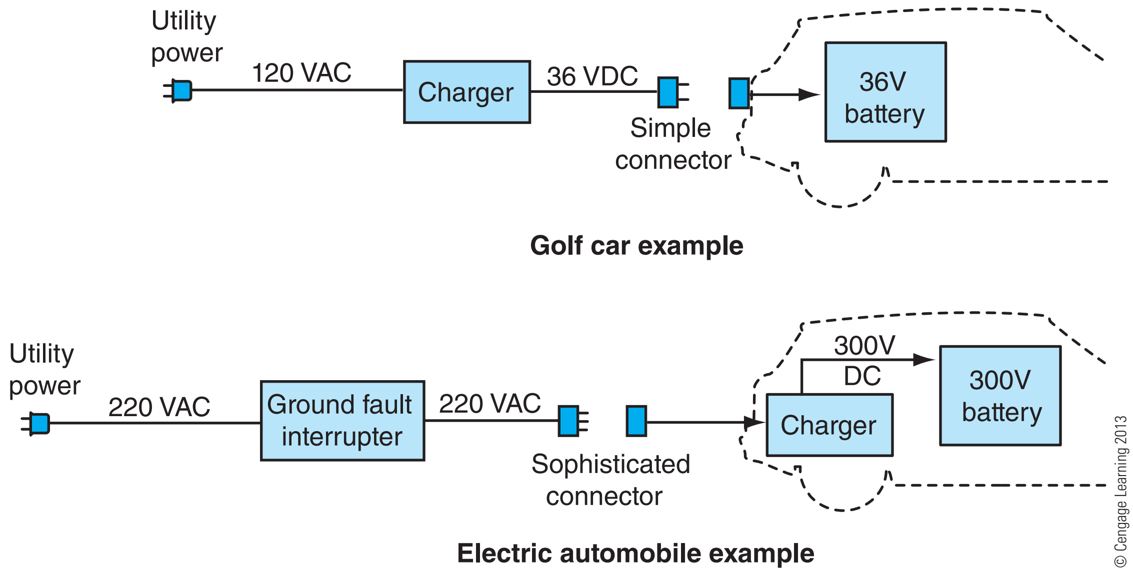

Figure 5-16 A block diagram of the golf car and electric automobile charging systems.

Figure 5-17 A high-voltage battery charger connected to an EV.

Conductive Charging

Conductive charging is a 110 or 220V recharging method. AC electricity from the local utility or other source is transformed to the voltage required for the battery pack, converted into DC, and fed to the batteries via conductive, metal-to-metal contact. With a conductive charger, a connector, such as the AVCON **(Figure 5-18),** safely makes the link between the power supply and the vehicle's charge port. The connector

nection to the vehicle's internal charge port. This type of charging is used with most on-board chargers. Some off-board chargers also use a conductive coupling.

The connector has multiple pins that carry data. This data is used to control the action of the charger based on the conditions of the battery pack. AVCON connectors have been installed in many applications. External chargers are available in many different sizes and can be wall or pedestal mounted **(Figure 5-19)** with an AVCON connector.

Figure 5-18 An AVCON charging coupler.

Courtesy of Avcon Corporation

Figure 5-19 An AVCON EV power pack charging system.

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Figure 5-20 On some vehicles, conductive charging is accomplished with a fuel nozzle–shaped connector that has round male pins that mate to female ends in the vehicle.

Other EVs use a different design of connector. Conductive charging is accomplished with a fuel nozzle–shaped connector called the ODU **(Figure 5-20).** The connector has many round male pins that mate to female ends in the vehicle. Similar to adding fuel to the vehicle, the connector is placed into an opening on the vehicle and refueling or recharging can take place.

Inductive Charging

Inductive charging is a 220 VAC recharging system that transfers electricity from a charger to the vehicle using magnetic principles. To charge the batteries, a weatherproof paddle is inserted into the vehicle's charge port **(Figure 5-21).** The paddle and charge port form a magnetic coupling. The external charging unit sends current through the primary winding inside the paddle. The resulting magnetic flux induces an alternating current in the secondary winding, which is in the charge port. The connection is basically a transformer with the primary winding in the paddle and the secondary winding in the vehicle. The induced AC is then converted to DC (within the vehicle) to recharge the batteries. There is no metal-to-metal contact between the charge paddle and the charge port of the vehicle. This system provides a safe and easy-to-use way to recharge the batteries.

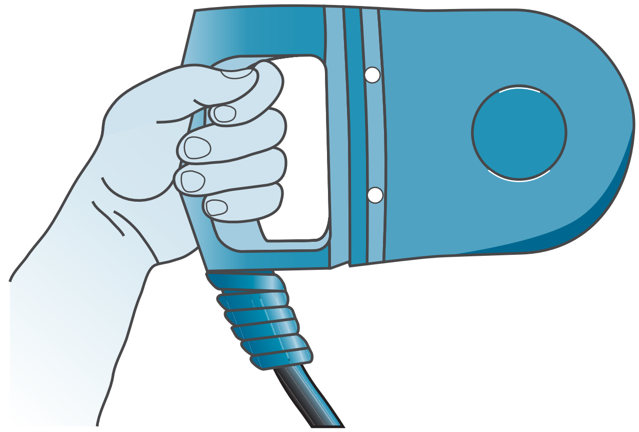

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Figure 5-21 A paddle-type inductive charging coupler.

Inserting the paddle begins the charging process. The insertion of the paddle completes a communication link between the charger and the vehicle. The charger displays what percent of charge remains in the batteries and an estimate of the time needed to fully charge the batteries. This link also allows the charging unit to enter into self-diagnostics and prevents the vehicle from being driven while the paddle is inserted in its port. If the charging cable becomes damaged or cut, power will shut off within milliseconds. The charging process ends immediately after the paddle is removed from the port.

Charge Times

There are three primary things that affect the required time to recharge the batteries: the current state

of the battery, and the type of charger used.

Charging Procedures

Each EV has a specific charging procedure. These procedures vary with the type of charger, charger

coupling, and battery. Always follow the procedure for the vehicle being worked on. The following are some general guidelines to follow:

- Make sure the gear selector is in the Park position and the parking brake is applied before charging.
- Before charging, make sure the motor switch is off and the key is removed.
- To reduce the likelihood of explosion or fire, charge the batteries in a well-ventilated area. Flammable gas may be produced by the batteries during charging.
- To avoid getting an electric shock, never operate the charger with wet hands.
- Avoid charging under high temperatures or direct sunlight.
- When the ambient temperature is high, charge indoors, in the shade, or at night.
- When the ambient temperature is low, it is recommended to charge indoors.
- Never touch the conductive terminals on the vehicle or coupler; you may get an electric shock.
- Do not modify the charge coupler.
- The charge coupler should be firmly installed without any tension on the cable.
- If the charge coupler is damaged, repair or replace it as soon as possible. The use of a damaged coupler can cause burns or electrical shock.
- Make sure water, dirt, or other foreign objects do not enter the charge port on the vehicle. This can cause a failure of the equipment or create an unsafe condition.
- When charging the batteries, always apply a full charge.
- Do not disconnect the charge coupler until the batteries are fully charged, unless it is necessary to prematurely stop charging.
- The auxiliary battery can discharge if the charge coupler is left inside the charge port for a long period of time after charging is completed.

ACCESSORIES

As with ICEVs, electric vehicles have a number of auxiliary systems and quite a few accessories. A major difference between BEVs and ICEVs is the operation of these systems. In an ICEV, most of this equipment is powered by the gasoline engine. Belts drive the power steering, air conditioning, and 12-volt generator; there is engine vacuum for the power brakes; and there is hot engine coolant for heating. In a BEV, the traction motor is not used to rotate belts and pulleys and there is no engine vacuum. Therefore, all of these auxiliaries and accessories are powered directly by the high-voltage battery or the auxiliary 12-volt battery (see **Table 5-5**). The 12-volt battery operates the lights, radio, and other 12-volt systems.

Some systems, such as the radio, lights, and horn, operate the same way as they do in a conventional vehicle. Other systems, such as the power steering and power brakes, require additional small electric motors, which have an impact on the vehicle's range. The range is especially affected by the air conditioning and heating systems. Because all accessories and auxiliary systems operate on electricity, their electrical power needs reduce the capacity of the battery. **Table 5-6** shows how the major systems affect the driving range of a typical BEV.

TABLE 5-5: COMPARISON OF TYPICAL ICEV AND BEV ACCESSORY OPERATION

Accessory	ICEV	BEV
Power steering	Fan belt drives power-steering hydraulic pump	Electric motor directly drives power steering
Power brakes	Engine provides vacuum for power assist	Electric motor operates a vacuum pump for power assist
Air		
Heating of passenger compartment	Hot water from engine cooling system	Electric heater or heat pump
12-volt accessories	Belt drives generator to charge battery	DC/DC converter reduces high voltage

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TABLE 5-6: THE IMPACT OF ACCESSORIES ON THE RANGE OF A BEV

Accessory	Range Decrease	Comments
Air conditioning	Up to 30%	Highly dependent on use, ambient temperature, cabin temperature, and air volume
Heating	Up to 35%	Highly dependent on use and ambient and cabin temperatures
Power steering	Up to 5%	Constant drain
Power brakes	Up to 5%	Drain with use of brakes
Defroster	Up to 5%	Depending on use
Others, such as lights, windows, door locks, stereo, power-assisted seats	Up to 5%	Depending on use

CAUTION *When working on BEVs, remember that some of the accessories may be powered by high voltage. Never attempt to work on these components (or the main propulsion system components) without thorough training that includes all safety procedures. Normally, the high-voltage components are housed in the controller or another safety housing, and the high-voltage cables are identified by their orange color.*

HVAC

To meet federal safety standards, all vehicles must be equipped with passenger compartment heating and windshield defrosting systems. In an ICEV, these systems use the heat of the engine's coolant. In a BEV, there is no engine and therefore there is no direct source for heat. The heat must be provided by an auxiliary heating system. Some electric vehicles use an electric resistance heater with a fan.

Other BEVs have liquid heaters. Water, or a mixture of water with ethylene glycol, is held in a tank. The liquid in the tank is kept heated by a resistive heating element submerged in the tank. When the driver turns on the heating system, a small pump circulates the heated liquid through a heater core in the passenger compartment. A fan moves air over the core to provide

BEV air conditioning systems also have a significant impact on the driving range. In many cases, the air conditioning system uses a high-voltage motor to rotate the compressor. Obviously, the energy used to power the air conditioning puts a drain on the battery pack. The amount of energy consumed by the air conditioning system depends on how often it is used, the outside temperature, and the selected temperature for the passenger compartment.

Many manufactured BEVs have been equipped with an electrically driven heat pump. A **heat pump** functions as either a heater or an air conditioner **(Figure 5-22).** It also uses much less energy than either. A heat pump does not produce heat; rather, it transfers heat. This is why heat pumps require less energy to operate.

Air, regardless of temperature, has heat. Naturally, the colder the air is, the less heat it has. When a heat pump is functioning as a heater, it takes heat from the outside air and transfers it to the passenger compartment. When it is functioning as an air conditioner, heat from inside the passenger compartment is transferred to the outside air.

Most vehicles equipped with a heat pump have auxiliary heating systems that provide additional heat when the outside temperatures are very low. These heating systems can be electrical heating elements or diesel fuel-fired heaters.

Some vehicles equipped with heat pumps have a feature that allows for warming or cooling of the passenger compartment while the batteries are being recharged. Because the charger is replacing the energy consumed by the heat pump, the batteries can still be fully charged.

Power Brakes

Many power brake systems use engine vacuum and atmospheric pressure to multiply the effort applied to the brake pedal during braking. Because there is no engine in a BEV, there is no direct vacuum source. However, normal vacuum-assist power brake systems

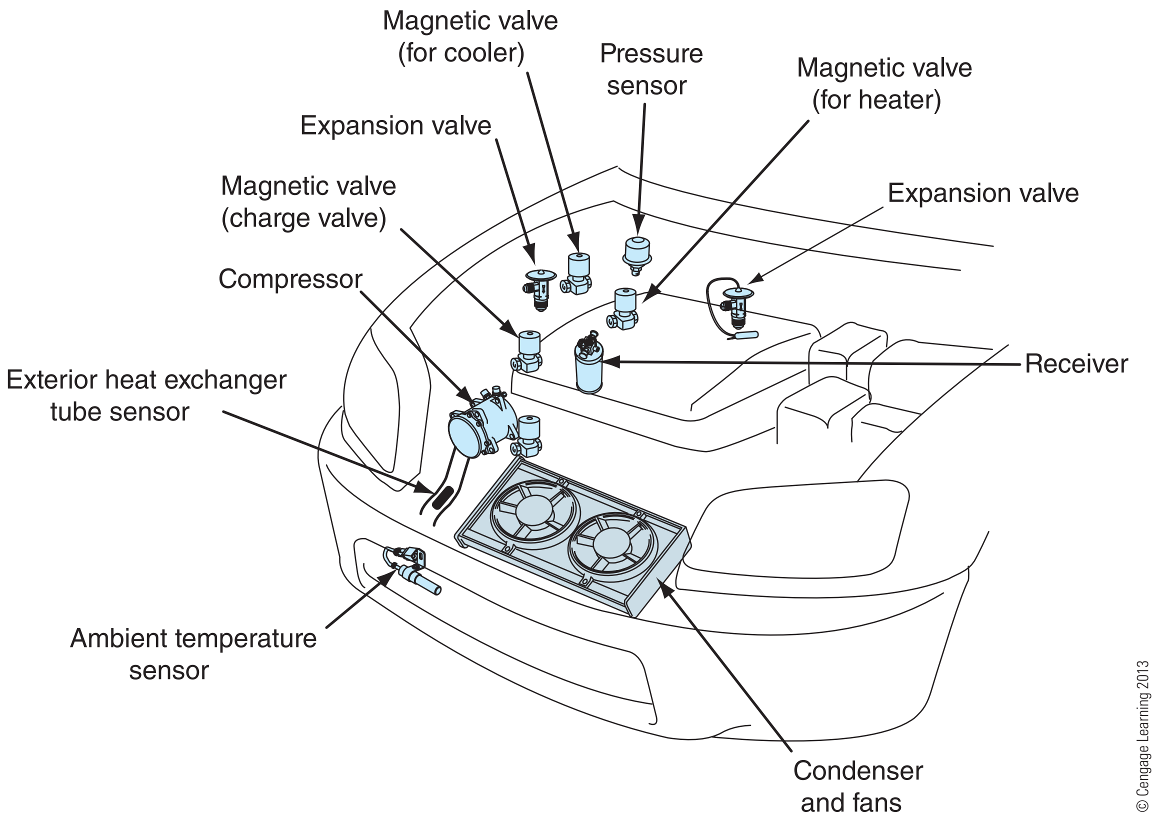

Figure 5-22 A heat pump system looks very much like a traditional air conditioning system.

can be used if fitted with an electrically powered vacuum pump. These pumps are similar to those used on diesel-engine vehicles. The pump may be connected to a storage tank. The tank reduces the time the pump needs to operate and therefore minimizes the effect the pump has on driving range.

Another type of power brake system uses hydraulic pressure, from a pump, to reduce the pedal effort required to apply the brakes. Some BEVs use an electric pump to provide the necessary hydraulic pressure **(Figure 5-23).** These systems are called **electro-hydraulic brake systems**.

Because both types of power brake systems for BEVs operate on electrical power, brake boost is available at all times. The rest of the brake system in nearly all electric vehicles is the same as that found on any vehicle.

Power Steering

Most vehicles use hydraulic pressure to reduce steering effort. In conventional vehicles, the power steering pump is driven by the engine. This pump can be driven by an electric motor, which is how many BEVs are equipped **(Figure 5-24).** The control for the pump can be programmed to provide more assist at lower speeds, and less at higher speeds. The system can also be programmed to only run the pump when it is needed; this reduces the effect power steering has on the driving range. These systems are called **electro-hydraulic steering systems**.

Many power steering systems are purely electrical and mechanical systems. An electric motor moves the steering linkage. These systems are programmable, and the energy consumed by the motor depends on the amount the steering wheel is turned. While driving straight, the motor may not run. However, when the steering wheel is fully turned, the motor is drawing its maximum current.

DRIVING AN EV

Driving a BEV is like driving any other vehicle but with some notable exceptions. There is still a steering

typically has adequate acceleration and can travel at highway speeds. The biggest difference for the driver is that attention must be paid to the consumption of energy. Failure to minimize consumption and carefully plan travel routes can lead to reduced power and a need to recharge the batteries at inconvenient locations

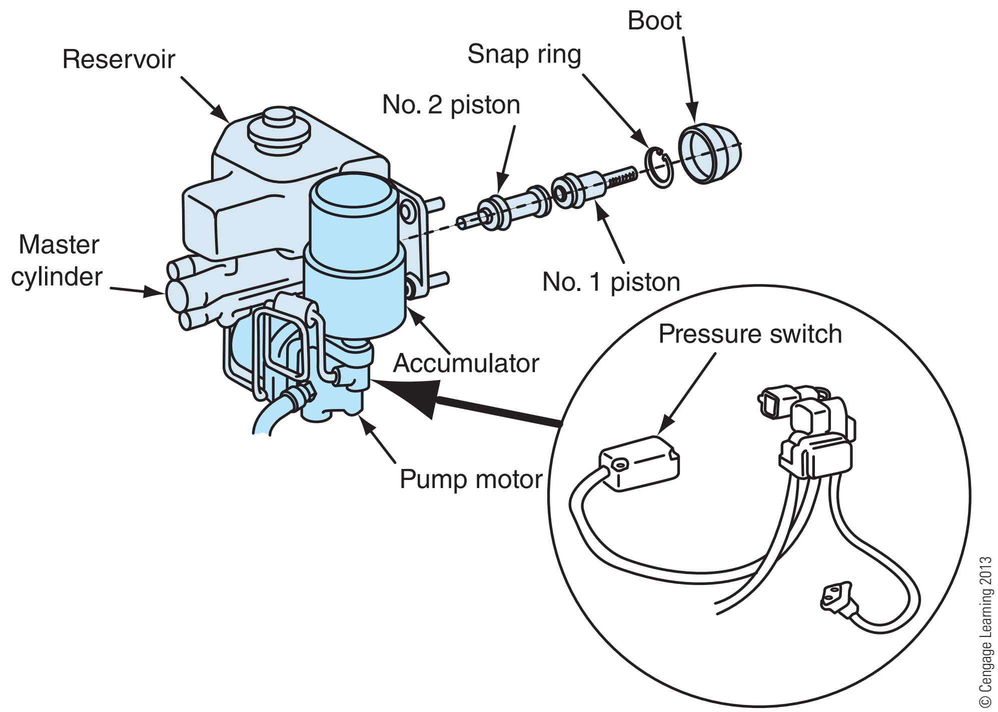

Figure 5-23 The pump assembly for an electro-hydraulic brake system.

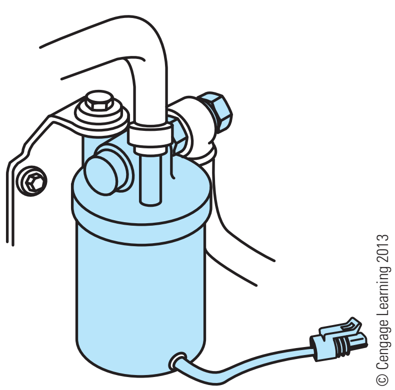

Figure 5-24 An electrically driven power steering pump.

or times. If the batteries are not charged, the vehicle will not move.

Starting

The biggest adjustment a driver needs to make when

it ready for action. A BEV has no noise or vibration when it is ready to go. The driver must look at the instrument cluster to determine it is ready. Like conventional vehicles, the ignition (motor) switch has several positions. One is "lock," during which the traction motor is off and the steering wheel is locked. The key can be removed only at this position. "Accessories" allows some accessories to work but the traction motor is off. "START" actually gets the traction motor ready to work, and "ON" is the normal position for driving. Never leave the switch in the ON position when the vehicle is not in use. Doing so can discharge the auxiliary battery and damage the traction motor.

Before starting, make sure the charge coupler is NOT connected to the vehicle. Always check that charging is completed, and then disconnect the charge coupler. The traction motor will not run with the coupler in place. Make sure the gear lever is in the Park position and that the parking brakes are on. The accelerator should never be depressed during starting.

To turn on the traction motor, turn and hold the motor switch to START with the brake pedal depressed until the READY light in the instrument cluster comes on **(Figure 5-25).** On some vehicles, a buzzer will sound when this happens. Once the

to allow it to move to the ON position. At this point, the traction motor will run when the accelerator is depressed and all accessories are ready to operate. If the READY light does not illuminate during the start process, there is a problem with the traction motor or its circuit, or the auxiliary battery is discharged.

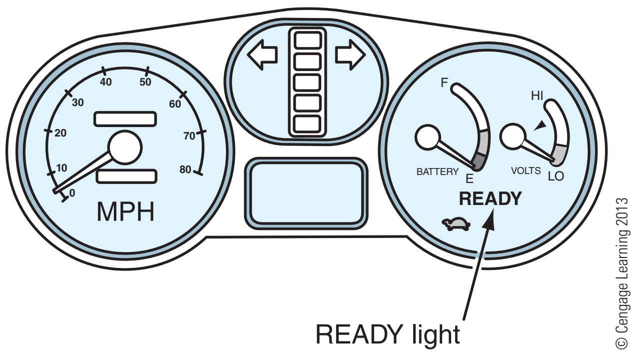

Figure 5-25 The READY light in the instrument cluster of an EV.

Driving and Braking

Most BEVs have a single-speed automatic transmission and the gearshift lever has five positions **(Figure 5-26):**

- **P**—Position for parking, engine starting, and key removal
- **R**—Reverse position
- **N**—Neutral position
- **D**—Normal driving position
- **B**—Position for engine braking (regenerative braking)

In addition to these positions, the vehicle may have an "engine brake (EB)" button or switch. When this switch is on, regenerative braking will slow the vehicle when the accelerator is released. When the shift lever is in the "B" position, more regenerative braking will take place.

Normally the shift lever can only be shifted out of "P" when the motor switch is in the ON position. When moving out of "P" into "D" or "R," the brake pedal must be depressed. It is important that the accelerator is not depressed when shifting gears. Doing this can cause the vehicle to unsafely and quickly move and can cause damage to the motor. Once the shift lever has been moved and with the brake pedal still depressed, the parking brake can be released.

To begin moving, press the accelerator. Drive normally with the realization that the accelerator is the only thing that controls vehicle speed. When the accelerator is released while driving in the EB mode, vehicle speed will decrease because the wheels are now turning the motor that just became a generator. Once coasting has been completed, the lever can be moved back into the "D" position.

To back up, bring the vehicle to a complete stop. Then depress the brake pedal and move the shift lever into the "R" position. It is important to keep in mind that a BEV can accelerate just as quickly in reverse as it does in drive. However, it is more difficult to steer any vehicle in reverse; therefore the accelerator should be gently pressed when backing up.

To park and shut down the vehicle, come to a complete stop. Then apply the parking brake. While depressing the brake pedal, move the shift lever to the

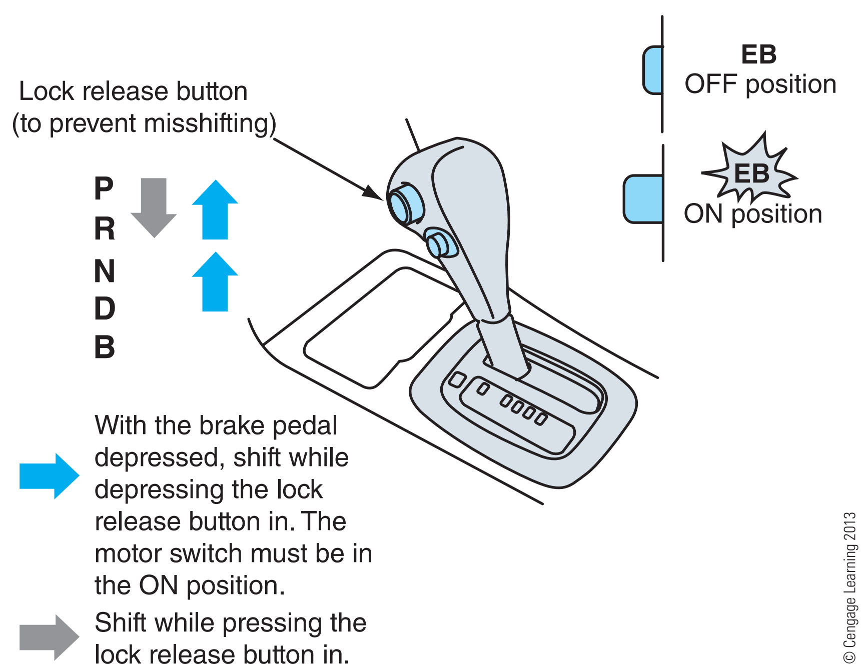

Figure 5-26 The possible gearshift positions for a single-speed transmission.

"P" position. Now turn the motor switch to the LOCK position and remove the key.

Maximizing Range

The driving range of a BEV is reduced by high driving speeds, stop-and-go driving, hills, cold weather (requiring use of heater), warm weather (requiring use of the air conditioner), and the condition and age of the battery. If these conditions are minimized, driving range can be extended. There are certain things a driver can do to extend the range and the life of the batteries.

- Avoid high-speed driving. Maintain a moderate speed on highways.
- Avoid driving up inclines.
- Avoid frequent speed increases or decreases. Attempt to drive at a steady pace.
- Avoid unnecessary stopping and braking.
- Avoid full-throttle acceleration; accelerate slowly and smoothly.
- The vehicle should be well maintained, including proper tire inflation pressures.
- Unnecessary weight in the vehicle will shorten the driving range.

NISSAN LEAF

The Nissan Leaf **(Figure 5-27)** is a true BEV with zero tailpipe emissions; it qualifies as a Zero Emission Vehicle (ZEV). It is rated at 106 MPGe for city driving and 92 MPGe on the highway and 99 MPGe for combined city and highway driving. The EPA estimates a driving range of 73 miles (Nissan claims a range of 100 miles) on a fully charged battery, and the electricity required to keep the car going for a year will cost $561.

This is a five-passenger car designed to be very aerodynamic. It has many energy-saving features, including light-emitting diode (LED) headlights, front UV-reducing solar glass, and regenerative braking.

The car has a top speed of over 93 mph and can accelerate from 0 to 60 mph in 10 seconds. It uses a front-mounted electric motor to drive the front wheels. The motor is rated at 80 kilowatts (110 HP) and 210 ft.-lb. The energy source is a 24-kWh lithium-ion battery that is capable of delivering up to 90 kilowatts of power.

Battery Pack

The battery pack **(Figure 5-28)** is made up of 48 modules, and each module contains four cells. The 192 stacked laminar cells have lithium manganate cathodes. The entire battery pack is air cooled (and heated when necessary) to protect the cells. The Leaf also has an auxiliary 12-volt lead-acid battery that provides power to the basic systems and accessories in the car, such as the sound system, headlights, and windshield wipers. An interesting touch is that some models of the Leaf have a small solar panel on the rear spoiler **(Figure 5-29)** to help trickle charge this auxiliary battery.

Although the Leaf's battery warranty is for eight years or 100,000 miles, the warranty only covers battery defects. It does not cover a gradual loss in battery capacity, nor does it cover failure resulting from not following the guidance recommended in the owner's manual for the battery, such as exposing the car to

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Figure 5-27 A Nissan Leaf.

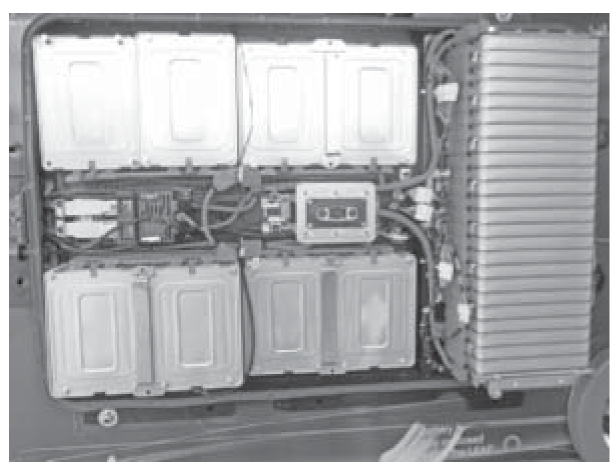

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Figure 5-28 The battery pack in a Leaf.

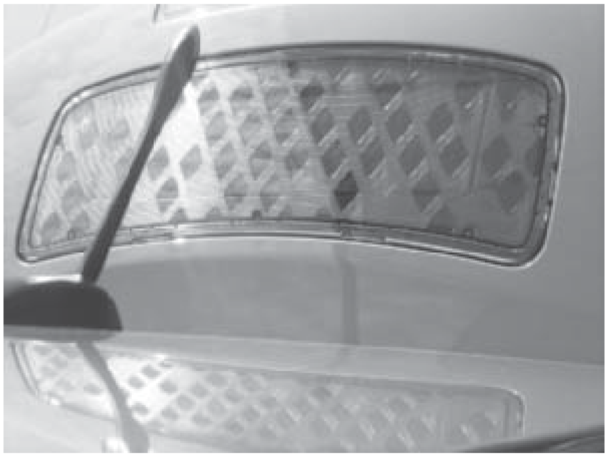

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Figure 5-29 The solar panel built into the spoiler on some models of the Leaf.

temperatures above 120°F for over 24 hours, or storing the Leaf in temperatures below −13°F for more than seven days.

Charging

The Leaf's charging port with two receptacles is located at the front of the car **(Figure 5-30).** One is a standard SAE J1772 connector for Level 1 and 2 recharging (120/220 volts AC). The other is a Level 3 DC connector designed by the Tokyo Electric Power Company (TEPCO) for high-voltage, DC fast charging (480 volts DC 125 amps) that uses the CHAdeMO protocol **(Figure 5-31).** CHAdeMO is the trade name of a quick charging method for BEVs that delivers up to 62.5 kW of high voltage through a special electrical connector.

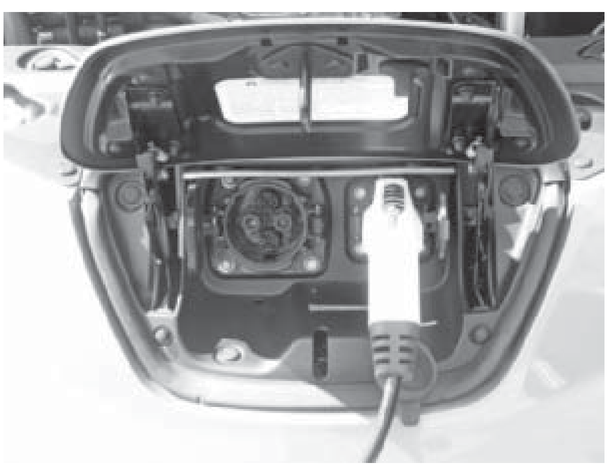

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Figure 5-30 The charging ports at the front of the Leaf.

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Figure 5-31 A Nissan charging station that can be installed in a home.

An SAE J1772 connector is designed for single-phase electrical systems with 120V or 240V. It has five pins with three different pin sizes **(Figure 5-32).** There are two AC lines, and they are the same size. Another size is for the Proximity Detection and Control Pilot pins. The third size is the ground pin.

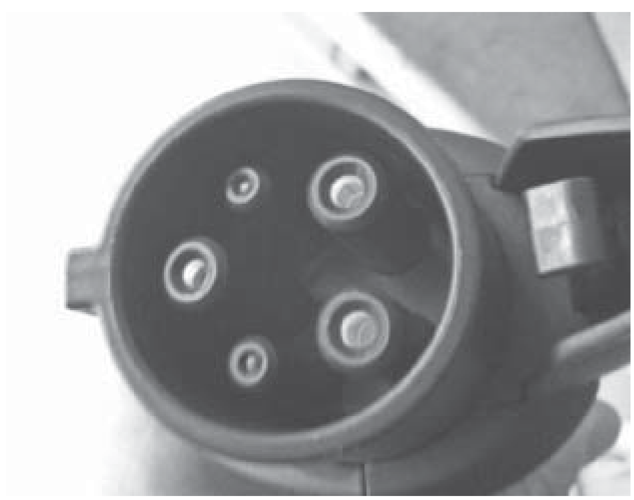

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Figure 5-32 The pins of an SAE J1772 connector.

The Proximity Detection feature of the connector prevents the movement of the car while it is connected to the charger. The Control Pilot pin is for communications between the battery and the charger. The connector also has various shock protection features that protect the consumer and the car during charging, including charging the battery when it is wet outside. When the male and female connectors are not mated, there is no voltage at the pins, and charging current does not flow until the vehicle allows the charger to begin charging.

Some models of the Leaf have a Quick Charge Port 3.3 kW on-board charger. Using this charger, the battery can be fully recharged from empty in eight hours from a 220/240-volt, 30-amp supply.

Leaf customers can purchase a 240-volt home charging station through Nissan. This charging unit is also eligible for a federal tax credit.

Telematics

The Nissan Leaf uses an advanced telematics system called "Carwings." The system sends and receives data via a built-in GPRS radio much like that used in cellular phones. Carwings is connected any time the car is within the range of a cell tower and provides information to the driver, such as the car's position, remaining range, and the location of charging stations available within that range. The system also monitors and compiles information about distances traveled and the amount of energy consumed **(Figure 5-33).** It also provides daily, monthly, and annual reports of that information, which can be viewed on the car's digital screens. Through Carwings, cell phones can be used to remotely turn on the air conditioner and heater and reset all charging functions.

Sound for Pedestrians

Because BEVs emit very little noise while they are moving, the Leaf is programmed to emit digital warning sounds, one for forward motion and another for reverse, to alert pedestrians, the blind, and others that it is moving close to them. This is called the Vehicle Sound for Pedestrians (VSP) system. This sound system moves from 2.5 kHz at the high end to a low of 600 Hz, which makes it audible for all age groups. The sound stops when the Leaf reaches 19 mph and begins again when the Leaf slows to less than 16 mph. The VSP system is controlled by a computer and synthesizer, and the sound is emitted from a speaker in the driver's side front wheel well.

MITSUBISHI i MiEV

The Mitsubishi i MiEV (*Mitsubishi innovative Electric Vehicle*) is a five-door hatchback **(Figure 5-34).** The driving range is rated at 62 miles by the EPA, based on the EPA's five-cycle test. When the vehicle is tested under its driving cycle for city conditions, the EPA's rated range is 98 miles. The car has a single permanent magnet synchronous motor mounted on the rear axle. The motor's output is rated at 47 kW and 130 ft.-lb. It uses a single-speed reduction gear transmission and has a 16-kWh lithium-ion battery pack. The car's top speed is 80 mph.

The EPA rates the Mitsubishi with a combined fuel economy of 112 MPGe, 126 MPGe in city driving, and 99 MPGe on the highway.

The battery pack, positioned under the floor, is made up of 88 cells. These cells are connected in modules of four, and the modules are connected in series to provide 330V.

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Figure 5-33 The "Carwings" display in a Leaf.

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Figure 5-34 A Mitsubishi i MiEV (*Mitsubishi innovative Electric Vehicle*).

There are two 4-cell modules placed vertically at the center of the pack and ten 8-cell modules placed horizontally. It is estimated that it takes 14 hours to recharge the battery with a 110-volt power supply and 7 hours with 220 volts.

In 2011, Mitsubishi introduced a lithium titanate oxide SCiB battery developed by Toshiba. SCiB batteries can withstand 2.5 times more charge/discharge cycles than a typical lithium-ion battery. In addition, recharging through CHAdeMO allows the battery to reach 80 percent capacity in 15 minutes, 50 percent in 10 minutes, and 25 percent in 5 minutes. With more efficient regenerative charging during braking or coasting downhill, the battery can deliver 1.7 times the driving range of a typical lithium-ion battery of the same size.

TESLA

The Tesla Roadster is a BEV sports car produced by Tesla Motors in California **(Figure 5-35).** It is a mid-engine, rear-wheel-drive car based on the Lotus Elise. It has a 248-HP (185-kW), three-phase, four-pole AC induction motor powered by a 53-kWh lithium-ion battery. The roadster has a single-speed fixed-gear transmission. The estimated range, as determined by the EPA, is 244 miles and has been rated to provide 120 MPGe.

Since this is a sports car, solid performance is one of the manufacturing goals. The Lotus is a good base to start with to provide excellent handling. The roadster can also accelerate from 0 to 60 mph in 3.9 seconds. A second model, called the Roadster Sport, can accelerate from 0 to 60 mph in 3.7 seconds. The top speed for both models is electronically limited to 125 mph.

Motor

The roadster is powered by a 248-HP (185-kW) electric motor that can provide 200 ft.-lb of torque from 0 to 6,000 rpm **(Figure 5-36).** The motor in the Sport Model has a higher-density stator and produces a maximum of 288 HP (215 kW). Both motors are designed to spin up to 14,000 rpm, and they weigh less than 70 pounds.

A Power Electronics Module (PEM) controls the action of the motor in response to many different inputs. One of these is the accelerator pedal. In response to the movement of the pedal, the module interprets this as a request for torque and sends the appropriate amount of current to the stator of the motor. When the pedal is released, the module reacts by switching the motor into its regenerative mode to charge the battery pack. The PEM can supply up to 900 amps to the stator. The motor is cooled by a fan that blows air over the cooling fins of the motor **(Figure 5-37).** While in the charge mode, the PEM changes AC voltage from the grid to DC voltages of 250 to 425 volts.

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Figure 5-35 The Tesla Roadster is an EV based on a gasoline-powered Lotus Elise.

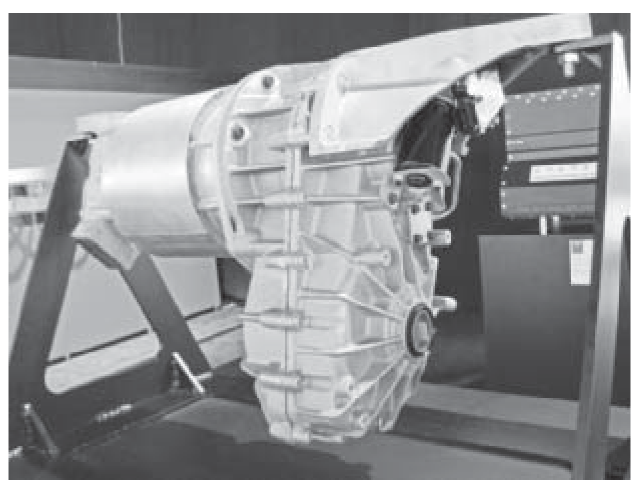

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Figure 5-36 The motor and transmission in a Tesla Roadster.

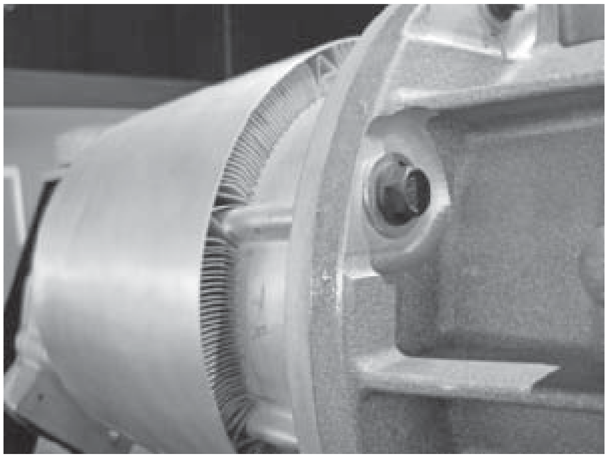

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Figure 5-37 The motor is kept cool by air passing through these specially designed cooling fins around the motor.

Battery

The pack weighs 990 pounds, stores 56 kWh of electric energy, and delivers up to 215 kW of electric power. Coolant is pumped continuously through the ESS when the car is running, and when the car is turned off if the battery pack retains more than a 90 percent charge. The coolant pump draws 146 watts.

Normally, lithium-ion cells are unable to be charged when the temperature drops below 32 degrees Fahrenheit. To enable charging during cold temperatures, the Tesla has a heater to warm the cells (when plugged in) to the appropriate charging temperature. When the temperature increases above a predetermined level, the A/C unit sends chilled coolant through the pack and the coolant continues to flow to maintain ideal temperatures even when the motor is turned off.

Charging

A full recharge of the battery system requires less than four hours using a High Power Connector that supplies 70 amps and 240 volts. Using a charger plugged into a 120V outlet and 15 amps provides five miles of range for each one hour of charging, and a complete recharge from empty requires about 48 hours. The Tesla uses

available through Tesla that allows recharging with a J1772 connector. The system controls temperature and voltage of the battery pack by monitoring more than 100 sensors.

There is a light ring around the charging port. The color of the lights lets the customer know the recharging status. When the charge port door is opened, the Vehicle Management System commands the PEM to send current to the light ring, and white LEDs turn on. When the charger is connected to the port and the driver closes the pilot switch, the lights turn blue. The PEM then monitors the current available from the charger and the battery's state of charge. The system then determines the level of current to use during the recharge. During charging, the light ring will flash. If the battery is empty, the lights will flash rapidly. As the battery charges, the rate of flashing slows. When the battery is completely charged, the lights turn green.

Model S

The Tesla Model S is a full-sized four-door BEV sedan developed by Tesla Motors. The Model S is designed to be a high-performance electric sedan. The chassis, body, motor, and energy storage system are designed by Tesla Motors.

The base model has a range of 160 miles when fully charged using a 42-kWh battery pack and is rated at 108 MPGe. It can accelerate from 0 to 60 mph in less than six seconds. The premium Signature Series has larger battery packs available: a 65-kWh pack with a range of 230 miles and an 85-kWh pack that has a range of 300 miles.

SMART FORTWO ELECTRIC DRIVE (OR SMART ED)

The Smart Fortwo electric drive (or Smart ED) is a BEV version of the Smart Fortwo **(Figure 5-38).** During its development, Smart developed and tested three generations of this BEV.

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Figure 5-38 A Smart Fortwo.

The first-generation Smart ED vehicles were powered by a rear-mounted 30-kW (41-HP) motor driving the rear wheels. It ran on sodium-nickel chloride Zebra batteries that had an output of 13.2 kWh. The estimated range was 68 miles, and it had a top speed of 75 mph. Eight hours were needed to totally recharge the batteries.

The second-generation Smart ED uses a lithium-ion battery supplied by Tesla Motors with a capacity of 16.5 kWh. This increased the range to 84 miles. However, a 20-kW (27-HP) motor was used, which lowered the top speed of the car to 62 mph. The EPA has rated the ED's combined fuel economy at 87 MPGe, 94 MPGe in the city, and 79 MPGe on the highway. The battery pack needs three hours to charge from 20 to 80 percent of its capacity with a standard 220V outlet. The battery pack can also be charged through a 110V outlet. To accommodate Level 1 and 2 charging, the car has a built-in 3.3-kW charger.

The third-generation Smart ED has a more powerful electric motor (74 HP and 96 ft.-lb). The car now has a top speed of 75 mph. It also uses a new lithium-ion battery pack that increases the range to 87 miles.

FORD FOCUS ELECTRIC

The Ford Focus Electric is a five-door hatchback BEV **(Figure 5-39).** The Focus Electric uses a 23-kWh, liquid-cooled lithium-ion battery pack that provides an all-electric range of 100 mi (160 km) and a top speed of 84 mph (135 km/h). The car relies on an electric motor rated at 100 kW (130 HP) and 181 ft.-lb of torque.

The battery system **(Figure 5-40)** uses a liquid cooling and heating thermal management system to precondition and regulate the temperature of the battery.

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Figure 5-39 A Ford Focus BEV.

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Figure 5-40 The battery pack in a Ford Focus BEV.

The thermal management system heats or chills a coolant before passing it through the battery's cooling system.

The charging port is located on the left front fender. A full recharge takes between three and four hours when the car's 6.6-kW charger is connected to a 240-volt outlet by a J1772 connector. The car also comes with a 120-volt cord that allows the charger to be connected to a standard household outlet. Using 120 volts, the battery pack can be recharged in 20 hours.

The Ford Focus Electric has a unique version of the MyFord Touch driver connect system adapted for electric vehicles. The system can display the battery's state of charge, estimated remaining range, distance to various charging stations, and how driving conditions are affecting the range. The display is integrated with the MyFord Touch map-based navigation system. Once the driver puts a destination, including the next charging point, into the navigation system, the system displays advice about maximizing the range during that trip. The navigation system also provides an EcoRoute option that is based on the characteristics of efficient EV driving. There is also a smartphone application that allows the owner to remotely charge the battery and control the accessories of the car.

BASIC DIAGNOSIS

diagnosing concerns on a conventional vehicle because there are fewer components. However, most manufactured BEVs have complex electronics that are unique and require a solid understanding of how the vehicle's systems operate. Fortunately, most BEVs have self-diagnostics with retrievable trouble codes.

CUSTOMER PROBLEM ANALYSIS CHECK

EV CONTROL SYSTEM Check Sheet	Inspector's Name

Customer's Name		Model	
Driver's Name		Model Year	
Date Vehicle Brought in		Frame No.	
License No.		Odometer Reading	km miles

Problem Symptoms	☐ READY does not turn ON ☐ Vehicle does not move ☐ Poor acceleration ☐ Noise ☐ Vibration ☐ Harshness ☐ Smoke is rising ☐ Smell of or the likes burn ☐ Other ______

Date Problem Occurred		
Problem Frequency		☐ Constant ☐ Sometimes(times per day/month) ☐ Once only ☐ Other ______
Condition When Problem Occurred	Weather	☐ Fine ☐ Cloudy ☐ Rainy ☐ Snowy ☐ Various/Other ______
	Outdoor Temperature	☐ Hot ☐ Warm ☐ Cool ☐ Cold(approx. ____°F/____°C)
	Place	☐ Highway ☐ Suburbs ☐ Inner City ☐ Uphill ☐ Downhill ☐ Rough road ☐ Other ______
	Traction Motor	☐ Just after starting vehicle(min.) ☐ Standing with READY ON ☐ Driving ☐ Constant speed ☐ Acceleration ☐ Deceleration ☐ Other ______

Condition of MIL	☐ Remains on ☐ Sometimes lights up ☐ Does not light up
DTC Inspection	☐ Normal ☐ Malfunction code(s) (code) ☐ Freeze frame data ( )

Figure 5-41 A checklist for inspecting and road testing a BEV.

Manufacturer-supplied checklists are especially helpful when deciding what should be known about a particular problem and repair **(Figure 5-41).** In the vehicle's service manual, there may be symptom-based diagnostic aids. These can guide you through a systematic process. As you answer the questions given at each step, you are guided to the next step.

When these diagnostic aids are not available or prove to be

spection and then take a logical approach to solving the problem. Logical diagnosis follows these steps:

1. Gather information about the customer's concern. Find out when and where it happens and what exactly happens.
2. Verify that the problem exists. Take the vehicle for a road test and try to duplicate the problem, if possible.
3. Thoroughly define what the problem is and when it occurs. Pay strict attention to the conditions present when the problem happens. Also pay attention to the entire vehicle; another problem may be evident to you that is not evi-

4. Research all available information and knowledge to determine the possible causes of the problem. Try to match the exact problem with a symptoms chart or think about what is happening and match a system or some components to the problem.

5. Isolate the problem by testing. Narrow the probable causes of the problem by checking the obvious or easy-to-check items.
6. Continue testing to pinpoint the cause of the problem. Once you know where the problem should be, test until you find it!
7. Locate and repair the problem, then verify the repair. Never assume that your work solved the original problem. Make sure the problem is resolved before returning the vehicle to the customer.

Precautions

During diagnosis and repair of a BEV, always keep in mind that the vehicle has very high voltage. This voltage can kill you! Therefore, always adhere to the safety guidelines given by the manufacturer. Here are a few of things that should be done to prevent being shocked by the vehicle's electrical system:

- Wear dry and undamaged insulated gloves while working on the vehicle.
- Disable or disconnect the high-voltage system. Do this according to the procedures given by the manufacturer.
- After the high-voltage system is disconnected, wait the prescribed amount of time before handling any part of the system.
- After the high-voltage system is disconnected, verify that the voltage has been safely disconnected.
- Always use insulated tools.
- When disconnecting electrical connectors, do not pull on the wires. When reconnecting the connectors, make sure they are securely connected.
- Do not leave tools or parts anywhere in the vehicle.
- Do not wear metallic objects such as rings and necklaces.

Self-Diagnostics

The vehicle's control unit or computer may have a built-in self-diagnostic system. In these systems, a malfu

propulsion system can be detected. When a fault is detected, the computer will store that information and may illuminate the **malfunction indicator light (MIL)** on the instrument panel. The faults held in the computer's memory can be retrieved as **Diagnostic Trouble Codes (DTCs)**.

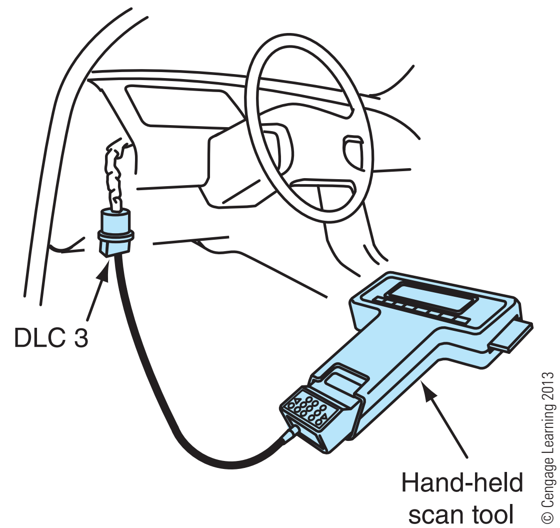

Figure 5-42 A scan tool connected to the DLC for testing the electric drive system on a BEV.

To retrieve these codes, connect the hand-held scan tool to the appropriate **Data Link Connector (DLC)** on the vehicle **(Figure 5-42).** The scan tool will also be able to display other operational data. Many scan tools also have a freeze frame feature. With this feature, the tool records the conditions that were present when a particular malfunction was detected.

Before connecting the scan tool to the vehicle, measure the voltage of the auxiliary battery. If the voltage is lower than specifications, recharge it before continuing with your tests. Also, inspect all fuses, fusible links, wiring harness, connectors, and ground in the low-voltage circuit. Repair them as necessary.

Turn the motor switch to the ON position and make sure the MIL is lit. If the MIL does not light, check for a burnt-out bulb, a bad circuit fuse, or an opening in the circuit. Again, correct the problem before proceeding. The MIL should go off when the READY lamp lights. If the MIL stays on, the computer has found a problem, and related information is stored in its memory. Turn the motor switch to the OFF position.

Make sure the scan tool is set up for the vehicle being tested. Then connect it securely to the DLC. Turn the motor switch to the ON position and turn the scan tool on. Check for DTCs and freeze frame data and record all codes and data displayed on the scan

mine what the DTCs indicate.

Following the correct procedures, verify the trouble and repair the problem. After completing any repair of the motor or related parts, erase the DTCs retained in the computer's memory with the scan tool. Then test it again to make sure the fault is no longer present.

Review Questions

1. Why are carbon dioxide emissions a concern?

2. List five things a driver of a BEV can do to extend the driving range of the vehicle.

3. Which of the following statements about the use of heat pumps in BEVs is NOT correct?
   A. A heat pump is very efficient at producing heat.
   B. When a heat pump is functioning as a heater, it takes heat from the outside air and transfers it to the passenger compartment.
   C. When it is functioning as an air conditioner, heat from inside the passenger compartment is transferred to the outside air.
   D. Most vehicles equipped with a heat pump have auxiliary heating systems that provide additional heat when the outside temperatures are very low.

4. What makes up the propulsion system in a BEV?

5. What basic factors affect the required time to recharge the battery pack in a BEV?

6. There are two basic ways a BEV is connected to an external source of electricity for charging: conductive and inductive. What is the difference between the two?

7. List three advantages for using an AC motor rather than a DC motor in a BEV.

8. Explain what the ratings of kilowatts and kilowatt-hours mean.

9. What is the purpose of an AC power inverter?

10. List five items that are included on the new Monroney sticker.

CHAPTER

6 Hybrid Basics and Series-Type Hybrids

Learning Objectives

After reading and studying this chapter, you should be able to:

- Explain why a hybrid vehicle is more efficient than a vehicle powered only by an internal combustion engine.
- Describe the basic difference between series and parallel hybrid configurations.
- Explain why hybrid vehicles are more expensive to manufacture.
- Describe the importance of electronics in the operation of a hybrid vehicle.
- Explain how the stop-start feature operates.
- Explain how regenerative brakes work.
- Explain the differences between a full, assist, and mild hybrid.
- Describe the primary advantage of plug-in hybrid vehicles.
- Describe the basic operation of a hydraulic hybrid.

Key Terms

assist hybrid
extended range EV
full hybrid
hydraulic hybrids
mild hybrid
plug-in hybrid electric vehicles (PHEVs)

INTRODUCTION

Hybrid electric vehicles (HEVs) are the most common electric drive vehicles manufactured for highway use today. Hybrid vehicles combine the technologies of battery-operated electric vehicles (BEVs) and internal combustion engine vehicles (ICEVs). HEVs are designed to take advantage of the positives of ICEVs and the positives of BEVs. They also suffer from some of the disadvantages of each, although these are minimized.

This chapter covers the basics of hybrid technology.

used to construct a current hybrid vehicle. It also discusses some of the primary benefits and features of the typical hybrid vehicle. Later chapters detail with each of the configurations and equipment options. This chapter also explores current series-type hybrids and other

hybrid designs currently in development, including plug-in hybrids, hydraulic hybrids, and various power-plant combinations.

WHAT IS A HYBRID VEHICLE?

A hybrid vehicle is one that has at least two different types of power or propulsion systems **(Figure 6-1).** Ideally, each of them works to improve the efficiency and performance of the other while minimizing the disadvantages of each. Today's hybrid vehicles have an internal combustion engine and a battery-powered electric motor. (Some have more than one electric motor.)

The logic for using two power sources is simple. A typical ICEV has more available power than it needs for most driving situations. Most ICEs can produce more than 150 horsepower, but only 20 to 40 horsepower are typically needed to maintain a cruising speed. The rest of the horsepower is needed only for acceleration and overcoming loads, such as climbing a hill. These high-output engines use quite a bit of gasoline when they are providing the power to accelerate. An electric motor consumes no fuel and can provide near-instantaneous power. Hybrid vehicles typically use a smaller ICE and an electric motor to provide the power for acceleration and overcoming loads.

Hybrid vehicles use much less fuel in city driving than comparable ICEVs. This is because the engine does not need to supply all of the power required for stop-and-go traffic. The power from the electric motor supplements the engine's power. There is also improvement in highway fuel mileage, because of the use of smaller and more efficient engines. In most cases, these advanced engines cannot produce the power needed for reasonable acceleration without the assistance of an electric motor.

The overall efficiency of a hybrid can be, and in most cases is, enhanced by a number of other features. One of these is the stop-start system. When a hybrid vehicle is stopped in traffic, the engine is temporarily shut off. It restarts automatically when the driver presses the accelerator pedal, releases the brake pedal, or shifts the vehicle into a gear. In addition, to reduce the required energy to drive the generator, hybrids have regenerative braking. Rotated by the vehicle's wheels, the electric drive motor acts as a generator to charge the batteries when the vehicle is slowing down or braking. This feature recaptures part of the vehicle's kinetic energy that would otherwise be lost as heat in a conventional vehicle.

Some hybrids can be plugged into the electric grid to recharge the batteries; these are called "plug-in hybrids." The rationale for these is that externally charging the batteries, in addition to regenerative braking and the ICE-driven generator, will decrease the use of gasoline and significantly increase the time the vehicle can be driven by electricity only.

Most hybrids use transmissions specifically designed to keep the ICE operating at its most efficient speed. Efficiency can also be increased by the use of low-rolling-resistance (LLR) tires, which are stiff and narrow to minimize the amount of energy required to turn them. Hybrids may also be lighter and designed to minimize aerodynamic drag.

Types

Depending on the system used, the ICE may power the vehicle by itself, or it may drive a generator, or both. The electric motor drives the wheels, sometimes alone,

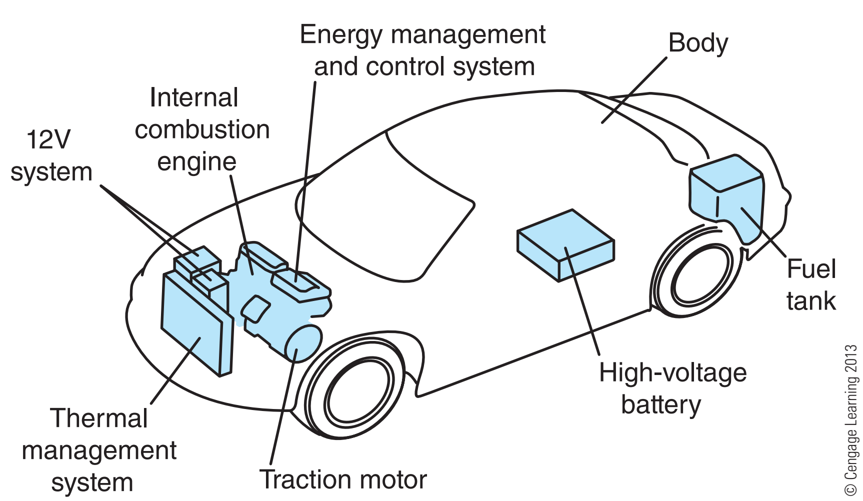

Figure 6-1 The main components of a hybrid electric vehicle.

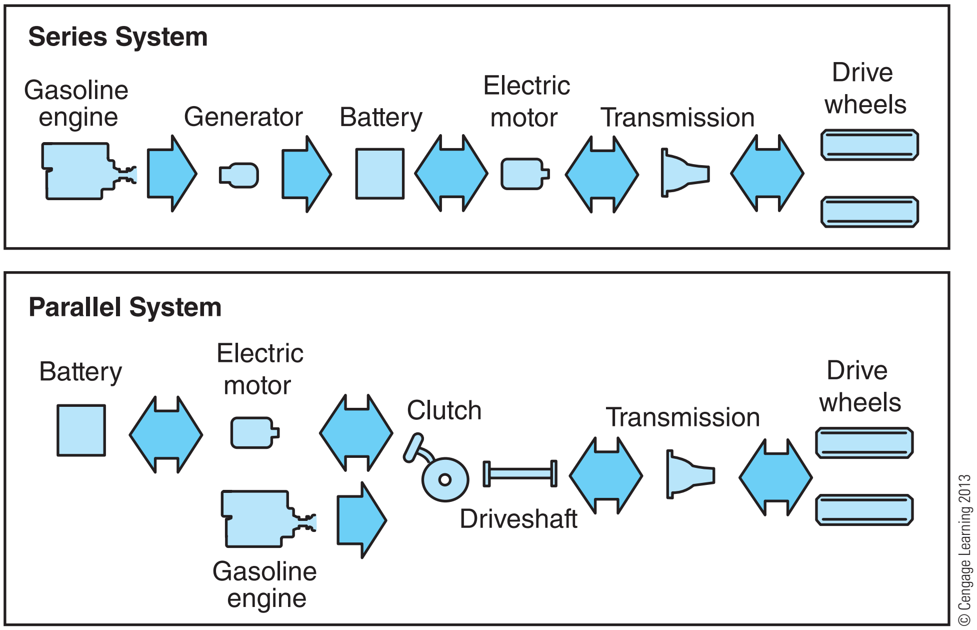

Figure 6-2 Basic layout of series and parallel hybrid powertrains.

or sometimes the engine and motor work together to provide the required power. Often, the motor is used as the propulsion unit when the vehicle is traveling at low speeds. Once a specific speed or load is reached, the engine takes over. The electric motor may also provide a power boost when there is a heavy load on the engine. The motor is powered by the batteries and/or ultra-capacitors, both of which are charged by the generator and regenerative braking. The engine may use gasoline, diesel, ethanol, methanol, compressed natural gas, hydrogen, or another alternative fuel.

Often hybrids are categorized as series or parallel types **(Figure 6-2).** In a series hybrid, the engine never directly powers the vehicle. Rather it drives a generator, and the generator either charges the batteries or directly powers the electric motor that drives the wheels. In a parallel hybrid, the engine, the motor, or both can power the drive wheels. The engine also drives the generator to charge the battery pack.

There are many variations of hybrid systems used by manufacturers today. Some vehicles labeled as hybrids do not fit into either category. These are called mild or micro hybrids.

Fuel

electric motor. By definition, an HEV is a vehicle powered by two separate energy sources. Some hybrids being developed combine a fuel cell with batteries to power electric motors. The electricity produced by the fuel cell can be used to charge the batteries and power the motor. Hydrogen fuel cells generate electric energy without combustion and therefore have zero emissions. Also, fuel cells produce DC voltage that can be used to power motors and lights and to charge batteries without additional electronics. Nearly all fuel cell vehicles have a series hybrid configuration.

BENEFITS OF A HYBRID

Hybrid vehicles have the potential to be two to three times more fuel-efficient than conventional vehicles, with much lower emission levels. Also, the combination of an engine and electric motor can provide increased power and/or additional auxiliary power for electrical devices. A hybrid vehicle has two main advantages over a battery-operated electric vehicle:

1. Drivers are more comfortable with HEVs because there are no battery range limitations (therefore no fear of being stranded), and the vehicles are refueled in the same way as any gasoline-powered vehicle.
2. A hybrid requires a much smaller battery than a pure EV, which dramatically reduces the ve-

   be as much as $30,000, whereas the battery cost in many hybrids is less than $5,000.

When comparing the pollution and fuel consumption of EVs and HEVs, it is important to remember that EVs are not completely pollution-free, nor oil-independent. Many of the electric power plants that

generate the electricity to charge EVs burn oil, natural gas, or coal. Only electric power produced by hydroelectric dams, wind turbines, solar, or geothermal plants are pollution-free and are renewable (they do not consume any type of fossil fuel). These clean sources, however, produce only a small fraction of the electricity in the United States today, and most electricity is generated by burning a fuel.

Although HEVs still burn gasoline and emit exhaust pollutants, the amount of pollution produced and gasoline consumed per mile are substantially less than in a typical gasoline-powered vehicle because:

- The gasoline engine can be smaller for the same level of vehicle performance because there is electric motor assist.
- The propulsion system can be designed to allow the engine to run at its most fuel-efficient speed.
- The engine can be shut off while the car is stopped at traffic lights, decelerating, or moving at low speed.
- Regenerative braking captures and recycles much of the energy used to slow down and stop the vehicle.

Fuel Economy

Hybrids consume significantly less fuel than vehicles powered by gasoline alone. Therefore, they can reduce the country's dependence on fossil fuels and foreign oil. (Fuel economy ratings for hybrid and conventional vehicles can found at *www.FuelEconomy.gov*.) **Table 6-1** compares the standard Ford Fusion to a Ford Fusion HEV. As you can see, there is a substantial difference in fuel consumption. Also, notice that the carbon footprint and the annual petroleum consumption ratings are much lower with the HEV.

HEVs typically have the same or greater range than conventional vehicles. For example, the Fusion HEV has a range of about 600 miles on a tank of fuel. That is about 200 miles more than a conventional Fusion. This extended range certainly offsets the disadvantage of a BEV, which has been impaired by a very short driving range.

Air Pollution

Hybrids can have more than 90 percent fewer emissions than the cleanest conventional ICE vehicles. HEVs also produce significantly lower total fuel-cycle ("well to wheel") emissions when compared to equivalently sized conventional vehicles.

The engine's power is boosted by electric motors that produce zero emissions. Also, the engine can be shut down when it is not needed. In addition, many HEVs can move in an electric-only mode. In this mode, the vehicle has no emissions. Clean electricity is also used to power many accessories and other equipment that typically are driven by the ICE. This means the engine has less work to do and therefore will use less fuel and emit fewer pollutants.

Hybrids will never be zero-emission vehicles, because they rely on an engine for much of their power. However, most are rated as being close to zero-emission vehicles.

Cost

HEVs have a higher initial cost than comparable conventional vehicles and tend to be heavier. The added weight decreases fuel economy, which is why some larger hybrid SUVs see little gain in fuel mileage.

TABLE 6-1: A COMPARISON OF A HYBRID WITH A NONHYBRID VEHICLE

2011 Base Ford Fusion		2011 Ford Fusion Hybrid
Regular gasoline	**Fuel Type**	Regular gasoline
22 city, 30 hwy, 25 combined	**EPA MPG Rating**	41 city, 36 hwy, 39 combined
$4	**Cost to Drive 25 Miles**	$2.56
1 gallon	**Fuel to Drive 25 Miles**	0.64 gallon
$70*	**Cost of Fill-Up**	$68*
394*	**Miles on a Tank**	597*
17.5		
$2,368*	**Annual Fuel Cost**	$1,535*
13.7 barrels (575 gallons)*	**Annual Oil Consumption**	8.8 barrels (370 gallons)*
8.7*	**Annual Tons of CO_2 Emitted**	6.4*

*Based on 55 percent city driving, 45 percent highway driving, 15,000 miles per year, and $4 per gallon of gasoline.

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TABLE 6-2: A QUICK LOOK AT SOME OF THE ADDITIONAL PRODUCTION COSTS FOR BUILDING A TYPICAL HEV

Why HEVs cost more to manufacture:	
Add	
Batteries, cooling system, and battery controller	$1,400
Electronic controls and inverter	$1,400
Electric motor (50 kW)	$600
Harness, safety circuitry, and AC/DC converter	$600
Added cost over standard vehicle	**$4,000**

Source: Energy and Environmental Analysis Inc.

The additional weight results from the addition of large battery packs and electric motor/generators. These same items contribute to the higher cost, as well. However, the cost of some of these items will decrease as the volume of production increases. Currently, an HEV costs nearly $4,000 more to produce than an ICE-only version. (See **Table 6-2.**)

Many believe the increased fuel economy of HEVs offsets their higher initial cost. Consumers pay more for an HEV but typically gain a substantial increase in fuel economy. The initial cost can also be partially offset by tax incentives. In the United States, a federal tax deduction for the purchase of a hybrid vehicle may be available on some vehicles, and some states may provide additional incentives or tax credits for purchasing a hybrid vehicle.

Not all automotive experts believe the savings on fuel does, indeed, offset the higher initial cost of an HEV. These opinions are based on the service life of an HEV. According to *www.edmunds.com*, gasoline would have to cost $5.60 a gallon for a Ford Escape Hybrid owner and $10.10 a gallon for a Toyota Prius owner to financially justify the higher initial cost of a hybrid. The debate will undoubtedly continue for quite some time. However, it is safe to say that most who buy hybrids are doing so for other reasons than using less fuel. These reasons are based on the benefits of hybrid vehicles such as lower emissions and decreasing the country's dependence on fossil fuels. Plus, some feel owning a hybrid makes a statement they want to make!

Availability

Hybrid vehicles are available in many shapes and sizes. Manufacturers are building or are planning to

Courtesy of American Honda Motor Co.

Figure 6-3 The look of a Honda Insight.

build a great variety of hybrid models. The public seems to have accepted hybrid vehicles, judging by the success of a few models. Initially, hybrid vehicles were designed to address the disadvantages of pure electric vehicles. A hybrid vehicle is much like a conventional vehicle, except it uses less fuel, emits fewer emissions, and operates quietly (sometimes). Most modern hybrids even look like conventional vehicles.

This was not the case when the first HEV was released for sale in North America. The Honda Insight was a small and different-looking car **(Figure 6-3).** It was also rather expensive. Honda did not sell many of these vehicles, but the Insight was a success for the automotive industry. It opened the consumer's eye to this new technology.

Shortly after the introduction of the Insight, Toyota brought the Prius to this country. The original Prius was also a small and different-looking car. Nevertheless, it was large enough to be deemed more practical, and it sold quite well. The Prius has since been redesigned and made larger. Newer designs of hybrids are considerably more conventional looking. Many look exactly the same, except for badging, as their nonhybrid counterparts. To consumers, today's HEVs are practical while providing improved fuel economy and reduced emissions.

Today's hybrids are not just about increased fuel economy. Many larger hybrids use the supplemental power from their electric motors to improve performance. Some hybrid sedans offer nearly the same performance as cars typically called "performance sedans."

TECHNOLOGY

technology. The switching between the electric motor and gasoline engine is controlled by computers, as are other features of the vehicle. The control systems are extremely complex. They have very fast processing speeds and real-time operating systems. The individual computers in the control system are linked together

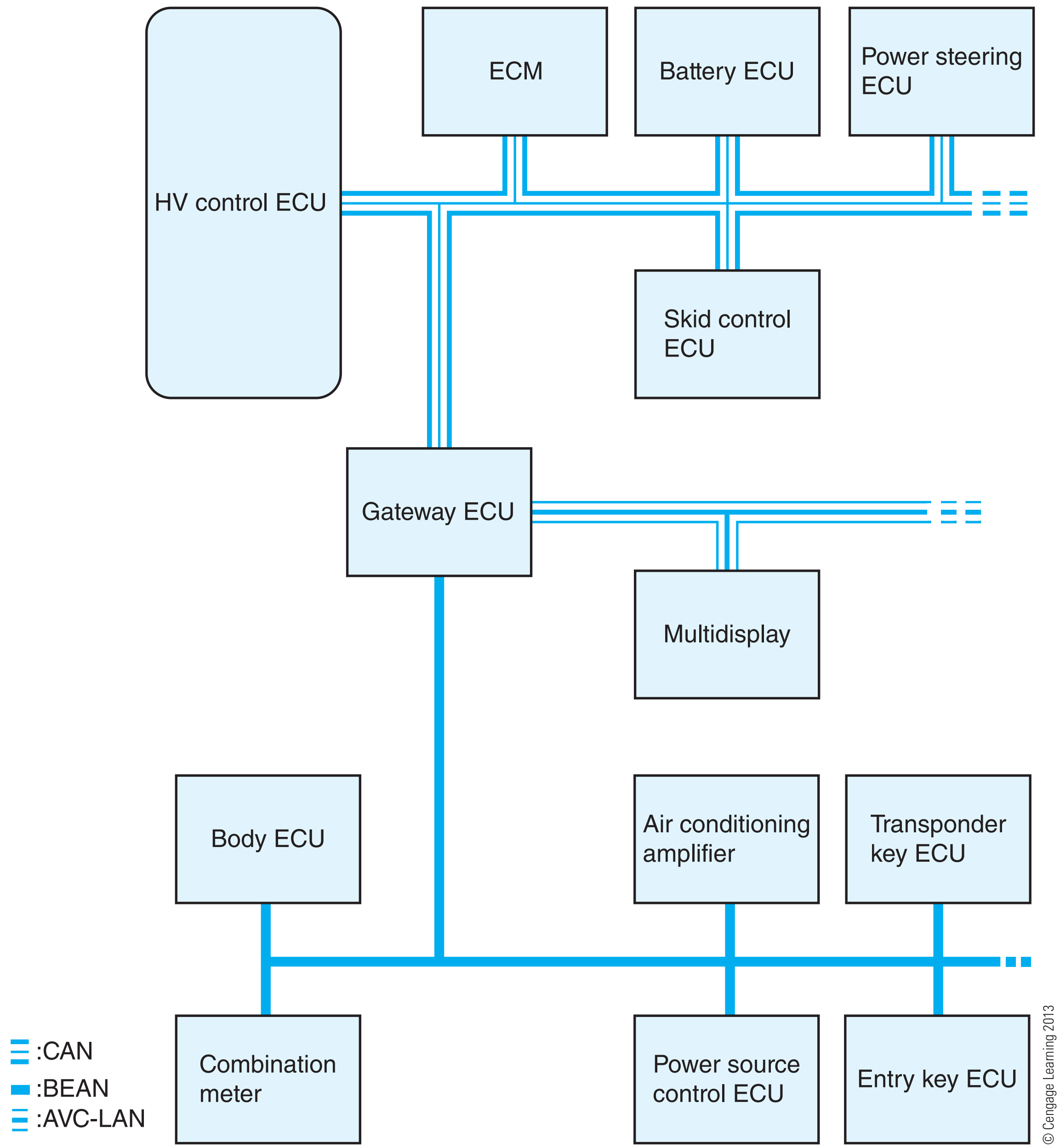

Figure 6-4 The individual computers in the control system are linked together and communicate with each other by high-speed "communication buses," known as CAN (Controller Area Network).

and communicate with each other by high-speed "communication buses." CAN (Controller Area Network) communications take place between many control systems **(Figure 6-4):** the electric motor controller, engine controller, battery management system, brake system controller, transmission controller, electrical grid

components that also must be controlled.

The basic components of a hybrid vehicle include batteries, fuel tank, transmission, electric motor, and internal combustion engine. Both the batteries and fuel tank store the energy needed to run the primary parts of the drivetrain. Obviously, the batteries store energy for the electric motor. The fuel tank is the energy storage device for the internal combustion engine. The battery pack must be larger and heavier than a typical fuel tank because batteries have a much lower energy density than gasoline.

The transmission used in an HEV can be a normal transmission or one especially designed for the vehicle.

engine to run at its most efficient speed during normal operating conditions. Often a continuously variable transmission (CVT) is used. These transmissions do not have fixed gear ratios; instead the overall drive ratio changes according to load **(Figure 6-5).**

The addition of an electric motor or motors to a conventional vehicle is what makes a hybrid fuel

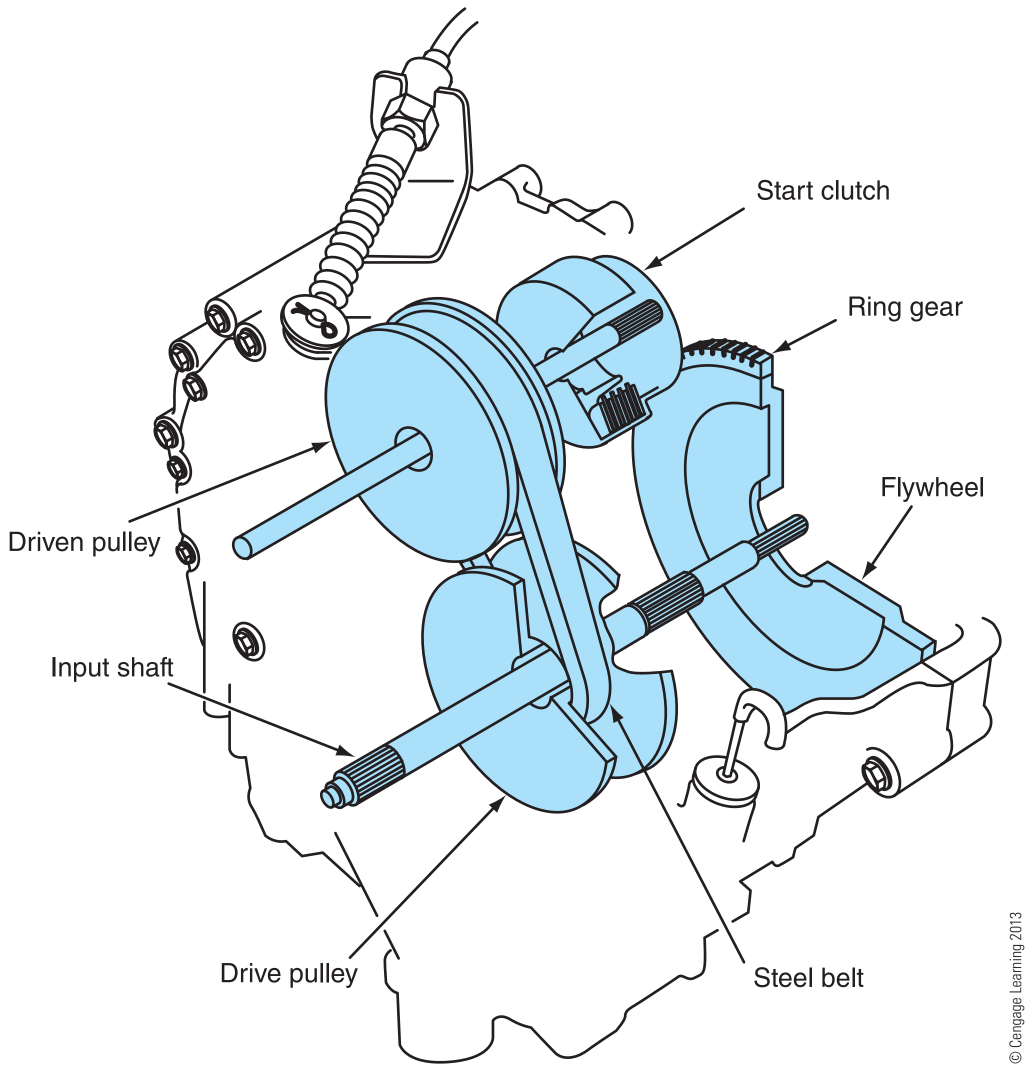

Figure 6-5 A CVT uses pulleys and a belt or chain to provide drive ratios that vary according to the needs of the vehicle.

efficient. The motor provides full torque at low speeds, which helps with good acceleration and uses zero fuel when it is operating on its own. The motors also have low production costs, low noise, and high efficiency. Advanced electronics allow the motor to act as a generator when its power is not needed. The electric motor can be configured, through electronics, to assist the engine during acceleration, passing, overtaking heavy loads, or hill climbing **(Figure 6-6).** The hybrid controller or computer control system coordinates or synchronizes the action of both.

Internal Combustion Engine

The engine found in most hybrids is a four-stroke cycle engine that burns gasoline. These engines are very similar to those used in conventional vehicles. The engine in a hybrid also uses advanced technologies to reduce emissions and increase overall efficiency.

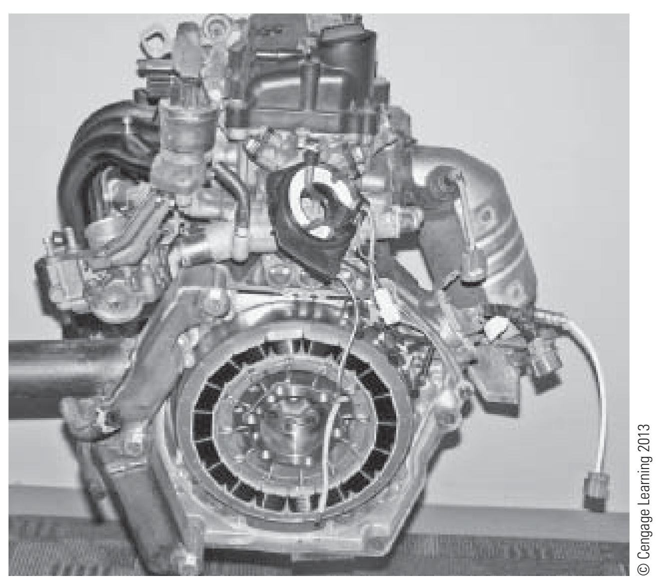

Figure 6-6 In this hybrid powertrain, the electric assist motor is mounted to the rear of the engine and then the transaxle is installed over it.

Diesel Engines

The engine in a hybrid does not need to run on gasoline. In other countries where diesel fuel is commonly used, hybrids are being tested with direct injection diesel engines. Diesel engines have the highest thermal efficiency of any internal combustion engine. Because of this efficiency, diesel hybrids can achieve outstanding fuel economy. Diesel engines do have drawbacks, and these define the reasons diesel automobiles are not common in the United States. These disadvantages include particulate matter and nitrogen oxides in the exhaust, noise, and vibration. However, with today's technology, many automotive diesels run quietly and cleanly. Diesel engines also have the ability to run on biodiesel fuel, which means a diesel hybrid would not need to use fossil fuels.

Stop-Start Feature

Stop-start systems automatically shut down the engine when the driver applies the brakes and brings the vehicle to a complete stop. This eliminates the need to waste energy on engine idling and can increase fuel economy by more than 5 percent. The benefit of these systems is most evident during stop-and-go driving. With the engine off, the vehicle's heating and air conditioning systems and its electrical systems continue to run using the battery power. The engine is restarted automatically when the driver releases the brake pedal or when the control system senses the need.

The point at which the engine is restarted is a defining element of mild and full hybrids. Electric components turn off the engine when the vehicle is stopped and quickly restart the engine when the brakes are released. Most mild hybrids have a belt-driven starter-generator **(Figure 6-7).**

Full hybrids can be powered by only the electric motor, the gasoline engine alone, or both. They have the stop-start feature, but the engine does not automatically restart when the brakes are released. Because full hybrids can accelerate with only the electric motor, the engine is not restarted until the engine's power is needed. This is determined by the control system and is based on the vehicle's load and the battery pack's state of charge.

Regenerative Brakes

Regenerative braking is the process that allows a vehicle to recapture and store part of the kinetic energy that would ordinarily be lost during braking. A vehicle has more kinetic energy when it is moving fast; therefore, regenerative braking is more efficient at higher speeds **(Figure 6-8).** When the brakes are applied in a conventional vehicle, friction at the wheel brakes converts the vehicle's kinetic energy into heat. With regenerative braking, that energy is used to recharge the batteries. Regenerative braking can capture approximately 30 percent of the energy normally lost during braking in conventional vehicles. It is claimed that the electric energy resulting

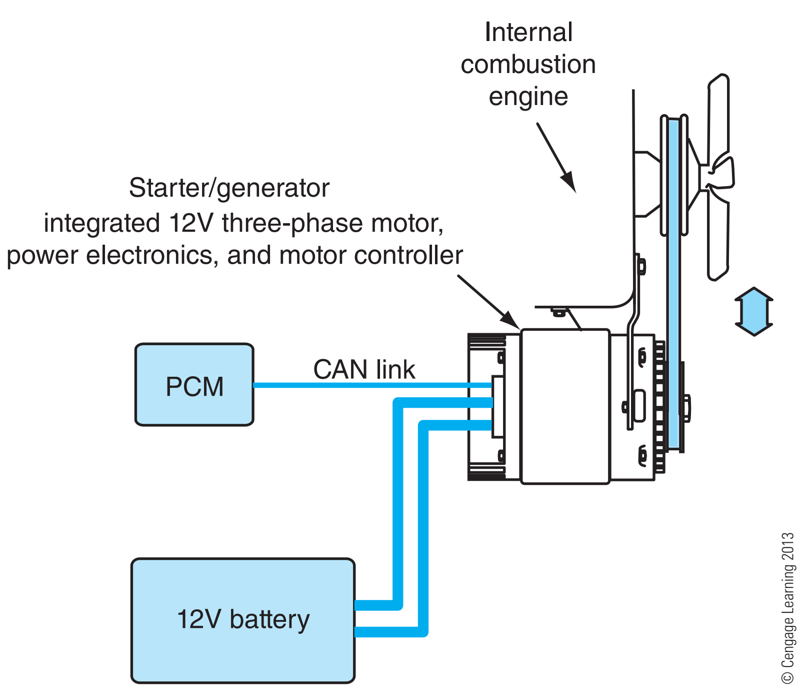

Figure 6-7 The basic configuration for a belt-driven starter/generator in a stop-start system.

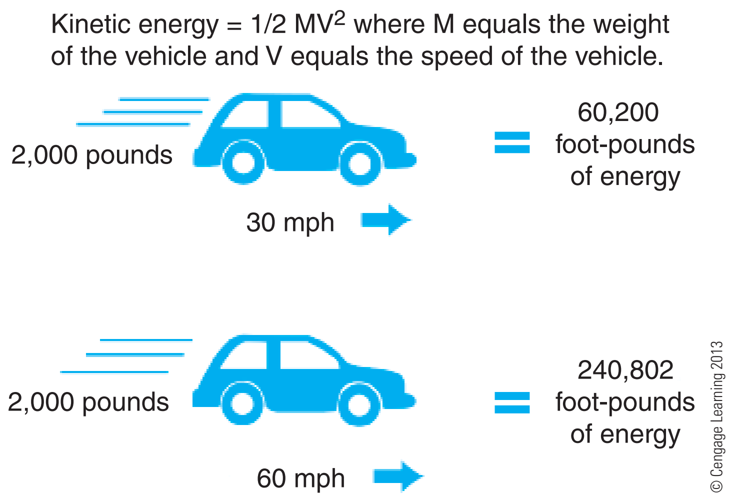

Figure 6-8 Kinetic energy increases exponentially with vehicle speed.

from regenerative braking supplies 20 percent of the energy used by a Toyota Prius while driving in city traffic.

In a regenerative braking system, the rotor of the generator is turned by the vehicle's wheels as the vehicle is slowing down. The activation of the generator applies resistance to the drivetrain, causing the wheels to slow down. The kinetic energy of the vehicle is changed to electrical energy until the vehicle is stopped **(Figure 6-9).** At that point, there is no kinetic energy.

In many hybrids, there is no separate generator for the braking system. Rather, the control system changes the circuitry at the motor and it acts as a generator. The motor now converts motion into electricity rather than converting electricity into motion. The captured energy is sent to the batteries or to an ultra-capacitor. Some hybrids use ultra-capacitorsbecause they can capture the energy quickly and can release it quickly during acceleration. Regenerative braking is not used to completely stop the vehicle. A combination of conventional hydraulic brakes and regenerative braking is used. Hydraulic, friction-based brakes must be used when sudden and hard braking is needed and during antilock brake activation.

The amount of energy captured by a regenerative braking system depends on many things, such as the state of charge of the battery, the speed at which the generator's rotor is spinning, and how many wheels are part of the regenerative braking system. Most current HEVs are front-wheel drive; therefore, energy can only be reclaimed at the front wheels. The rear brakes still produce heat that is wasted.

Brake-By-Wire Systems. By-wire systems are those that are controlled and operated by electricity and have no mechanical or hydraulic connections. Traditionally, brake systems use both mechanical and hydraulic systems. They rely on hydraulic pressure forced through brake lines to stop the vehicle. With regenerative

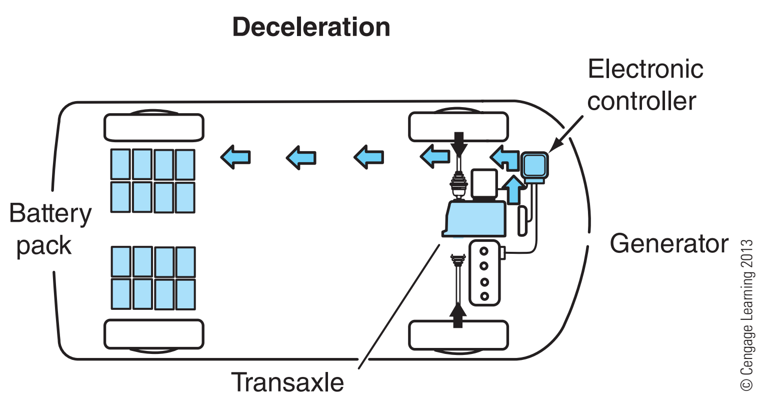

Figure 6-9 During deceleration, kinetic energy is used to drive a generator, which recharges the batteries.

braking, part of the braking is done by the interaction of magnetic fields in the motors; the rest is done through hydraulics. However, some hybrid vehicles will be fitted with electromechanical brakes at two wheels (both wheels are on the same axle), in addition to a regenerative braking system.

When the brake pedal is depressed, a signal is sent to the motors, which apply brake pads at the individual wheels. By eliminating the hydraulic system, the weight and space required for the brake system is reduced. These systems also provide for electric parking brakes, which can be controlled to prevent their application any time the vehicle is moving.

ACCESSORIES

Hybrids can have a number of auxiliary systems and quite a few accessories. In a conventional vehicle, nearly all of these are powered by the engine. In an HEV, there is an engine and a high-voltage system. The accessories are powered by either, depending on the model. Some systems, such as the radio, lights, and horn, operate the same way as they do in a conventional vehicle. Other systems, such as the power steering and power brakes, may be operated by small electric motors. It must be remembered that when working on HEVs, these auxiliaries and accessories may be powered by high voltage. Never attempt to work on these components (or the main propulsion system components) without thorough training that includes all safety procedures. Normally, most of the high-voltage components are clearly identified and the high-voltage cables are orange. Often, 42-volt cables are colored yellow rather than orange.

HVAC

All vehicles are equipped with passenger compartment heating and windshield defrosting systems. In an HEV, the engine can be used to supply the heat, so heating and defrosting systems are similar to those used in conventional vehicles. Some hybrids, however, have additional electric heaters. These keep the passenger compartment warm when the engine is off.

HEV air conditioning systems are typically identical to those used in conventional vehicles, except a high-voltage motor may be used to rotate the compressor **(Figure 6-10).** This increases the efficiency of the engine and allows for conditioned air when the engine is off.

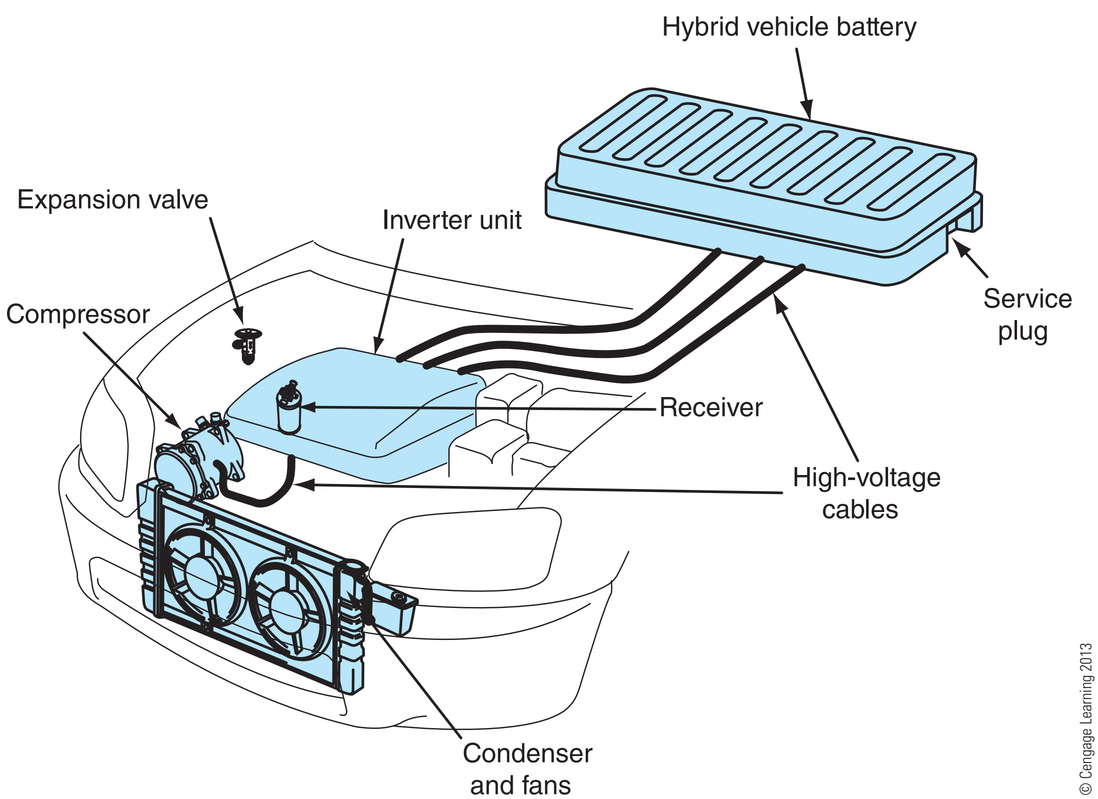

Figure 6-10 HEV air conditioning systems are typically driven by a high-voltage motor rather than the engine's crankshaft.

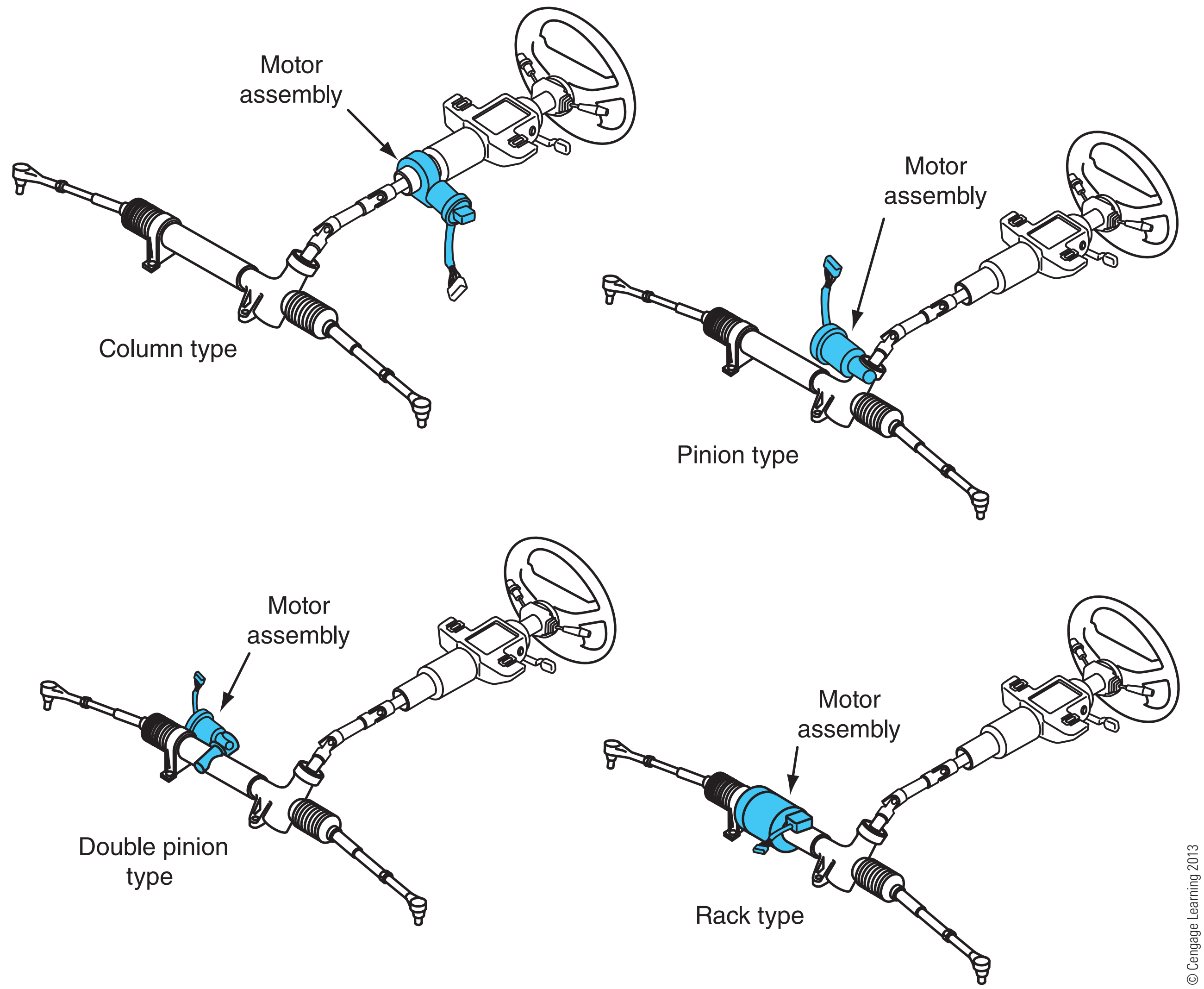

Figure 6-11 The different designs of vehicle-speed-sensing electric power rack-and-pinion steering systems used in hybrid vehicles.

Power Brakes

Many power brake systems use engine vacuum and atmospheric pressure to multiply the effort applied to the brake pedal during braking. Because there is an engine in an HEV, there is a natural vacuum source. Some HEVs have an electrically powered vacuum pump fitted to the vacuum assist power brake system. This allows for power boost when the engine is off. Other hybrids have an electro-hydraulic brake system. An electric pump provides the necessary hydraulic pressure

Power Steering

Power steering systems in HEVs are typically pure electrical and mechanical systems **(Figure 6-11).** An electric motor directly moves the steering linkage. These systems are also very programmable, and the energy consumed by the motor depends on the amount the steering wheel is turned. While driving straight, the motor may not run. However, when the steering wheel is fully turned, the motor is drawing its maximum current.

TYPES OF HEVs

A series-type HEV is moved by the power of a single

vehicle; rather it drives a generator **(Figure 6-12).** The generator, in turn, charges the batteries. The current trend is to develop series hybrids, also called **extended range EVs**. This type of hybrid uses an ICE to run a generator to charge the battery pack. In a parallel hybrid, the electric motor and

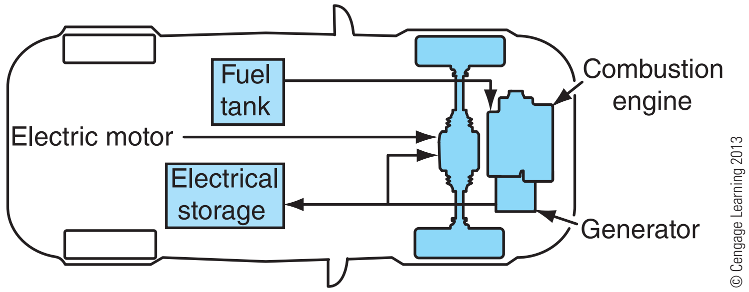

Figure 6-12 A series hybrid configuration.

ICE work together (in parallel) to power the vehicle **(Figure 6-13).**

Many current hybrids use a combination of the series and parallel hybrid configurations. In this design, the vehicle can be driven by either the engine or the electric motor **(Figure 6-14).** The hybrid control system shuts off the engine when there is ample power from the motor to move the vehicle. The engine is turned on when extra power is needed or when the batteries need to be recharged.

There are two other variations of the series and parallel configuration: the fuel cell hybrid and the "roadway-coupled" hybrid. In the fuel cell hybrid, the fuel tank is replaced by a hydrogen tank, and the engine and

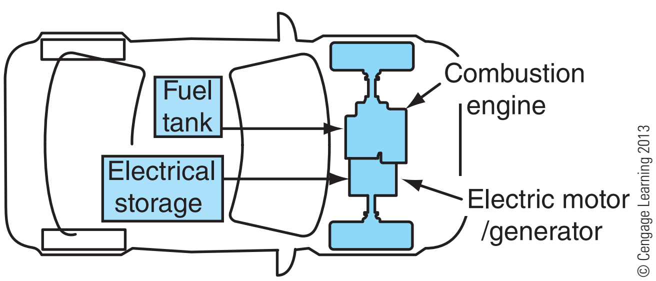

Figure 6-13 A parallel hybrid configuration.

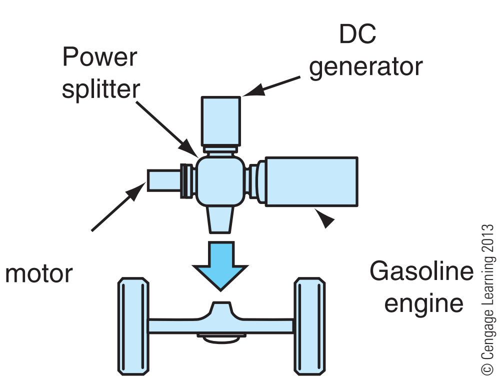

Figure 6-14 The power splitter allows the ICE and/or the electric motor to power the vehicle.

generator are replaced by the fuel cell. Because the output of the fuel cell is only electricity (there is no mechanical motion), fuel cells can *only* be used in a series configuration. In the roadway-coupled hybrid, the engine and electric motor are not connected within the vehicle. Instead, one set of wheels is powered by the engine, and the other set is powered by the motor. The coupling between the two is made by the road through the tires. This system is shown in **Figure 6-15** and is often referred to as a split hybrid design.

Hybrid configurations are further defined by the role of the electric motor. Naturally, the more the electric motor powers the vehicle, the less time the ICE must run **(Figure 6-16).** A full hybrid is a vehicle that can run on just the engine, just the batteries, or a combination of the two. The Prius and the Escape are examples of full hybrids. An **assist hybrid** cannot be powered only by the electric motor. The electric motor helps or assists the engine to overcome increased load. At all other times, the vehicle is powered by the engine. A micro or **mild hybrid** is a vehicle equipped with stop-start technology combined with regenerative braking. The electric motor/generator never drives the wheels or adds power to the drivetrain.

Many different types of hybrids have been released or are about to be released. The manufacturers call all of them "hybrids," but they differ greatly in design and purpose. This has led some to categorize them by feature and purpose, rather than configuration. The currently available hybrids can be classified as:

- *Conventional vehicle* (not really a hybrid), which has stop-start and possibly regenerative braking.

  braking, electric motor assist, and an operating voltage less than 60 volts.
- *Full hybrid,* which has stop-start, regenerative braking, electric motor assist, an operating voltage greater than 60 volts, and can be powered by electricity only.

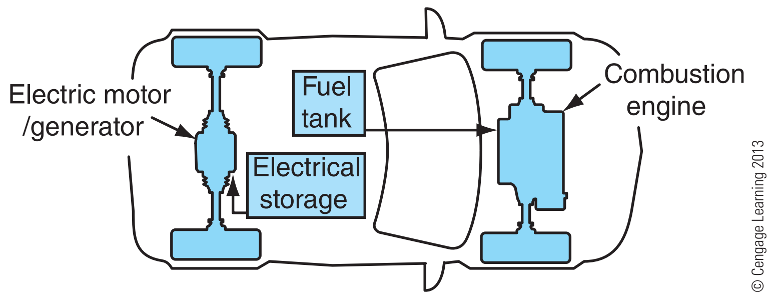

Figure 6-15 A split hybrid configuration.

	Fuel economy improvement				Driving performance	
	Idling stop	Energy recovery	High-efficiency operation control	Total efficiency	Acceleration	Continuous high output
Series	●	◎	●	●	○	○
Parallel	●	●	○	●	●	○
Series/parallel	◎	◎	◎	◎	●	●

◎ Excellent ● Superior ○ Somewhat unfavorable

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Figure 6-16 A comparison of the fuel efficiencies of the various hybrid configurations.

- *Performance hybrid* (some call these "muscle hybrids"), which is a full hybrid designed for improved acceleration rather than fuel economy.
- *Plug-in hybrids,* which are full hybrids that can use an external electrical source to charge the batteries, thereby extending the electric-only driving range.

SERIES HYBRIDS

According to the SAE, a series hybrid is a vehicle that uses one power source to provide energy for another power source. In this case, a series hybrid uses an engine to drive a generator and its output powers electric motor(s). Although much development is taking place with series hybrids, currently there are only two series hybrids available to the public: the Chevrolet

CHEVROLET VOLT

The Chevrolet Volt **(Figure 6-17)** is a four-passenger hatchback that is called an extended range EV by GM. However according to the SAE, it should be classified

Figure 6-17 A Chevrolet Volt.

a vehicle with two or more on-board energy storage systems that provide propulsion. With a gasoline tank to supply fuel for an engine and a battery pack to power electric motors, the Volt is a hybrid. However, for most of its use, the gasoline engine does not power the drive wheels. Therefore, the Volt is not a true

series hybrid as it can act as a BEV, a series hybrid, and, at times, as a parallel hybrid.

The Volt is an electric-drive vehicle, powered by a 16-kWh Li-Ion battery, using an internal combustion engine to run a generator to serve as a range extender by providing electrical power for the motors. The Volt uses the energy stored in a battery pack to power the drive wheels during the first 25 to 50 miles of operation. Once battery power is depleted, the engine turns on to provide the power to extend the driving range up to an additional 300 miles. Rather than rely on the engine as the sole source for supplying electrical power, the Volt is designed have the electrical grid serve as the primary source for the stored energy required to power the motors.

When the initial battery capacity drops below a predetermined level and while the Volt is operating in series hybrid mode, the control system will select the most efficient operating mode to provide good performance and increase high-speed efficiency. This will include starting the engine to drive the generator, the output of which is used to power the electric motor(s). Again during predetermined conditions, the second motor may turn on to assist the primary motor or power the vehicle by itself. Also at certain loads and speeds, the engine may be mechanically linked, by a clutch, to the output of the planetary gear set.

The Volt has a healthy price tag of about $41,000 at this writing. That price is currently decreased by federal tax breaks of $7,500 and other credits allotted by different states. Unfortunately, the cost difference between the Volt and the similar Chevrolet Cruze can only be offset by many miles of pure EV operation in the Volt.

Due to the weight of the battery pack (435+ pounds), the Volt is rather heavy (approximately 3,800 pounds). This weight decreases the overall efficiency of the Volt; however, it will consume little or no fuel when it is used as a pure commuter car (less than 40 miles per day).

In spite of the weight, the Volt has respectable acceleration. It can accelerate from 0 to 60 mph in approximately 9.2 seconds. It also moves with very little noise, even when the engine is running. The engagement of the engine to drive the generator is also barely perceptible to the occupants.

To

signed with many mileage-extending features, such as:

- A coefficient of drag of 0.29
- Low-rolling-resistance tires
- Heated seats that can be preselected to avoid the need for the heating system
- A Bose Energy Efficient Series sound system that uses 50 percent less energy than other systems
- Electrical motors constructed to provide the required power with a minimal amount of energy

Powertrain

Under the hood of a Volt there is a conventional engine along with the necessary electrical and hybrid components. All of the high-voltage cables are orange, and many have a warning label attached to them. It is important to remember that the A/C compressor and other necessary accessories are powered by 360V **(Figure 6-18).**

The Volt powertrain has two AC permanent magnet electric motors—a 111-kW (149-HP) main traction and a 55-kW (74-HP) generator/motor—plus a 1.4-L four-cylinder gasoline engine rated at 84 HP and 90 ft.-lb of torque. The generator/motor has two basic functions: as a generator it converts engine power into electricity and as a motor it helps drive the wheels. The motors are powered by the energy stored in the battery pack or by the energy produced by the generator. The gasoline engine is primarily used to spin the generator. A planetary gear set and three clutches manage and distribute power from the electric motors and gasoline engine to power the wheel **(Figure 6-19).**

The 16-kWh lithium-ion battery pack can be charged by plugging the car into a 120-240-volt AC residential electrical outlet. The Volt comes with an

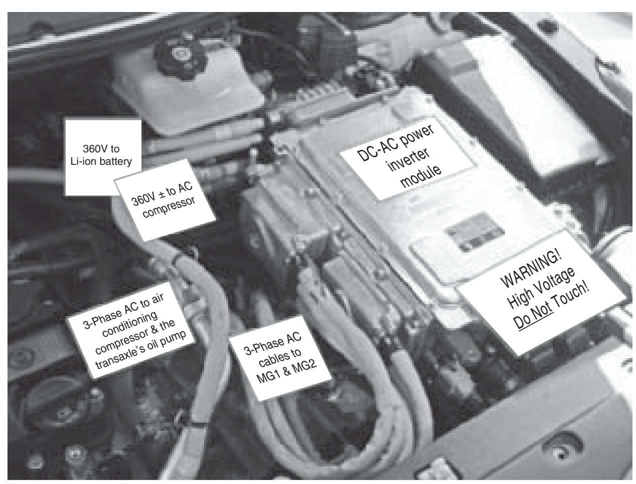


Figure 6-18 Under the hood of a Volt there is a conventional engine along with the necessary electrical and hybrid components. All of the high-voltage cables are orange, and many have warning labels attached to them.

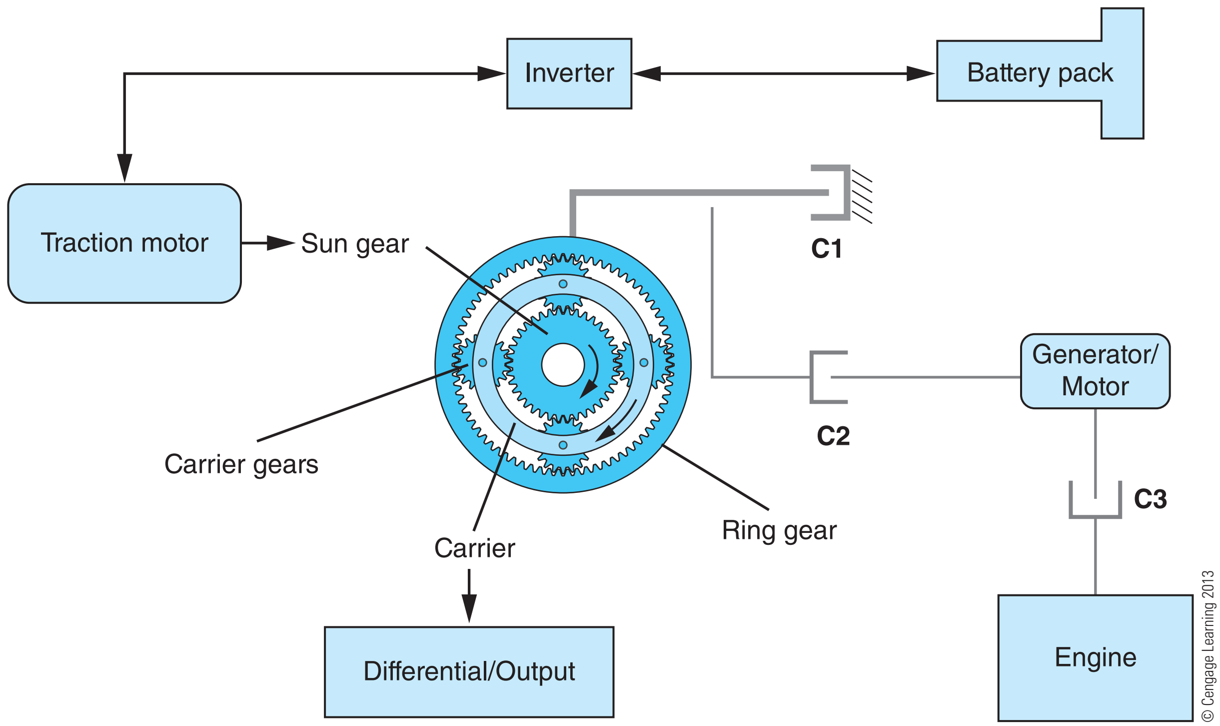


Figure 6-19 The main components of a Volt's powertrain.

Figure 6-20 The charging nozzle for a Volt.

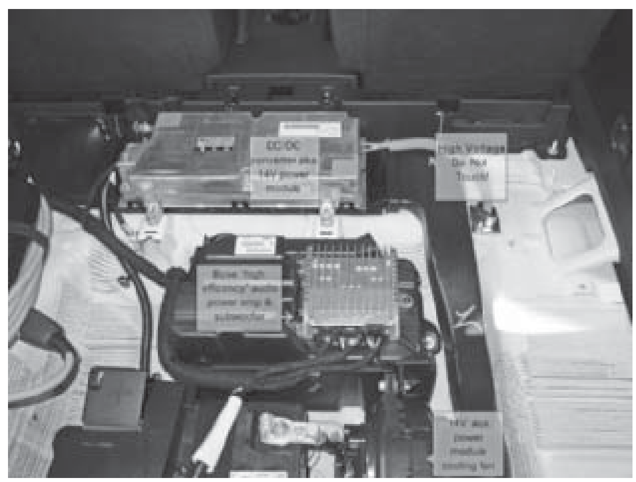


Figure 6-21 The various components in the luggage compartment of a Volt.

SAE J1772-compliant charging cord **(Figure 6-20).** An external charging station is not required to recharge the battery pack.

The charger, as well as other components necessary for the sound system and the battery maintenance and cooling, are located in the luggage compartment **(Figure 6-21).**

Basic Operation

The drivetrain (called the "Voltec platform") allows the Volt to operate as a pure battery electric vehicle for 25 to 50 miles. This range is affected by many things, including: road conditions, driving mannerisms, driver comfort settings (e.g., HVAC), and weather. Once the battery pack's state of charge (SOC) is depleted to a predetermined level, the vehicle operates as a series hybrid whereby the engine starts and powers the generator. The output of the generator either provides power for the traction motor or recharges the battery

300 miles the car's driving range. To help with recharging the battery pack, the Volt also has a regenerative braking system.

When the car is in this series mode at higher speeds and loads, (normally above 30 miles per hour and/or under acceleration) the generator will function as a

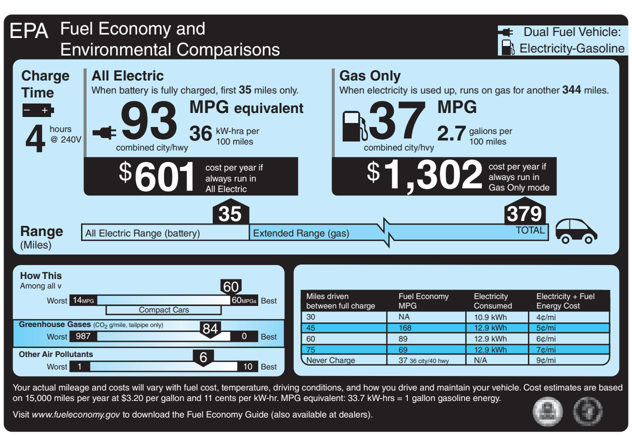
motor and aid the main traction motor. Also under particular conditions, the engine can mechanically engage to the output of the planetary gear set and assist both electric motors in driving the wheels; therefore the Volt can operate as a series-parallel hybrid when additional power is required.

Economics

The Volt's fuel efficiency **(Figure 6-22)** is rated by the EPA as 93 MPGe all electric/37 mpg gasoline only/60 MPGe combined (electric + gasoline). GM claims for the average consumer, it will cost $1.30 each day to keep the 16-kilowatt-hour battery fully charged. This comes out to less than 4 cents per mile if the Volt is only run in its BEV mode.

Theoretically, no fuel would be involved to power the car if the battery pack was recharged by wind-, solar-, or hydro-generated electricity and the Volt is only used to drive short distances. If and when this is the case, the gasoline stored in the tank can become stale, and the stagnant engine can become poorly lubricated. Both of these can cause problems. To prevent this, the engine management system monitors the time since the engine was last run. If that time exceeds a predetermined interval, the system will tell the driver to drive beyond the all-electric range before recharging so the engine can consume some gasoline. If the driver fails to run the engine, the system will automatically begin its maintenance mode, which starts the engine to consume some of the aging fuel and circulate the lubricants within the engine.

Emissions. The Volt is classified as an Ultra Low Emission Vehicle (ULEV) by the California Air Resources Board (CARB). CARB rated the Volt's carbon monoxide (CO) emissions at 1.3 g/mile (0.81 g/km), and the EPA's rating is 84 grams of carbon dioxide (CO_2) per mile (52.5 g/km). CO and CO_2 emissions are produced by the engine in extended range mode.



U.S. Environmental Protection Agency

Figure 6-22 An EPA sticker for a Volt.

BATTERY PACK

The Volt has a 6-foot long, 435-lb (197-kg) lithium-ion battery pack that stores 16 kWh. The battery pack contains 288 cells **(Figure 6-23)** wired in series and parallel to provide the desired voltage and current output. The cells are six and one-half by nine inches in size and less than one-quarter inch thick and are arranged into nine modules. The cells and modules are arranged around an aluminum cooling fin to help prevent hot or cool spots on the flat, rectangular cell.

The Volt has a thermal management system to monitor and maintain the battery pack temperature. The battery pack can be warmed or cooled by a unique liquid cooling circuit that is similar to, but independent of, the engine cooling system. The system tries to keep the battery's temperature close to room temperature for maximum efficiency. While the battery is being

LG Chem, Korea

Figure 6-23 The Volt's battery pack consists of 288 of these Li-Ion cells.

charged, the system can preheat it during cold weather and cool it in hot weather. The battery's thermal management system can also be powered by the battery or the engine while driving.

The battery pack itself costs about $8,000 to $10,000, or about $500 per kWh. The Volt's battery has a warranty of eight years or 100,000 miles (160,000 km), and the warranty covers all other battery components. All rechargeable batteries will degrade over time, and GM estimates the Volt battery will degrade only 10 to 30 percent after 8 to 10 years. To ensure the battery pack lasts that long, the energy management system only allows for 10.4 kWh to be used. The battery management system also runs more than 500 diagnostics 10 times per second to monitor the battery pack.

Because the energy in the battery pack never is completely depleted and therefore never receives a full charge, the life of the pack is extended. The management system only allows the battery to operate within an SOC of a predetermined level; once that level is reached the engine starts to maintain a charge near the lower level. The minimum SOC varies with the current operating conditions. It is important to note that the car has a normal 12-volt battery, in addition to the high-voltage battery pack.

Charging Methods

CAUTION *If the vehicle is in a collision, the sensing system may disconnect the high-voltage battery and the car will not start. The* Service Vehicle Soon *message in the Driver Information Center (DIC) will also be displayed. Before the vehicle can be operated again, it must be inspected and any problems corrected.*

The Volt is equipped with a 120-volt charger that plugs into any household wall outlet; the battery can receive a full charge in 10 to 12 hours. The charger is located in the trunk **(Figure 6-24)** along with the tire emergency repair kit (air compressor and tire sealant). Charging time can be reduced if the owner invests in the installation of a 240-volt charger package, which reduces

charger, along with a 20-ft., 120V charging cord is stored under the rear luggage compartment. One end of the cord is fitted with the charging plug. This fuel nozzle–type plug fits into a charge port located on the left side of the car. The other end goes into the wall outlet.

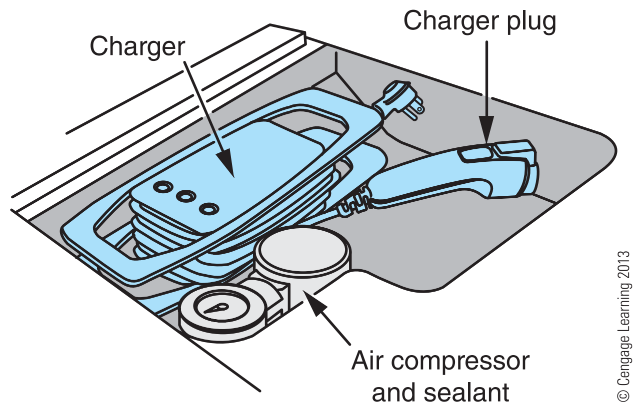


Figure 6-24 The charger assembly located next to the tire repair kit in the Volt's trunk.

Plug the cord into the wall and check the indicators on the charger **(Figure 6-25).** When both indicators are green, the cord connections are good and the battery pack can be charged. If any of the indicators are flashing red, the battery pack cannot be charged. A flashing red light can mean one of the following: the AC voltage is out of range, the AC outlet does not have a proper safety ground, or there is a fault in the charge cord or charger.

When both indicators are green, open the charge port door by pressing the release button on the inner trim panel of the driver's door. The door also can be opened with the remote key transmitter. The charging

Figure 6-25 The charging unit has a series of lights that indicate the charging status.

plug has a built-in flashlight that can be used by squeezing the lever on the plug. Once the electrical connection is made between the plug and the car and the lever released, the flashlight will turn off. When the cord is connected to both the outlet and the car, the charging status indicator (CSI) on the top of the instrument panel near the windshield should be lit **(Figure 6-26).** The horn should also sound to indicate the system is ready to recharge the battery.

The color and action of the CSI indicates the status of the charge. The action of the horn also gives an indication of the charging status **(Table 6-3).**

Recharging can be controlled at the center stack inside the car or remotely through a smartphone application. The charge level button allows for two modes of charging: normal or reduced. It is important to note that the charge level cannot be changed once the charger is connected to the car. Normal is the recommended charge level, and it will cause all four charge indicators to light. When Reduced is selected, two charge indicators will be lit. A reduced level of charge is only used when there may not be an ample supply of current available to charge at the normal rate.

WARNING *Using the charge cord in a worn or damaged AC outlet may cause a fire. Periodically check the wall plug and charge cord while the car is charging. If the wall plug feels hot, unplug the charge cord and have the AC outlet replaced by a qualified electrician. Replace the charge cord if the AC wall plug or cord is damaged.*

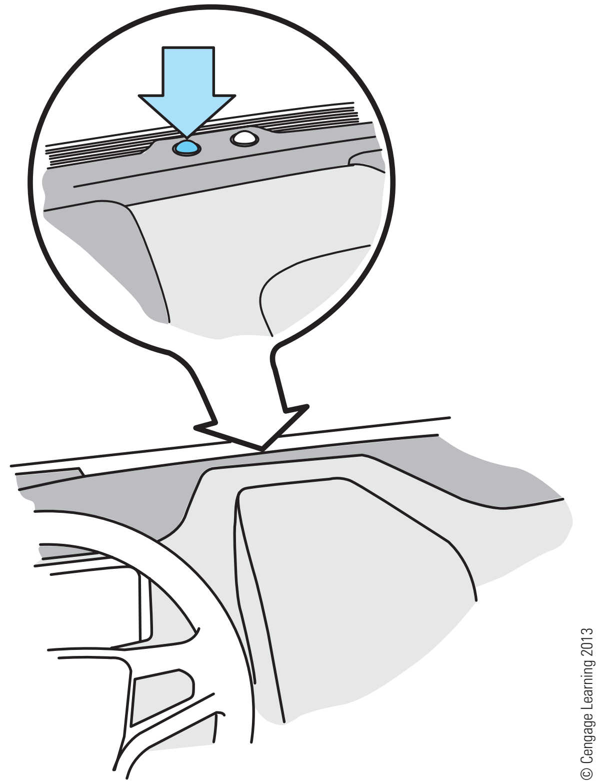


Figure 6-26 The charging status indicator (CSI) located on the top of the instrument panel near the windshield.

The charging plug is removed by squeezing its lever before attempting to pull it out. The charge port door can then be closed and the charger and charge cord returned to the rear luggage compartment.

TABLE 6-3: THE ACTIONS OF THE CSI AND THE HORN GIVE AN INDICATION OF THE CURRENT CHARGING PROCESS

CSI	Horn	Explanation
Solid green	One chirp	Charge has begun
Long flashing green	Two chirps	Charging is delayed
Short flashing green	None	Charging is complete
Yellow (upon plug-in)	None	Charge cord is OK but the car is not yet charging
Yellow (after plug-in)	None	Check MIL
Solid green or long flashing green	Four chirps	Insufficient time to fully charge
None (upon plug-in)	None	Check cord connection
None (after green or yellow CSI)	None	Check cord connection
None	Repeated chirps	Electricity was interrupted before charge was complete

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Programmable Charging

The vehicle has three ways (modes) to program how the vehicle is charged. The current charge mode status is displayed on the center stack **(Figure 6-27),** as well as the time estimates for a complete charge. One program mode is "Immediately"; this means the battery pack will begin to charge as soon as the charger circuit has been completed **(Figure 6-28).**

Another mode is called the "Delayed Rate and Departure Time." In this mode, the system estimates the charging start time based on the utility rate schedule, utility rate preference, and the desired departure time for the current day of the week. In this mode, charging will be done during the least expensive rate periods while providing a full charge before the departure time **(Figure 6-29).**

The driver also has the option of defining the preferred charge rate **(Figure 6-30).** The system will charge the battery according to the rates selected and will attempt to fully charge the battery prior to the programmed departure time.

In addition to the selection of the charging mode, the system can display an Energy Usage screen. This screen displays information about all of the drive cycles since the last time the high-voltage battery was fully charged **(Figure 6-31).** It displays a graph that represents the percentage of distance traveled using the Electric Mode versus the Extended Range Mode. The displayed Lifetime Fuel Economy is the average fuel economy during the life of the car.

An Energy Efficiency screen can also be displayed to show the efficiency of the drive cycle based on driving style and climate control settings. Driving in a more efficient manner results in the display of a high percentage for driving style. Minimizing the use of the climate control system results in a higher percentage for climate setting.

Jump-Starting. The use of jumper cables may be required to start the Volt if the 12-volt battery is totally depleted. The 12-volt battery in the Volt may also be

Figure 6-27 An example of the charging status as displayed on the center stack.

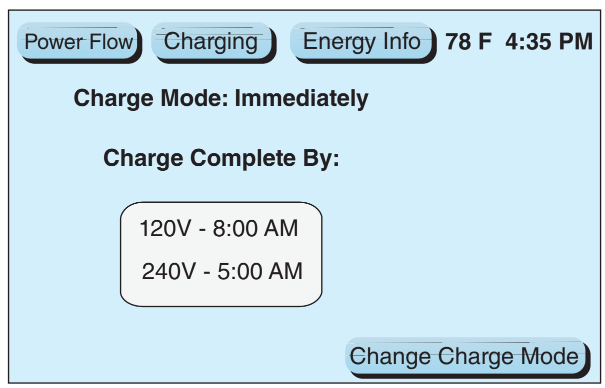

Figure 6-28 The information that is displayed on the current charge status screen.

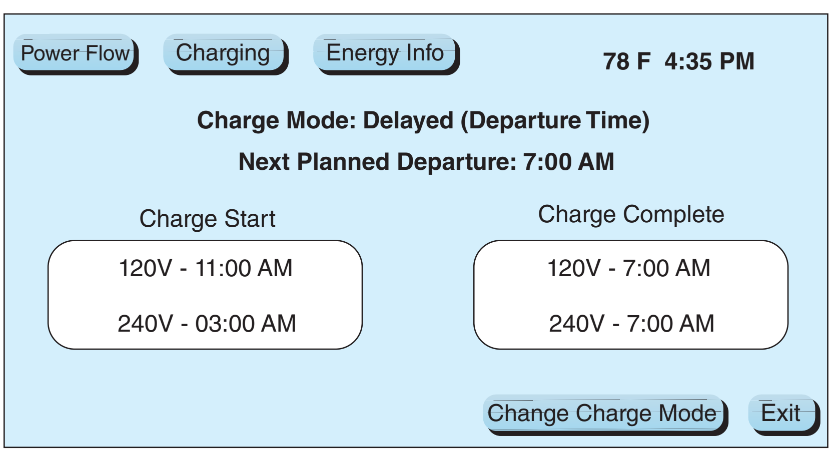

Figure 6-29 The information displayed on the Delayed Rate and Departure Time screen.

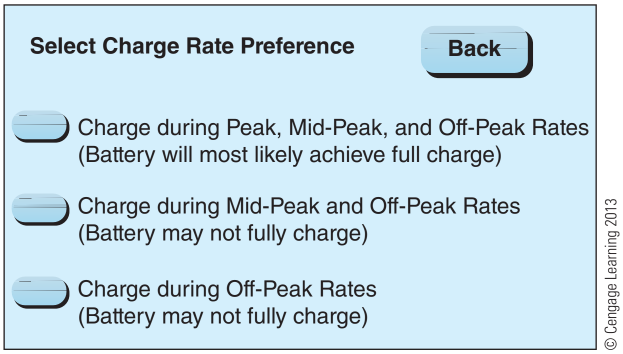

Figure 6-30 The driver's options for selecting preferred charge rates.

used to start another disabled vehicle. Normal safe procedures for jump starting must be adhered to. Basically, jump-starting is connecting cables between the batteries of two vehicles to assist in the starting of one of the vehicles. To jump-start a Volt, the remote positive (+) and negative (−) terminals can be accessed under the hood by opening access covers.

WARNING *The high-voltage battery should not be jump-started either with another vehicle or with a battery charger. Personal injury, death, or damage to the vehicle can result.*

Basic Operation

The Volt has two primary power modes: all battery-electric (charge depleting), in which the battery is the only source of power for the electric motors; and extended range (charge sustaining), in which the battery and engine work together to power the traction motor and to improve overall efficiency. Each of these two power modes is supported by two unique operating modes **(Table 6-4).**

The Volt's drivetrain is a compact unit that includes the engine, motor/generator, planetary gear set, three clutches, the traction motor, and the power electronics unit. The power electronics unit has three insulated gate bipolar transistor (IGBT) inverters: one for each motor, and one for an electric oil pump. The traction

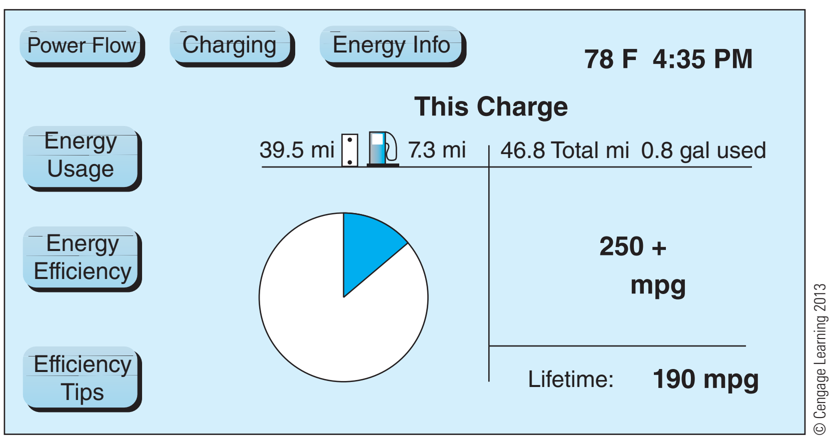

Figure 6-31 The information displayed on the energy usage screen.

TABLE 6-4: AN OVERVIEW OF THE DIFFERENT OPERATING MODES

Power Mode	Charge Status	Operating Mode	Power Source
All-electric	Charge depleting	Low-speed, one motor (MG-B)	Battery
All-electric	Charge depleting	High-speed, two motor (MG-B + MG-A)	Battery
Extended Range	Charge sustaining	Low-speed, one motor (MG-B)	Battery + ICE-driven generator
Extended Range	Charge sustaining	High-speed, two motor (MG-B + MG-A)	Battery + ICE-driven generator; plus supplemental torque from MG-A and ICE

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motor, the motor/generator, and the engine are directly (or indirectly) connected to the planetary gear set. This enables the unit to function as a variable-speed transmission.

The main traction motor (MG-B) is always connected to the sun gear. The ring gear is either being held stationary by a clutch or driven by either the motor/generator (MG-A) or the ICE. The final drive gears (differential) are permanently connected to the planetary carrier; the result is a 2:16 final drive ratio.

The engine and MG-A are only connected to the planetary gear set when the appropriate clutch is applied. The application of the clutches is crucial to the overall efficiency of the drive unit. Two of the clutches are used to either lock the ring gear of the gear set or connect it to MG-A, depending on the operating mode. The third clutch connects the ICE to MG-A to provide an extended driving range. Following is an overview of what takes place during each of the operating modes:

All-Electric, Charge Depleting, Low-Speed, One Motor (Figure 6-32)

In this mode, the ring gear is held (locked to the case) by clutch C1. Clutches C2 and C3 are not applied, therefore MG-A and the ICE are not coupled to the planetary gear set. MG-B is coupled to the sun gear and causes it to spin. With the ring gear locked, power flows from the sun gear to the planetary carrier gears with a speed reduction of 7.0:1. Since the planetary carrier is permanently coupled to the final drive, MG-B propels the vehicle.

All-Electric, Charge Depleting, High-Speed, Two Motors (Figure 6-33)

At about 70 mph, MG-B begins to lose a great deal of efficiency due to its rotational speed. At high speeds, it is consuming a great amount of electrical power and is quite inefficient, especially when considering the low amount of torque required to maintain high vehicle speeds. To improve efficiency, C1 is disengaged, allowing the ring gear to rotate. At the same time, C2 is applied and connects MG-A to the ring gear. MG-A is energized by current from the inverter and runs as a motor. The ICE remains disengaged from the generator-motor. The two motors operating in tandem provide power to move the vehicle. Connecting MG-A to the ring gear allows for an electrically controlled "variable" reaction member in the gear set. By varying the amount of current to MG-A, the speed of the ring gear changes, and the gear set acts as a variable transmission.

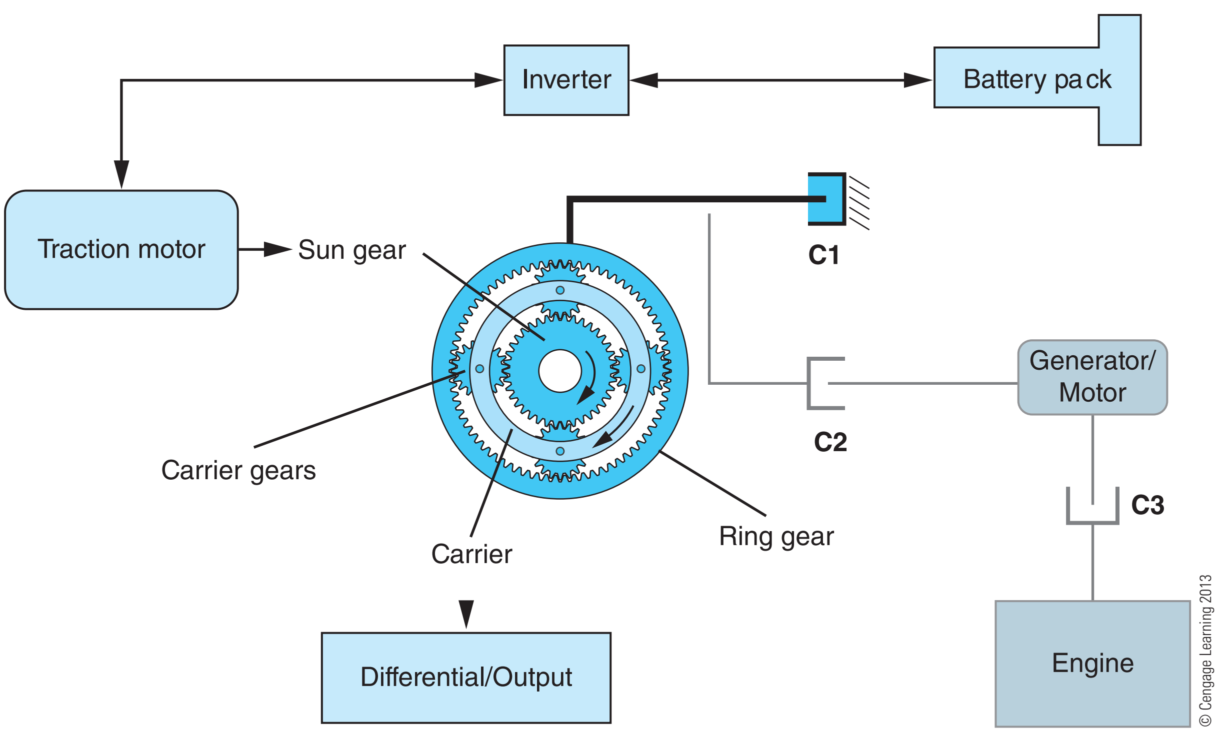

Figure 6-32 Power flow while the Volt is operating in the All-Electric, Charge Depleting, Low-Speed, One Motor mode.

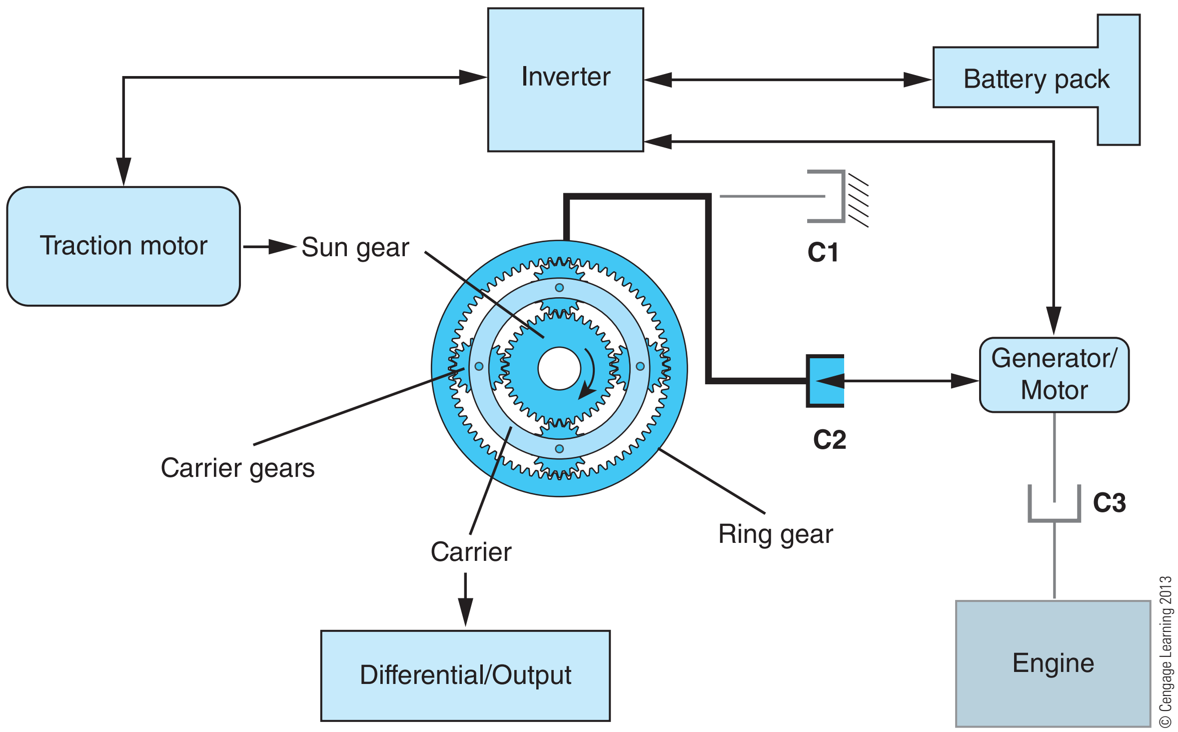

Figure 6-33 Power flow while the Volt is operating in the All-Electric, Charge Depleting, High-Speed, Two Motors mode.

The use of two motors is more efficient than driving with just the larger electric motor running at high speeds. As the speed of MG-A is increased, the speed of MG-B decreases and therefore uses less current. The speed of MG-B in this mode drops to about 3,250 rpm from 6,500 rpm in the one-motor mode. The end result is simply that less current is required to power two motors (one small and one large) operating at low to moderate speeds as compared to a single large motor operating at very high speeds. Thus this is more electrically efficient (by about 10 to 15 percent) and adds about 2 miles to the EV range at these speeds.

Extended Range, Charge Sustaining, Low-Speed, One Motor (Figure 6-34)

Once the pure EV range is depleted (battery at approximately 22 percent SOC) the system moves into the extended range power mode. To switch to this mode, clutch C1 is applied and C2 is disengaged, uncoupling MG-A from the ring gear. Then C3 is applied and electrical power is briefly sent to MG-A to start the ICE. Once the ICE starts, MG-A no longer receives electrical power, and it becomes a generator. The electrical power generated by MG-A is routed directly to MG-B through the system's power electronics. The system will also control the ICE so it runs at the appropriate speed (900–4,400 rpm) to allow MG-A to generate the correct amount of electrical power for the driving conditions. During most conditions, MG-A will provide enough power to maintain minimum battery SOC, and will allow the Volt to remain in the extended range mode until it is plugged in. However during hard acceleration, additional power can be drawn from the battery for short durations.

Extended Range, Charge Sustaining, High-Speed, Two Motors (Figure 6-35)

At high road speeds, MG-B needs to run at a high speed in order to maintain vehicle speed. High motor speeds are inefficient as there is a need for very high current draw. To offset this, the two-motor electric propulsion strategy used in range mode. In this mode, both motors draw electrical power from the battery, and the effective gear ratio of the planetary gear set is numerically lower, which reduces the rotational speed of MG-B.

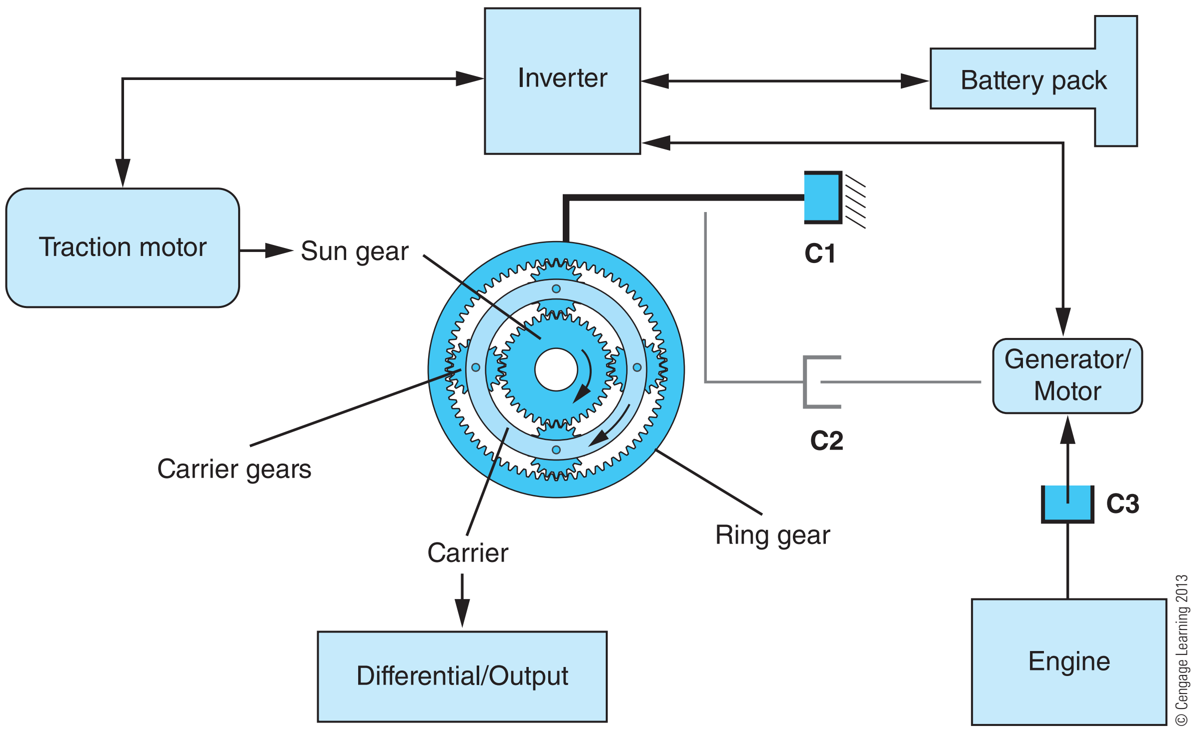

Figure 6-34 Power flow while the Volt is operating in the Extended Range, Charge Sustaining, Low-Speed, One Motor mode.

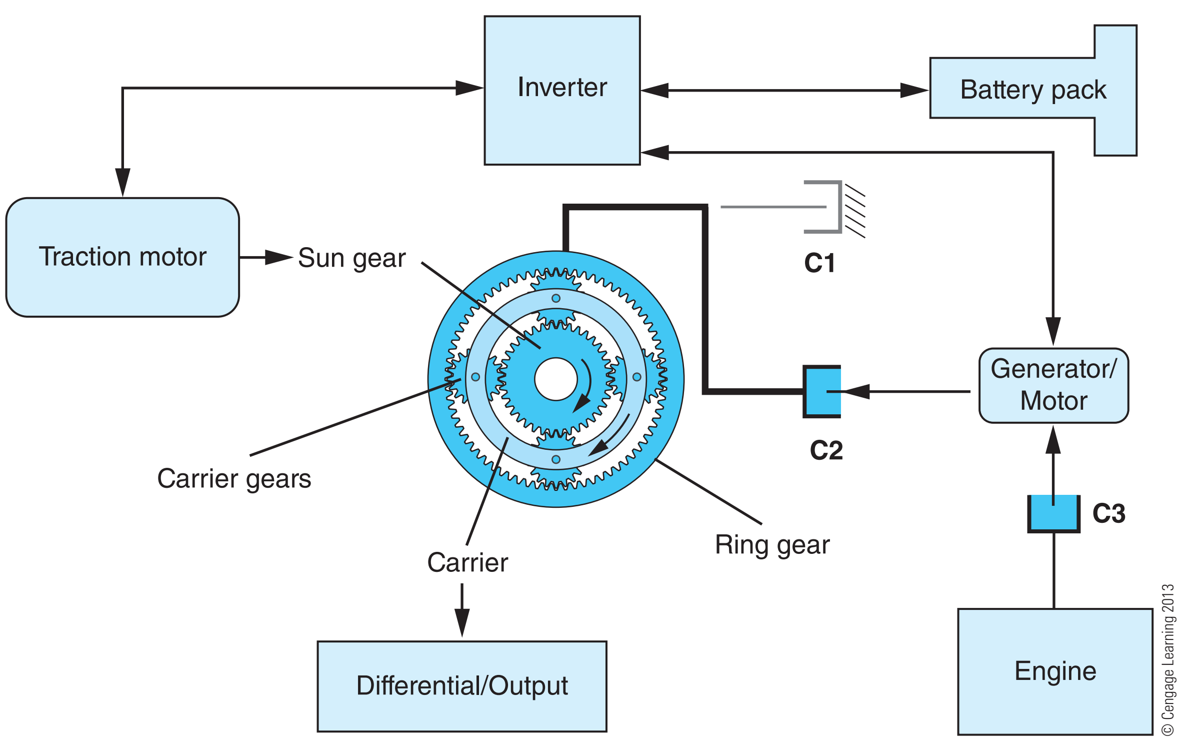

Figure 6-35 Power flow while the Volt is operating in the Extended Range, Charge Sustaining, High-Speed, Two Motors mode.

To do this, the ring gear is released as C1 is disengaged. Then C2 is applied to couple the ring gear with MG-A. C3 remains applied and the engine continues to run. The ICE drives MG-A and supplies torque to the ring gear through the motor/generator. It is important to note that MG-A is acting as a motor, not a generator. Therefore the torque and speed from the engine is assisting MG-A as it rotates the ring gear. This combined mode (MG-A + ICE power) results in the sun gear rotating at a lower speed, and net efficiency improves by nearly 15 percent.

Driver-Selected Operating Modes. The Volt offers the driver three modes to select from: Normal, Sport, and Mountain. The modes are selected by the Drive Mode button on the console **(Figure 6-36)** and the modes are displayed on the DIC. The Normal mode is designed for normal conditions and will achieve the highest efficiency for those conditions. Each time the car is started, it will return to Normal mode. The Sport mode causes the engine to run at a higher speed, and the response to movement of the throttle pedal is quicker. There is little performance gain while operating in this mode, but there is a more responsive feel from the powertrain. The Mountain mode should be selected before climbing steep, uphill grades and when expecting to drive in very hilly or mountainous terrain. This mode increases the minimum battery SOC to around 45 percent to help the Volt maintain performance on steep and long grades. The driver will hear more engine noise when operating in Mountain mode due to the higher rate of power generation required to maintain this mode. Also while in this mode, the car will have less responsive acceleration.

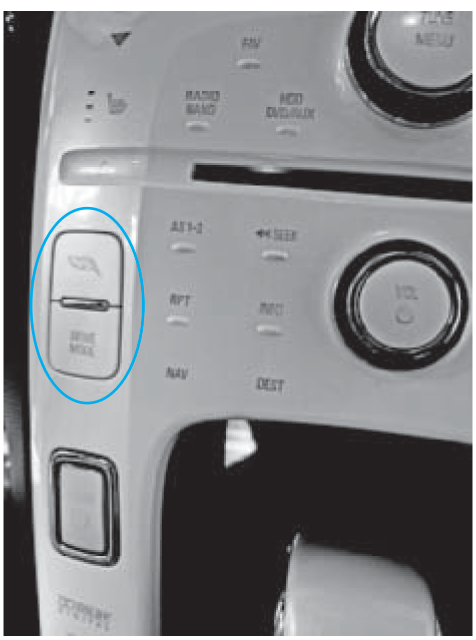

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Figure 6-36 The drive mode switch on the center stack.

Regenerative Braking. The Volt uses regenerative braking to convert kinetic energy to electrical energy. This energy is then stored in the high-voltage battery pack, which helps to increase energy efficiency. When pressure on the accelerator is reduced or the brake pedal is pressed down, MG-B temporarily operates as a generator and restores a portion of the battery's charge. The hydraulic brake system works with regenerative braking to ensure effective and safe braking and deceleration. A control unit interprets the braking request and uses regenerative braking, conventional hydraulic braking, or a combination of both as necessary.

Out of Fuel/Engine Unavailable. If the car runs out of fuel, or if there is a fault that prevents the ICE from starting, the Volt can continue to be driven in EV mode. However, the vehicle will have less responsive acceleration. Driver Information Center (DIC) messages will indicate reduced propulsion power, that the engine is not available, and the need for fuel or service. Once the car is refueled, or the problems are corrected, the engine will start the next time the Volt is turned on to perform a self-test, and DIC messages will not be displayed. Once the engine successfully starts, normal operation will continue in either Electric or Extended Range Mode.

COOLING SYSTEM

The Chevy Volt is equipped with four independent cooling systems or "loops":

- The engine cooling system and heater loop
- The electric drive unit cooling system
- The power electronics cooling system
- The battery cooling system

All four systems have a dedicated radiator and coolant sandwiched together **(Figure 6-38)** and mounted in the traditional location at the front of the engine compartment. The radiators are primarily cooled by air routed from the air dam below the car. There is also a pair of variable-speed, 12V electric cooling fans that provide extra air flow when needed.

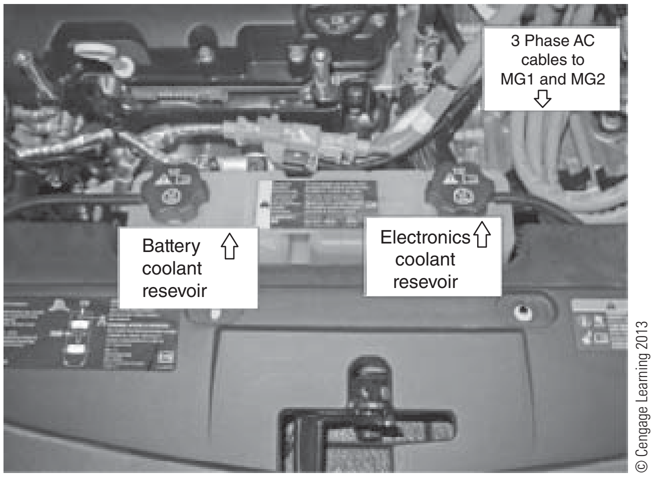

Figure 6-37 The separate coolant reservoir tanks for the battery and the electronics cooling systems.

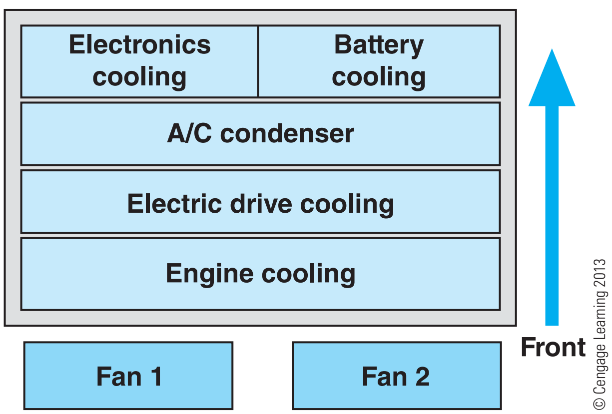

Figure 6-38 The composition of the radiator of a Volt.

Engine Cooling System and Heater Loop

The engine cooling system (and heater loop) uses a radiator, Dex-Cool, two 12V variable-speed radiator fans, a 12V coolant pump, a coolant flow bypass valve, a 360V coolant heater, and a cabin-mounted heater core. When the ICE is running, coolant is circulated through the engine by a belt-driven water pump. A thermostat regulates normal engine operating temperatures, but it can be electrically heated to speed its openi

engine is first started and the thermostat is closed, a hot water bypass line allows heated coolant to flow to the electric pump and heater core. When the thermostat opens, coolant flow is permitted through the radiator.

This entire sequence, as well as the production of heat while the ICE is not running, is controlled by the coolant flow bypass valve. This valve is, in turn, controlled by the Hybrid Powertrain Control Module (HPCM), which monitors the status and temperature of the engine. Its primary function is to ensure the appropriate amount of heat for the passenger compartment and maintain an acceptable engine temperature.

The bypass valve has two positions. When the engine is not running and the car is in the electric-only mode, the valve is commanded to be in its engine bypass mode. Coolant is then circulated, by the electric pump, through the 360V heater and then through the heater core inside the passenger compartment. The amount of current going to the electric heater is controlled to provide the desired amount of heat by using the least amount of electrical energy.

Once the engine starts and warms up, additional heat is available to assist the fan-driven cabin heater. The bypass valve is moved to a position where the coolant loops from the ICE and the electric heater are connected. This connection permits the sharing of coolant between the engine and heater core, and subsequently the 360V heating element (CHCM) power level will be reduced and/or cycled OFF/ON as the engine turns on and off during extended range (charge-sustaining) operation in order to maintain cabin comfort while utilizing the most efficient heat source.

Electric Drive Cooling System

The electric drive cooling and lubrication system is designed to maintain the internal temperature of the transaxle used in the Volt. This drive unit contains a pair of motor/generators that are used to propel the Volt with electric power as well as to generate electricity to replenish the high-voltage battery's SOC. The motor/generator units use and produce great amounts of electrical energy; therefore a considerable amount of heat is generated when they are in operation. Pressurized automatic transmission fluid (Dexron VI®) circulates throughout the drive unit to lubricate all of its gears, bearings, and bushings; to cool the motor/generators and other components; and to create the necessary hydraulic pressure to apply the three multi-disc clutches in the drive unit.

The ATF is pressurized by a three-phase AC pump assembly located inside the transaxle, where there is

the two pumps makes sure that ample fluid pressures and flow are always present whether or not the ICE is running.

From the transaxle, fluid is directed to the transmission fluid heat exchanger mounted between the engine cooling radiator and air conditioning condenser.

The cooling loop is fitted with a fluid bypass device to allow fluid to continue to flow if the car has a restricted cooler.

Power Electronics Cooling Loop

The charger and power electronics modules are cooled with the same Dex-Cool coolant loop. The electronics system's radiator is the upper half of the dual radiator assembly, and is above the high-voltage battery cooling system. The standard plug-in battery charger changes 120-240-volt household AC from the grid into DC, which is necessary to charge the high-voltage battery pack. During this conversion, much heat is produced and if left unchecked, the heat could destroy the battery pack.

The electronics cooling loop is designed to make sure the main electronics in the system do not overheat. This is especially true of the inverter. The inverter module uses IGBTs to convert the DC current from the high-voltage battery pack into three-phase AC. The AC voltage is needed to drive the motor/generators. The IGBTs also convert AC to DC during regenerative braking to recharge the batteries. When IGBTs do their thing, they create a great amount of heat, and that heat must be dissipated before it destroys the transistors.

To dissipate and control the heat, the HPCM controls the electric pump as well as the cooling fans' speeds based on temperature sensors mounted in the radiator. The electronics coolant pump is activated whenever the Volt is turned on and during 120-240-VAC plug-in charging. The 12V pump controls the flow of coolant as it passes through the plug-in battery charger, radiator, power inverter module, and then back to the electric pump. The system also has an air separator to prevent air bubbles from affecting cooling performance, and it also has a surge tank that acts as a coolant reservoir.

High-Voltage Battery Cooling System

The battery cooling system has an independent 12-volt coolant pump, a refrigerant-to-coolant heat exchanger, and a three-way coolant flow control valve. It also has a designated surge tank and radiator. The surge tank is in the same assembly as the electronics reservoir/tank, but they are separate tanks. Likewise, the battery cooling system shares a radiator assembly with

of this is used only for battery cooling.

This system is designed to keep the temperature of the high-voltage battery at an acceptable level when it is being charged and discharged. The battery pack has internal coolant passages that allow coolant to flow over and between the individual battery cells. The cells can be cooled or heated by the flow of coolant in those passages. At the coolant inlet of the battery's housing, there is an inline filter to remove any debris that may be in the coolant.

The temperature of the cells is constantly monitored by the control system. When all sensors indicate that the battery pack's temperature is normal, the three-way flow control valve (operated by the HPCM) directs coolant from the battery pack through the radiator, and then to the 12V electric pump, which sends the coolant through the battery pack. If the temperature of the battery is too low, the flow control valve directs the coolant over a 360V heating element, rather than sending it to the radiator. The element heats the coolant to the desired temperature. If the battery gets too hot, the cooling fans will run at maximum speed. If the temperature continues to rise, the system will activate the electric A/C compressor. The compressor will continue to run until the desired temperature is met. The coolant in the battery will now move through the chiller in the A/C system.

DISABLING A VOLT

The Manual Service Disconnect (MSD) can be removed to isolate the HV battery from the car **(Figure 6-39).** The MSD physically interrupts the high-voltage cables inside the battery. The MSD is located under the center console box. Instructions for removing the MSD are also found there.

First Responder

Explicit instructions are given for the emergency personnel if the Volt has been in an accident. These instructions include what to do to disable power and

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Figure 6-39 The Manual Service Disconnect (MSD) is located under the center console box.

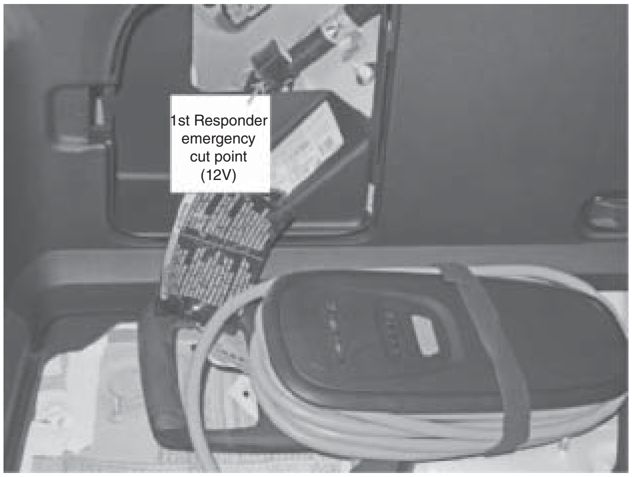

Figure 6-40 The cut line for the 12V system for first responders.

Figure 6-41 A two-door Fisker Karma.

the areas where the car should not be cut to extract someone from inside the car. These areas shield high-voltage cables or components or shield air bags and other safety devices.

The First Responder cable cut tag is wrapped around the low-voltage positive battery cable and is located in the rear compartment behind the fuse panel door. To help ensure that low voltage is not holding the high-voltage contactors closed, cut the cable before any extrication work is performed. The cable cut tag is yellow and wraps around the low-voltage positive cable to indicate where emergency personnel must cut the cable **(Figure 6-40).**

FISKER

Henrik Fisker and Bernhard Koehler founded Fisker Automotive, a manufacturer which introduced the world's first luxury hybrid electric vehicle, the Fisker Karma **(Figure 6-41).** The 2012 Fisker Karma in electric-only mode is rated by the EPA at a combined 52 MPGe.

In electric-only mode, the Karma will travel about 32 miles, according to the EPA. Fisker, however, still claims that range is at least 50 miles. In the range-extender mode, the Karma is rated at 20 mpg.

The Karma is a series hybrid with two electric motors

in front of the limited-slip differential and the other behind it. The Karma has two 201-HP, liquid-cooled permanent-magnet AC motors with a maximum torque of 981 ft.-lb and 402 HP. The car is fitted with a single-speed transmission. A new model, the Karma Surf, is basically a station wagon and relies on the battery pack and gasoline engine used in other Karma models.

After the pure EV driving mode and when the battery reaches a 15 percent SOC, the car automatically switches to the range-extender mode. A direct-injected, turbocharged four-cylinder engine rated at 260 HP is used to drive a 235-HP generator, which provides power for the electric motor. The ICE can support the electric motors for about another 250 miles. Since the car has a 9.5-gallon gas tank, the car has a total driving range of 300 miles.

The Karma is equipped with a 600-pound, 20-kWh lithium-ion nanophosphate battery pack mounted lengthwise in the center of the car. The battery pack also serves as a structural member for the car. This battery design allows for very wide SOC operation and should have a life of 10 years or 100,000 miles (160,000 km) under normal use.

Driver-Selected Operating Modes

The Karma offers the choice of two driver-selected operating modes: Stealth and Sport. In Stealth mode, the Karma is programmed to enhance the overall efficiency and extend the range of the car. This mode allows the car to operate initially in the EV mode and when the battery is depleted, it moves into the extended range mode.

To take advantage of the 402 HP available from the motors, the driver can select out of the Stealth mode and into the Sport mode by tapping the left

modules use both the energy in the battery and the output of the generator to send power to the motors. In the Sport mode the system supplies the motors with all of the available energy from the battery and generator. In the Sport mode, the motors can supply up to 981 ft.-lb of torque and allow the car to accelerate

from 0 to 60 mph in 6.3 seconds, with a top speed of 125 mph.

The Karma also has a Hill mode that provides enhanced brake regeneration during extended coasting and downhill driving. In this mode, the car uses the drag of the engine to help the car slow down and stop, while charging the battery by capturing the car's kinetic energy. This mode is engaged by moving the right-hand steering wheel paddle in varying amounts. This captures kinetic energy during deceleration.

Battery Charging

The Karma comes with a standard 110V convenience charger. There is also an optional 220/240V high-voltage charging station that can be installed in a home or workplace. Actual charge times vary with the battery's remaining charge and whether 110V or 220V is used. It typically takes 14 hours to recharge the battery with 110V and 12 amps, and only 6 hours when 220V at 12 amps is used.

Solar Roof. Karmas have a solar glass roof designed to extend the driving range an additional 200 miles (depending on climate conditions) annually.

Driver Controls. To keep things simple, the Karma has only four buttons in the dash to control its various features. In addition to the operating mode switch (which includes the START/STOP switch), there is a button for central locking, hazard lights, and electric glove box release. All of the choices are displayed on a 10.2-inch touch screen Command Center **(Figure 6-42).**

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Figure 6-42 The instrument assembly for a Fisker Karma.

PLUG-IN HYBRIDS

Plug-in hybrid electric vehicles (PHEVs) are full hybrids with larger batteries and the ability to recharge from an electric power grid. They are equipped with a power socket that allows the batteries to be recharged when the engine is not running. The socket can be plugged into a normal 110-volt outlet. Charged overnight, PHEVs can drive up to 60 miles without the engine ever turning on. When the batteries run low, the engine starts and powers the vehicle and the generator to charge the batteries.

The biggest advantage of plug-in hybrids is that they can be driven in an electric-only mode for a much greater distance. During that time, the vehicle consumes no fuel. Under normal conditions, a plug-in hybrid can be twice as fuel-efficient as a regular hybrid. A fully charged PHEV will produce half the emissions of a normal HEV. This is simply due to the fact there are no emissions when the engine is not running. **Table 6-5** compares the various hybrid configurations and the resultant fuel economy.

The manufacturing costs of a PHEV are about 20 percent higher than a regular HEV. The increase in cost is mainly due to the price of the larger batteries. Of course, as battery technology advances and more high-tech batteries are produced, the cost will decrease. It is projected that consumers will accept PHEVs because they have a driving range that is equal to or greater than that of a conventional vehicle with very low emissions and improved fuel economy.

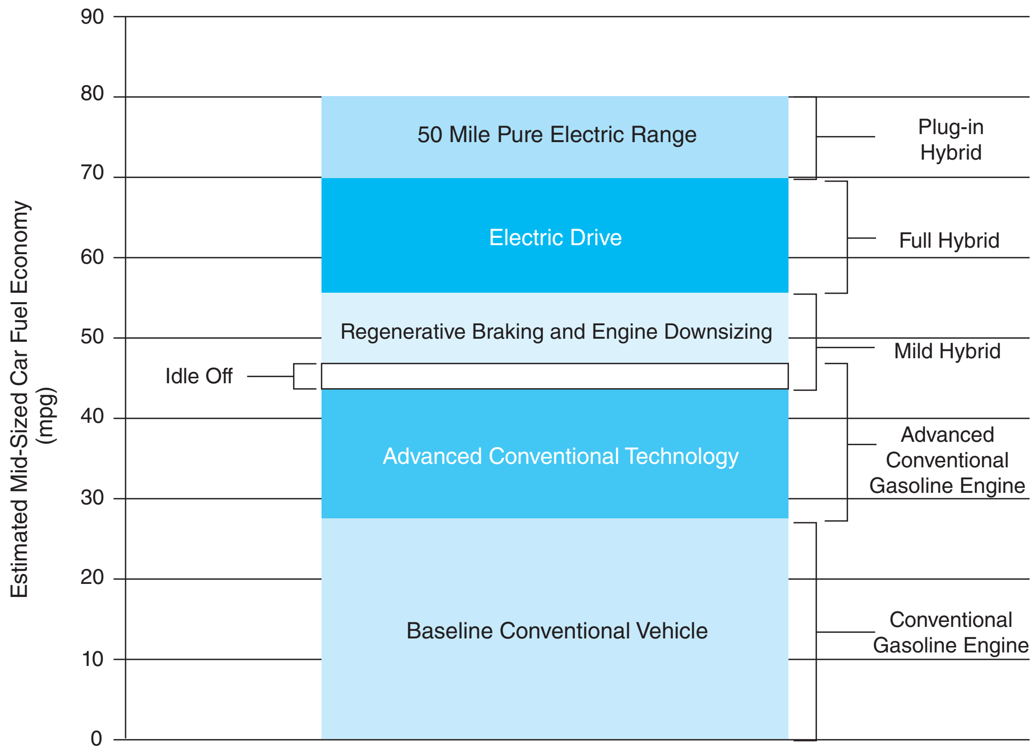
Note: Hybrid fuel economy levels assume specific engine and battery motor sizing in a mid-sized vehicle parallel hybrid driveline configuration. Altering that sizing, the driveline configuration, or the vehicle type will affect the fuel economy to some degree. This should only be used as a general guide.

Mercedes-Benz Sprinter

Mercedes-Benz has built a Sprinter equipped with a diesel engine and an electric motor. This utility van is

tween the transmission and clutch. The motor uses energy from a nickel-metal hydride (NiMH) battery pack and has an electric-only driving range of up to 20 miles (30 km). The battery requires approximately six hours recharging when plugged into a conventional

TABLE 6-5: 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.

electrical outlet. The battery is also recharged by the engine and through regenerative braking.

HYDRAULIC HYBRIDS

Hydraulic hybrids function in the same way as hybrid electric vehicles, except energy for the alternative power source is stored in tanks of hydraulic fluid under pressure rather than in batteries. Also, rather than being fitted with an electric motor, these vehicles have a hydraulic propulsion system, which can power the vehicle by itself.

The SHEP (Stored Hydraulic Energy Propulsion) system captures energy during braking and uses that energy when the vehicle is accelerating from a stop. Like
a large percentage of the energy normally lost during braking. That energy is stored in hydraulic tanks attached to the vehicle's chassis **(Figure 6-43).** The system also aids in the halting of the vehicle. When the brake pedal is depressed, the control unit opens solenoids that send fluid from the low-pressure tank to the pump at the driveshaft. As the driveshaft turns, it turns the pump, and fluid pressure increases. This causes the pump and driveshaft to slow down. The fluid under pressure now moves to the high-pressure tank for storage.

During acceleration, the system's computer instructs the pump to send the stored high-pressure fluid back to the driveshaft and to the low-pressure tank. At this point, the vehicle moves without power from the engine and without burning any fuel. Once the computer senses that the energy stored in the tanks has been used, the engine will start and take over the operation of the vehicle. The energy is restored in the tanks during the next brake application.

The basic components of the hybrid propulsion system **(Figure 6-44)** are:

- Hydraulic Storage: Two hydraulic tanks (accumulators) are installed under the vehicle to store the kinetic energy captured during braking. One tank stores high pressure fluid and the other serves as a reservoir for low pressure fluid.

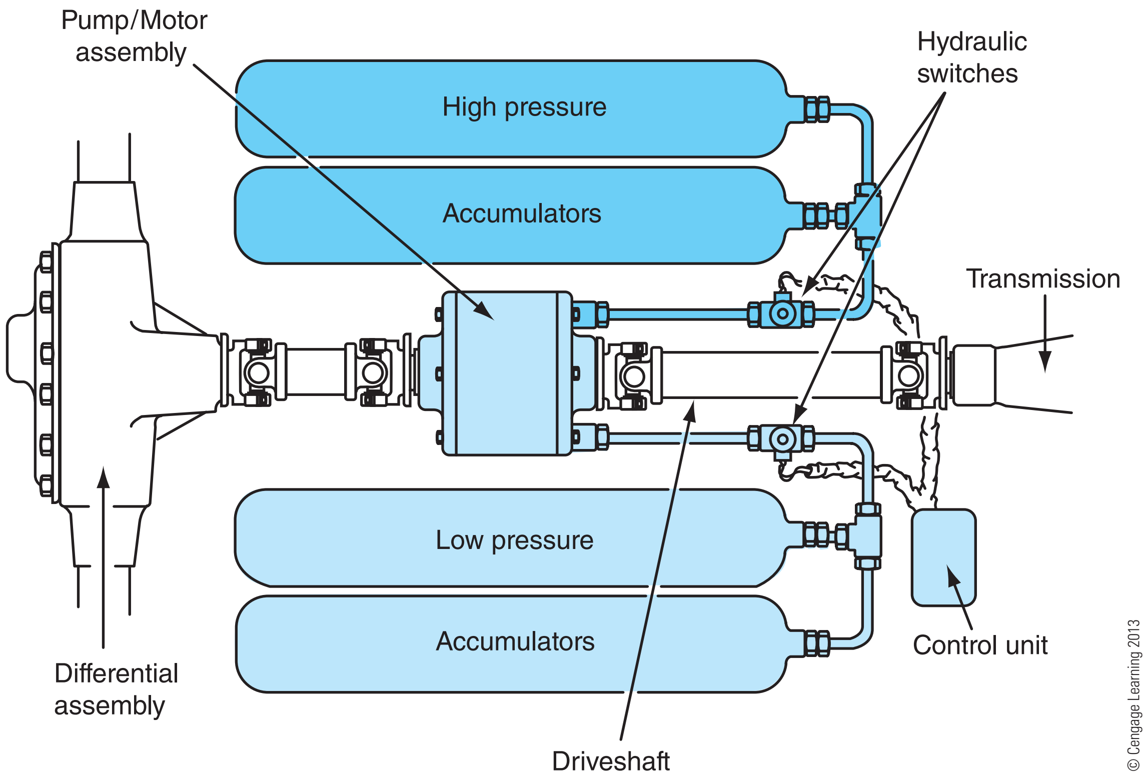


Figure 6-43 The layout of a full series hydraulic hybrid in an urban delivery vehicle.

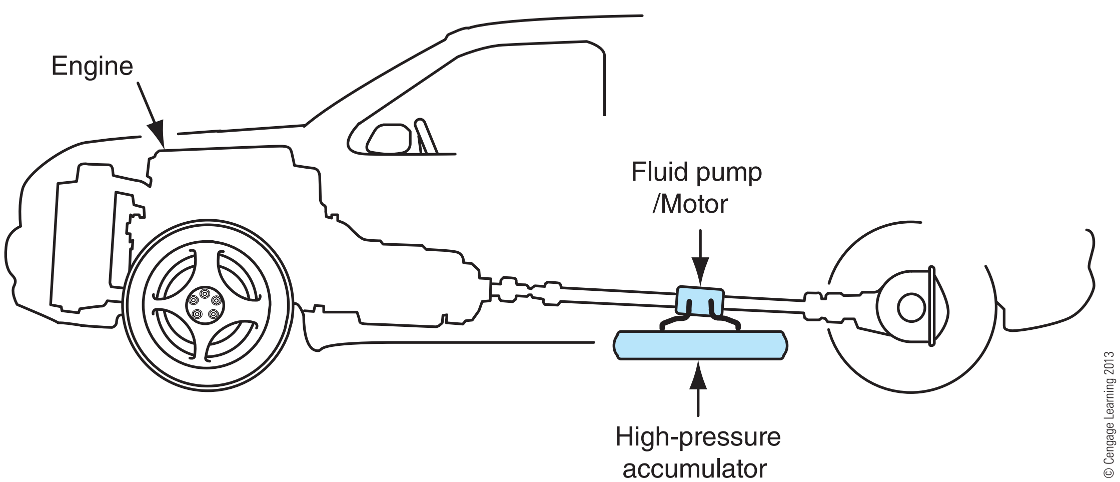


Figure 6-44 The location of the major components of a hydraulic hybrid system.

- Pump/Motor Assembly: A variable-displacement hydraulic pump is used to transfer the energy stored in the tanks to the vehicle's drive shaft. This also serves as a motor to rotate the drive shaft and a pump that transfers high-pressure fluid to the storage tank.
- Electronic Control System: Monitors and controls the entire system.

Hydraulic hybrid technology is being developed for use in heavy vehicles like buses, trucks, and military vehicles. Currently, the United Parcel Service (UPS) is experimenting with this technology in its delivery vehicles. It is projected that hydraulic hybrids will use 60 to 70 percent less fuel than conventional delivery vehicles. The trucks will also have lower emissions because the engine is not used during acceleration.

Review Questions

1. Where is the Manual Service Disconnect (MSD) of a Volt located?
   A. Under the hood next to the inverter
   B. In the rear luggage compartment with the charger
   C. In the center console box
   D. In the rearmost section of the battery pack

2. Describe the importance of electronics in the operation of a hybrid vehicle.

3. Explain why a hybrid vehicle is more efficient than a vehicle powered only by an internal combustion engine.

4. Which of the following statements is NOT true about stop-start systems?
   A. Only mild hybrids are equipped with this feature.
   B. Stop-start systems automatically shut down the engine when the driver applies the brakes and brings the vehicle to a complete stop.
   C. The engine is restarted automatically when the driver releases the brake pedal or when the hybrid control system senses the need.
   D. Most mild hybrids have a belt-driven starter-generator that restarts the engine when necessary.

5. Describe the basic difference between series and parallel hybrid configurations.

6. Explain how the battery pack of a Volt is cooled when its temperature increases too much.

7. Explain why hybrid vehicles are more expensive to manufacture.

8. Describe the basic operation of a hydraulic hybrid.

9. Explain how regenerative brakes work.

10. Describe the primary advantage of plug-in hybrid vehicles.

CHAPTER

7 Mild and Assist Hybrids

Learning Objectives

After reading and studying this chapter, you should be able to:

- Describe the difference between a mild and an assist hybrid.
- Identify the advantages of the stop-start feature in hybrids.
- Describe the operation of an integrated starter alternator flywheel-mounted hybrid system.
- Explain how a belt alternator starter system works.
- Describe the basic operation of GM's eAssist system.
- Explain why high voltage is needed in assist-type hybrids.
- Describe the basic operation of the hybrid system used in Honda's Insight.
- Describe the differences between the first, second, and third generations of Honda's IMA system.
- Describe the basic electronic control system used in Honda's hybrids.
- Explain the advantages and disadvantages of using a lean-burn engine.
- Describe the operation of a cylinder idling system.

Key Terms

Active Control Engine Mount (ACM)
Active Noise Control (ANC)
assist hybrids
battery condition monitor (BCM)
belt alternator/starter (BAS)
continuously transmission (CVT)
cylinder idling system
electro-hydraulic power steering (EHPS)
integrated motor assist (IMA)
integrated starter alternator damper (ISAD)
intelligent-Dual & Sequential Ignition (i-DSI) system
intelligent power unit (IPU)
Recovery System)
linear air-fuel (LAF) sensor
mild hybrid
motor control module (MCM)
motor power inverter (MPI)
nitrogen-oxide-adsorptive catalytic converter
PCU (power control unit)
Variable Cylinder Management (VCM)
variable valve timing and lift control for economy (VTEC-E)

INTRODUCTION

This chapter covers the common hybrid designs that are not considered "full" hybrids. The two primary classifications of these less-than-full designs are mild and assist hybrids. Although some would move some assist designs into the mild category, this chapter will refer to all hybrids that do not have the ability to use the electric motor in propulsion as mild hybrids. (Some call mild hybrids "micro" hybrids.) The discussion of assist hybrids includes those hybrids that use an electric motor to assist the engine but do not have the ability to move the vehicle solely by battery power **(Table 7-1).**

Nearly all **mild hybrid** vehicles are fitted with a flywheel/alternator/starter or a belt-driven alternator/starter hybrid system. These systems provide for stop-start. Strong motors are used to spin the engine fast enough to provide for quick engine restarts. Because most of the vehicle's accessories are powered by the energy stored in the battery, they continue to run when the engine is off. Regenerative braking is also used to supplement the recharging capability of the generator. Fuel consumption is decreased because the engine does not run when it is not needed.

Assist hybrids typically have an electrical motor connected in series with the engine. The motor adds power to the output of the engine when needed. When the motor is not assisting the engine, it may serve as a generator. The motor also provides for stop-start. Fuel consumption is decreased because of the stop-start feature and, with the assist of the motor, smaller and more efficient engines are used.

Stop-Start

A stop-start system turns the engine off when the vehicle comes to a complete stop. The moment the driver lifts his or her foot off the brake pedal, the engine restarts. Since the engine is not running, fuel is not being burned. The effect stop-start systems have on fuel consumption varies, but in all cases there is a significant fuel savings.

All hybrids have some sort of stop-start operation. The components that allow for this are determined by the type of hybrid the vehicle is and the manufacturer. Generally, stop-start systems require new software for the engine control system, a more powerful battery, a powerful starter, various sensors, and an electric auxiliary water pump.

Stop-start systems are not limited to just hybrid vehicles. To reduce fuel consumption, manufacturers are installing these systems on their nonhybrid vehicles. The converted vehicles will not have regenerative braking and will require less complex systems.

TABLE 7-1: COMPARISON OF TYPICAL MILD AND ASSIST HYBRIDS

Feature	Mild Hybrid	Assist Hybrid
Stop-start	Yes	Yes
Motor/generator	Yes	Yes
Regenerative		
Engine assist	No	Yes
Pure electric driving	No	No
Typical system voltage	42V	144V
Average fuel savings	10%	20%

FLYWHEEL/ALTERNATOR/STARTER HYBRID SYSTEM

The flywheel/alternator/starter assembly replaces the starter and generator used on a conventional engine. The assembly is sometimes called an **integrated starter alternator damper (ISAD)**. In most applications, the ISAD is positioned between the engine and the transmission **(Figure 7-1),** although it can be mounted to the side of the transmission.

The compact assembly does not require the very high voltages required by other hybrid systems. Most ISAD systems rely on 42-volt power sources. The ISAD allows for regenerative braking.

General Motors

In 2005 and 2006, General Motors Corp. offered a hybrid model of their Chevrolet Silverado and GMC

Courtesy of Continental Automotive Systems

Figure 7-1 An ISAD assembly.

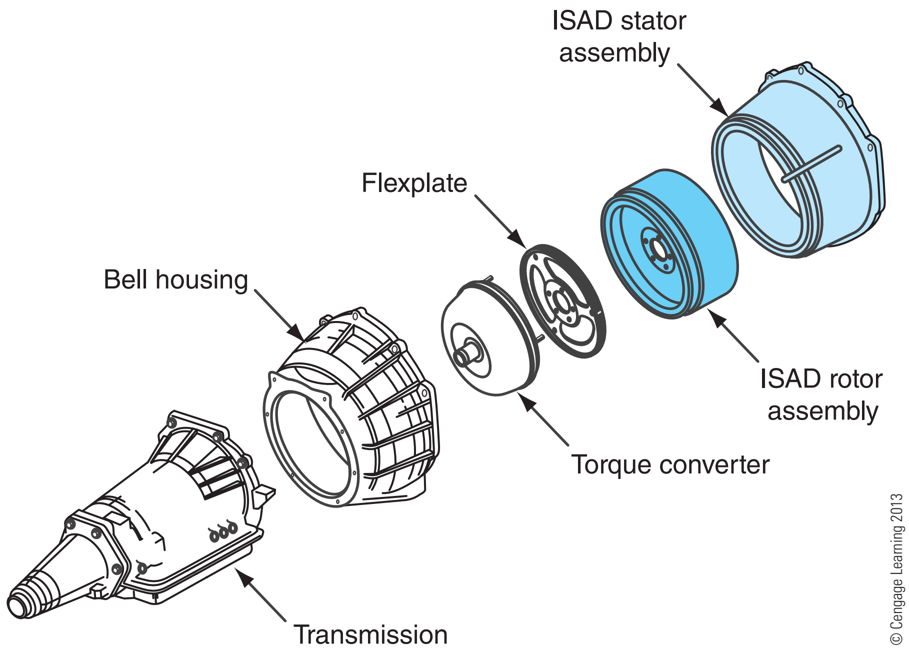


Figure 7-2 The main components of an ISAD assembly.

Sierra full-sized pickup trucks. These were equipped with an ISAD system. The system was designed to provide:

- Quick and quiet engine starting
- Stop-start technology
- Damping of driveline vibrations
- Charging voltages for the batteries
- Regenerative braking
- Generation of electricity for auxiliary electrical outlets

The ISAD system replaced the conventional starter, generator, and flywheel with an electronically controlled compact AC asynchronous induction motor. This unit was housed in the transmission's bell housing. The stator of the starter/generator was mounted to the engine block and the rotor was attached to the end of the engine's crankshaft **(Figure 7-2).** As the crankshaft rotated, so did the rotor, and vice versa. When the unit was operating as a motor, current was sent to the stator. When it was functioning as a generator, current flowed from the stator. As a generator, the unit provided up to 14,000 watts of continuous electric power.

The electricity generated by the system was used to recharge the 12- and 42-volt battery packs, both of which were used to power the various vehicle systems. The electricity could also be used to run power tools or home appliances **(Figure 7-3).** These trucks had four 120V, 20-amp AC power outlets. The auxiliary outlets could power up to four accessories while driving or

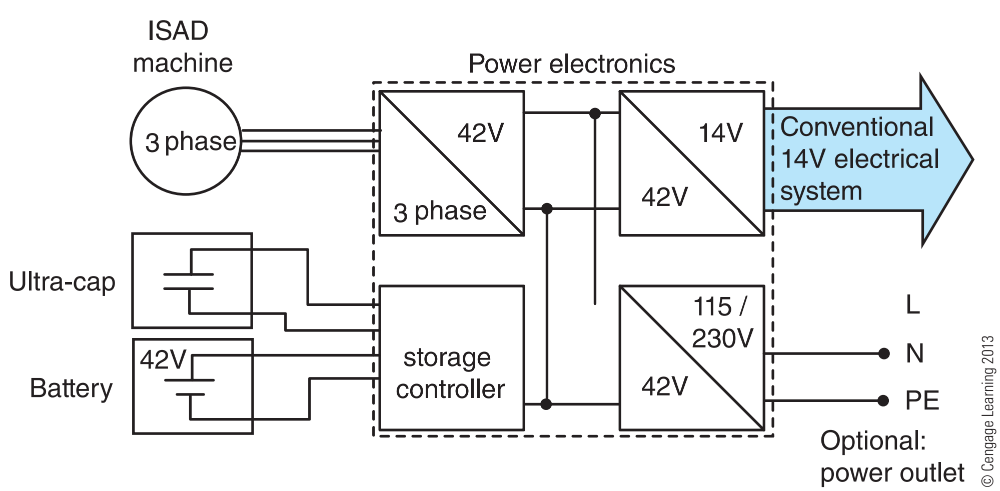


Figure 7-3 A simplified electrical circuit for an ISAD system.

when the vehicle was parked, as long as the engine was running. It was claimed the generators could power tools or appliances for up to 32 hours on a full tank of gasoline. When providing electrical power, the system was designed to turn the engine off when the fuel level got low. This feature allowed the vehicle to be driven somewhere to be refueled. All power supply circuits were protected by circuit protection devices and a ground fault detection system in case of overloads and short circuits.

The overall performance of the trucks was the same as that of nonhybrid models. The Silverado and Sierra had the same 5.3L Vortec V8 engine and four-speed automatic transmission. Because the electric motor provided no power assist, their power output ratings were also identical. This meant these hybrid trucks had the same towing capacity and payload ratings as a conventional pickup.

As with most hybrids, the reduction in fuel consumption of the hybrid pickup was mostly noticeable during city driving. The Environmental Protection Agency (EPA) mileage ratings for a Sierra 4WD hybrid with an automatic transmission were 17 mpg city and 19 mpg highway. The ratings for a similar nonhybrid model were 15 mpg city and 18 mpg highway. This amounted to an approximate gain of 12 percent during city driving.

This hybrid system improved fuel economy and reduced emissions. It allowed for regenerative braking, which decreased the recharging duties of the generator. That, in turn, decreased the load the generator put on the engine. The major contributor to fuel efficiency was the stop-start feature. An additional feature to save fuel was the shutdown of the engine's fuel injection system whenever the vehicle was coasting, decelerating, or braking.

The transmission in the hybrid models was slightly modified to meet the demands of the system. The torque converter was smaller and had a stronger lockup clutch. The transmission was also fitted with a stronger input shaft and an auxiliary oil pump. The pump provided for sufficient line pressure in the transmission when the engine was restarted during the stop-start sequence.

Batteries. Energy for ISAD was stored in three 12-volt valve-regulated lead-acid or AGM batteries. These batte

system and the starter/generator. A conventional 12-volt battery supplied the power for all other electrical items, such as lighting, wipers, and sound systems.

Control Module. A starter/generator control module controlled the flow of electricity in and out of the starter/generator. In doing so, it controlled the operation of the hybrid system and the power module. The power module was responsible for all electrical conversion and inversion processes: 42-volt DC was converted to AC for starting, and the AC was converted to 42-volt DC for recharging. The module also converted 42-volt DC power to 12-volt DC to charge the under-hood battery; 12-volt DC power was converted to 42-volt AC for jump-starting; and 42-volt AC power was converted to 120-volt AC for use at the electrical outlets.

Accessories. To maintain the operation of accessories and auxiliary equipment when the engine was shut off during stop-start, many accessories were powered by the 42-volt battery pack. When the engine was off during stop-start, an electric pump continued to circulate hot water through the heating system during cold weather; in warm weather, cold, dry air was moved through the vehicle's ventilation system. Power steering was provided by an electrically driven hydraulic pump. The **electro-hydraulic power steering (EHPS)** system operated whether the engine was running or not, and it provided fluid under pressure for the Hydroboost power brake system.

BELT ALTERNATOR/STARTER HYBRID SYSTEM

A **belt alternator/starter (BAS)** system **(Figure 7-4)** replaces the traditional starter and generator in a conventional vehicle. The unit is located where the generator would normally be, and is connected to the engine's crankshaft by a drive belt. This unit serves as the starting motor and generator. When the engine is running, a drive belt spins the rotor of the motor/generator and the motor/generator acts as a generator to charge the batteries. To start the engine, the motor/generator's rotor spins and moves the drive belt, which in turn cranks the engine. These systems can provide stop-start, regenerative braking, and high-voltage generation.

A typical BAS includes the motor/generator, electronic controls, and a 42-volt battery. The ability to start the engine quietly and quickly is important to the operation of the stop-start feature; therefore the system

permanent magnet or an induction motor. The required electronic controls for the system depend on the type of motor used. Some systems are also equipped with a conventional starting motor. These are used during extremely cold temperatures. Once the engine is warm, the BAS takes over.

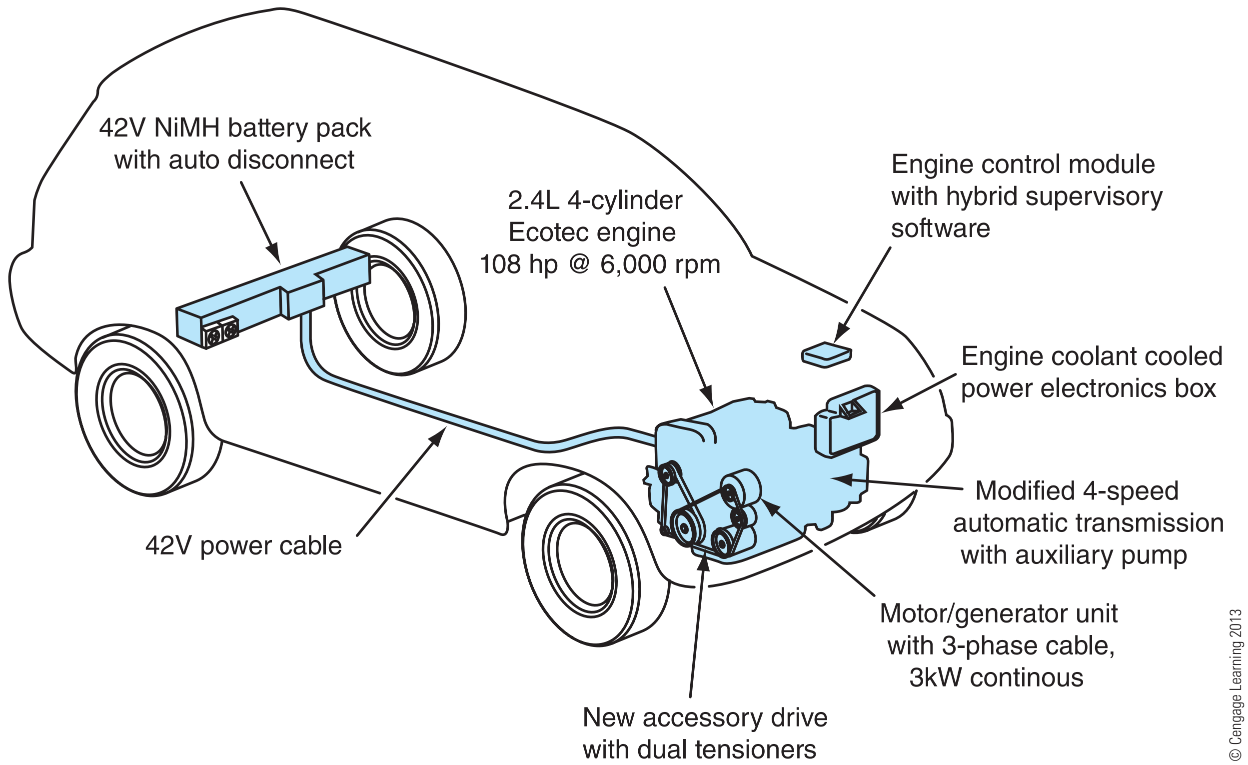


Figure 7-4 GM's BAS hybrid system and key components.

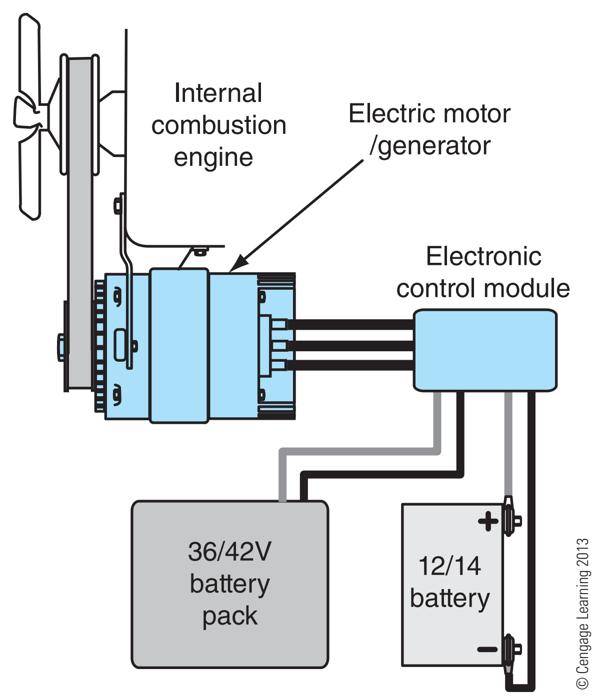
General Motors

GM used the BAS hybrid system in 2006 through 2008 in some Saturn models and the 2009 through 2010 Chevrolet Malibu. The stop-start feature should result in an 8 to 10 percent fuel economy improvement in city traffic, and lower emissions.

The system is based on a dual-voltage architecture of 42V/14V (36V/12V). 42 volts represent three 12V batteries. Engineers decided to take advantage of the fact that a 12-volt battery receives a 14-volt charge (3 times 14V equals 42V). The 42-volt NiMH battery pack provides power for the motor/generator and some accessories **(Figure 7-5),** whereas the traditional 12-volt battery powers typical auxiliary devices, such as lights. The system's electronic circuitry monitors many vehicle operating conditions and controls the operation of the motor/generator and the engine. The electronics must synchronize the activity of the motor/generator with engine systems, such as the fuel injection system. Without precise control, early fuel shutoff during

possible. Nor could there be regenerative braking.

When working as a generator, the electric motor/generator provides more than twice the output of a typical generator. It is capable of providing 3,000 watts of continuous power. The generator's output of 42 volts of AC is converted to 42 volts of DC and is used to



system.

charge the battery pack. A DC/DC converter is used to convert the 42-volt output to 14 volts to charge the conventional 12-volt battery and power most of the vehicle's electrical accessories. An inverter takes

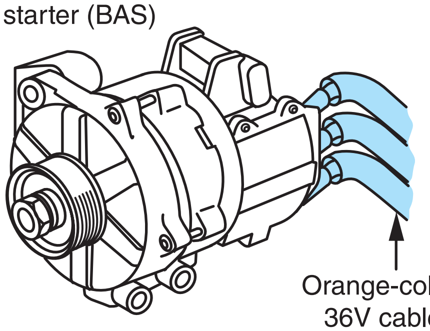


Figure 7-6 The connections at the rear of an early GM BAS.

the 42 volts of DC from the batteries and converts it to 42 volts of AC to power the motor.

On the rear of the BAS unit are three large orange cables that carry the 42 volts to the battery pack **(Figure 7-6).** The BAS's output is controlled by two modules: a main generator control module and an auxiliary control module. The generator control module converts the generator's three-phase, 42-volt AC output to 42 DC volts to keep the hybrid battery charged. In the stop-start mode, the generator module also converts 42 volts DC from the hybrid battery back to 42 volts AC when the BAS unit requires power to restart the engine.

The auxiliary control module operates in the same way as a conventional voltage regulator. It also converts the alternator's 42V AC output to 12 volts DC. The output from the auxiliary module is used to meet the vehicle's electrical needs and to maintain the charge of the regular 12V.

The generator control module can get very hot, and excessive heat can destroy it. Therefore it must be kept cool, and it has a separate coolant pump to keep engine coolant circulating through the module when the engine is off during stop-start. That pump shares an electrical circuit with a second electric pump that keeps coolant circulating through the heater core when the engine is off and the vehicle is in the stop-start mode. Power for both pumps is controlled by the generator module.

A third pump is used to keep transmission fluid circulating in the transmission when the engine is off during stop-start. This pump is controlled by a separate transmission fluid pump control module.

ASSIST HYBRIDS

Assist hybrids use an engine as the primary source of power for propulsion. An electric motor is used to add torque to the engine's output, when extra power is needed. When the motor is not assisting the engine, it works as a generator to charge the batteries and power some of the electronic systems. The motor also provides for stop-start. The motor never powers the vehicle on its own; therefore, these hybrids are fitted with lower-voltage systems than full hybrids.

Honda's hybrids are the most common assist hybrids on the road today; however, many late-model Hondas are full hybrids. Many different manufacturers are developing assist hybrids. Nearly all of them are using either a belt-driven motor/generator or an integrated motor/generator positioned between engine and transmission. An ISAD system is very similar to Honda's Integrated Motor Assist (IMA) system. Honda introduced the basic concept of placing an electric motor between the engine and transmission, and many variations of their design have been developed.

DaimlerChrysler

DaimlerChrysler made available to fleet customers a diesel hybrid Dodge Ram pickup called the "Contractor Special." This hybrid was built on a conventional heavy-duty chassis, and it used a diesel engine fitted with the ISAD system. The ISAD system provided stop-start and was able assist the engine during acceleration and other times of heavy loads. The ISAD unit also served as a generator when the engine was running and when the vehicle was coasting or braking. The electric motor could assist the engine, but it could not propel the vehicle on its own.

The basic system was similar to that in the GM hybrid trucks, except for the use of a diesel engine. The Ram HEV, like GM's hybrid pickups, offered the capacity of serving as a generator to power tools and appliances through 110/220-volt AC outlets **(Figure 7-7).**

Figure 7-7 Dodge Ram HEV concept vehicle electric power access.

In addition, the basic electrical architecture of the truck was a dual-voltage system using 42 volts for the ISAD system and some accessories, and a separate 12-volt battery for other accessories and devices.

Because fuel economy is a major reason why consumers buy hybrid vehicles, the Ram hybrid with a diesel engine should have been popular. However, this was not the case. Although, a diesel engine tends to be more fuel efficient than a comparable gasoline engine, many things about a diesel affected sales (noise, smell, etc.). DaimlerChrysler estimated that the Ram hybrid would use 15 percent less fuel than a nonhybrid diesel Ram truck. The engine, in both cases, was a Cummins 325-horsepower (242.5 kW), 5.9L turbo-diesel engine with 600 ft.-lb (813.4 Nm) of torque.

These trucks are longer available, and the company known as DaimlerChrysler no longer exists. In a very short period of time, Chrysler separated from Daimler and became an independent car company that went bankrupt, and then was purchased by Fiat. With Fiat's presence in Europe and its available cash for research, there will soon be more hybrid Chrysler products.

General Motors eAssist

eAssist is offered on many late-model GM cars. The system is based on previously used BAS systems. This new system is more powerful and provides stop-start, additional torque to the driveline during heavy loads, and regenerative braking. The result of these features is a nearly 25 percent increase in fuel economy. The availability of added torque from the BAS unit allows the cars to use a smaller engine, which also decreases fuel consumption. Typically, the BAS unit is fitted to a 2.4L, direct-injected four-cylinder engine, rated at 182HP and 172 ft.-lb.

The BAS is connected by a drive belt to the engine's crankshaft. The BAS unit is a three-phase AC induction motor that is connected to a 115-volt lithium-ion battery **(Figure 7-8).** The motor can provide an 11-kW (15HP and 79 ft.-lb) boost during acceleration. It can also recover 15 kW of electricity through regenerative braking to charge the battery.

The air-cooled 0.5 kWh lithium-ion battery and its electronic controllers, along with a conventional 12V battery, are housed in a single 65-pound unit behind the rear

provides the power for the BAS unit so that it can assist the engine when the car is accelerating and provide power to the stop-start system. The separate starter battery is a traditional 12-volt lead-acid unit.

When the car comes to a complete stop, fuel delivery is shut down and the BAS brakes the engine to

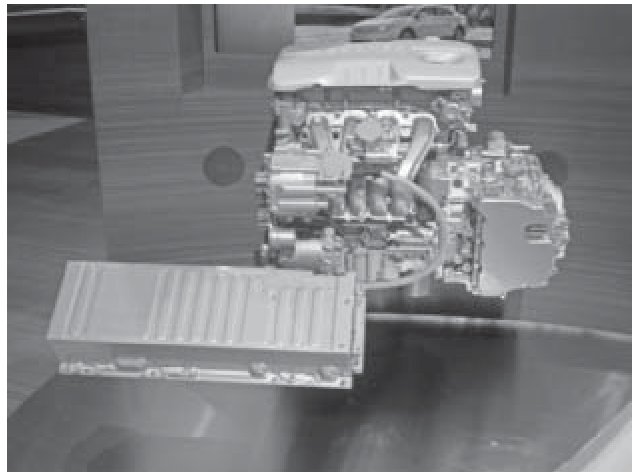


Figure 7-8 The main components of a GM eAssist system.

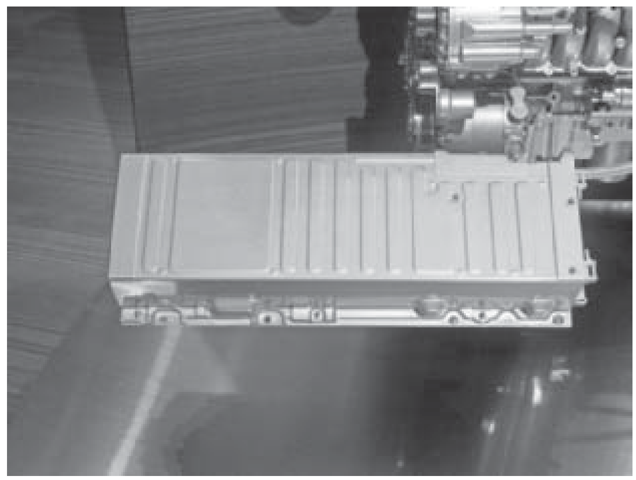


Figure 7-9 The battery pack for a GM eAssist system.

stop it at the position that will result in the smoothest restart. As soon as the driver releases the brake pedal, the BAS instantly spins the engine up to 500 rpm before the ignition and fuel delivery systems are turned back on. During deceleration, the fuel to the engine is shut off, the torque converter clutch is locked, and the engine spins with the car's wheels while the BAS unit regenerates electricity.

Many other fuel-saving features are incorporated into these cars, such as:

at highway speeds to reduce drag

- Underbody panels designed to smooth airflow underneath the car
- A revised, low-friction automatic transmission
- Low-rolling resistance tires
- Electric power steering

HONDA'S HYBRIDS

The public acceptance of hybrid technology can be largely credited to Honda. With the introduction of the Insight in December 1999, Honda became the first manufacturer to offer hybrid vehicles in North America. The Insight, with a very different look and two seats, received the attention of the public **(Figure 7-10).** They especially noticed the high fuel economy ratings. The Insight has been America's most fuel-efficient car every year since its introduction. The Insight has an electric motor positioned between the engine and transmission.

In 2002, Honda applied its hybrid technology to the Civic. This car was not noticeably a hybrid. In fact, it looks much the same as a conventional Civic. Sales of the hybrids were, and continue to be, good. Reduced emissions and great fuel economy contributed to their success. The Civic Hybrid is based on the same technology as used in the Insight and has been recently modified to make it more efficient. Today, the Civic Hybrid is listed in the top five most fuel-efficient cars as rated by the Environmental Protection Agency. The hybrid is also certified as a ULEV (Ultra-Low Emission Vehicle).

In 2005, Honda introduced the Accord Hybrid. Following the same formula as the Civic, the Accord looks like a normal car and applies the technology used in the Insight to achieve lower emissions and good fuel economy.

Honda Insight

The Honda Insight was equipped with the first generation of Honda's **Integrated Motor Assist (IMA)** hybrid system. It had a 1.0L, three-cylinder engine and a 144-volt electric motor positioned between the engine and the transmission. The Insight was designed to be extremely fuel efficient and had a driving range of 700 miles. Its aluminum body was very light; therefore a small internal combustion engine (ICE) could be used to propel it. These two factors greatly contributed to the high fuel economy ratings of the Insight. The electric assist makes up for any power deficiencies of the engine. The Insight also met CARB's ULEV standard.

The shape of the car also contributed to its efficiency. When a car is moving, it is pushing through air. This is called aerodynamic drag, and power is required to push the car through the air. To minimize air drag, the Insight had a teardrop shape, with the back of the car being narrower than the front. The rear wheel openings were partially covered by skirts, preventing air from moving into the wheel wells. The underside of the car was flat, and panels were used to close off some of the openings under the car. The result of these efforts was that air can easily move under, over, and around the car.

IMA. The IMA combines the engine with an ultra-thin permanent magnet electric motor **(Figure 7-11).** The brushless motor receives its power from a 144-volt NiMH battery pack, through the **PCU (Power Control Unit)**. The engine is the primary power source for driving, and the motor provides additional power only when needed. The motor produces 13 horsepower and 36 ft.-lb of torque. The motor also cranks the engine at 1,000 rpm for quick starting. As in other hybrids, the motor also works as a generator to recharge the battery pack. The maximum output of the generator is 10 kilowatts (69.4 amps at 144 volts).

The synchronous AC motor has a three-phase stator and a permanent magnet rotor that is directly connected to the engine crankshaft. There are three commutation

Courtesy of American Honda Motor Co. Inc.

Figure 7-10 A Honda Insight.

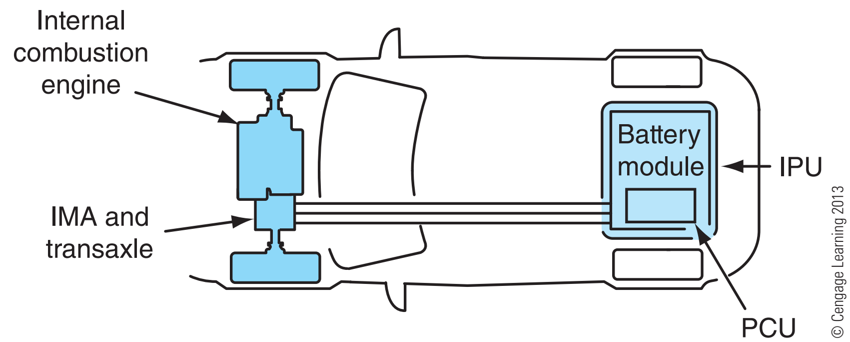


Figure 7-11 The basic layout of the IMA system in an Insight.

sensors mounted inside the motor/generator that give the **motor control module (MCM)** information about the rotor's position.

WARNING *The IMA motor/generator has a very strong permanent magnet rotor. All iron, magnetic, and electronic materials must be kept away from the rotor. People with pacemakers should not handle an IMA rotor.*

WARNING *Do not handle the rotor without the special tools to remove and replace it. The magnetism is very strong, and personal injury can result! In addition, improper procedures can damage the rotor or stator.*

Electronic Controls. The ICE is controlled by the Powertrain Control Module (PCM). This module is much like one used in a nonhybrid but has been programmed to interact with the IMA system. The IMA system is controlled by the components housed in a single unit called the **Intelligent Power Unit (IPU)**, which is connected to the motor/generator by high-voltage cables **(Figure 7-12).** The IPU contains the following:

- Battery module (BM)
- Battery condition monitor (BCM)
- Motor control module (MCM)
- Power control module (PCM)
- Motor drive module (MDM)
- Voltage converter module
- DC/DC converter

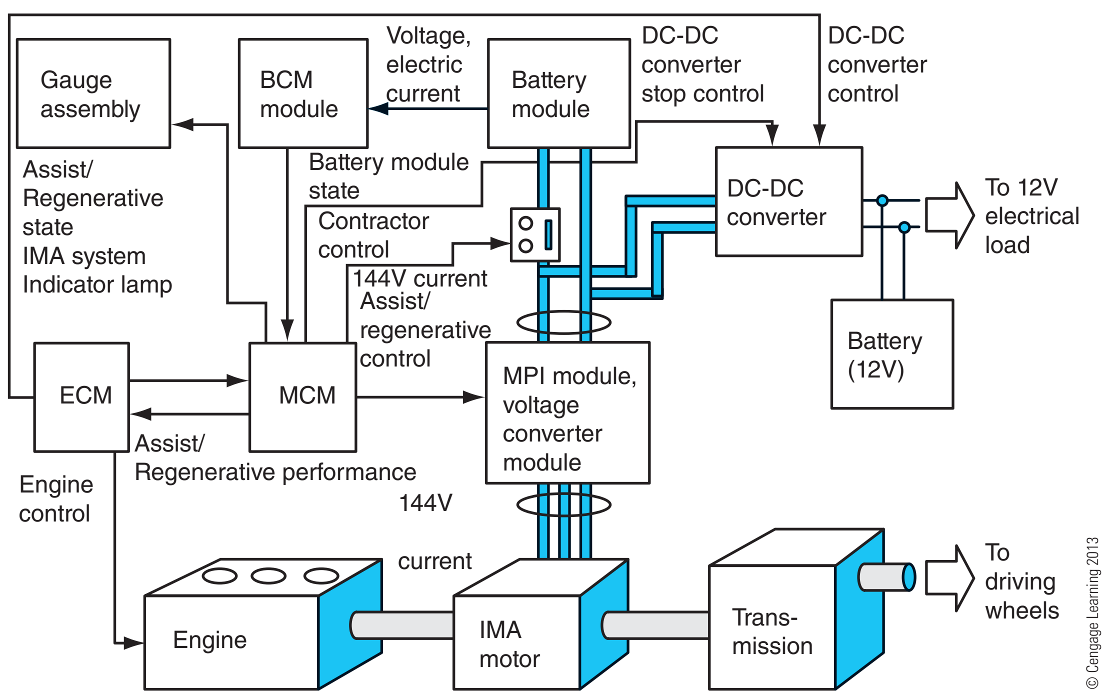


Figure 7-12 A look at the electronics that allow the IMA system to work.

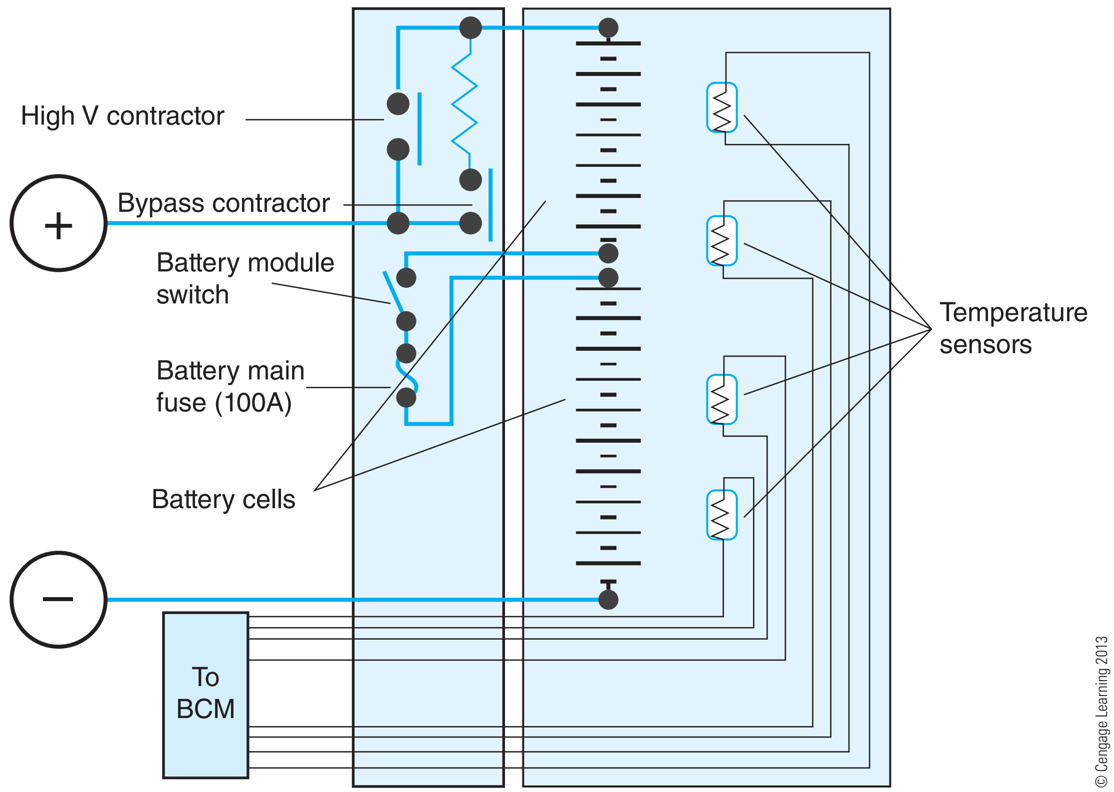


Figure 7-13 The battery module in an Insight.

CAUTION *Because the IMA motor/generator has a permanent magnet rotor, it will ALWAYS generate power when the engine is rotating!*

WARNING *Any time that the engine is spinning, the orange high-voltage cables could have high voltage. Keep away from all orange cables when the engine is running.*

The 144-volt nickel-metal hydride battery pack **(Figure 7-13)** weighs only 48 pounds. The pack consists of 20 modules connected in series. Within each module are six 1.2V cells, each about the size of a conventional D battery. The maximum capacity of the battery pack is 6.5 amp-hours (Ah).

The high-voltage contactor and bypass contactor are connected at the positive (+) output terminal of the battery module. These contactors are controlled by the

the high-voltage circuits. Current flows through the bypass contactor and bypass resistor when the capacitors in the power control module are being charged.

The battery condition monitor measures battery voltage, battery input/output current, and battery temperature. The module has four thermistor-type temperature sensors, 10 voltage sensors, and a current sensor. The condition of the battery is sent to the motor control module.

Heat is generated during charging and discharging, and this heat can have a negative effect on the battery. To control the temperature, the battery condition monitor controls a two-speed cooling fan that prevents the battery module from overheating. If the monitor detects a fault in the battery module, it sends a signal to the motor control module, which then turns on the IMA system indicator in the instrument panel.

The motor control module controls the motor/generator through the **motor power inverter (MPI)** and the voltage converter unit in the motor drive module. Through communication with the PCM and **battery condition monitor (BCM)**, the MCM directs the motor drive module to control the motor assist feature, as well the action of the regenerative braking system. The operating conditions, such as engine load, are used to determine the appropriate action of the

the motor control module limits the activity of the motor/generator to prevent excessive battery drain and overcharging. On some vehicles, the battery condition monitor is built into the MCM.

The motor power inverter and voltage converter change DC power into three-phase AC power for the

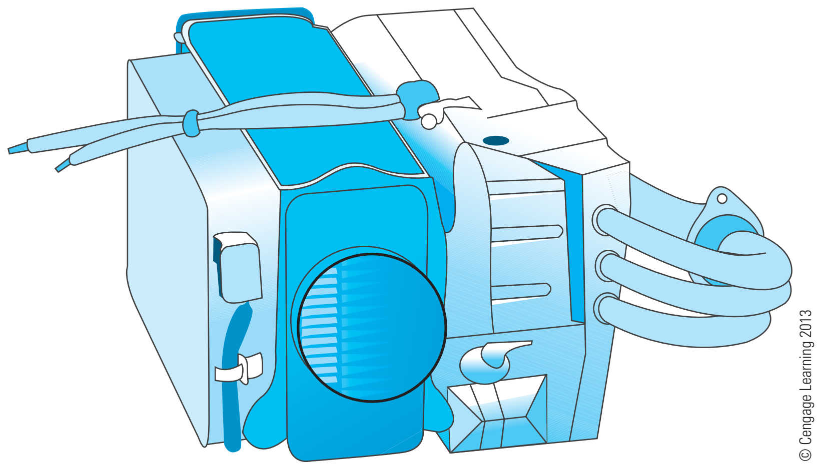


Figure 7-14 The PCU (power control unit) used in an Insight.

motor during assist and convert AC power into DC to charge the batteries during regeneration. The MCM always needs to know the position of the motor/generator's rotor within the stator. Three Hall effect sensors, called the *motor commutation sensors,* monitor the rotor.

The MCM also sends signals to control the IMA display in the instrument cluster. This display informs the driver of the operating modes and condition of the system. The MCM also stores fault (DTC) codes and operates the IMA warning lamp. Scan tools are used to retrieve the DTCs through a 16-pin data link connector.

The power control unit **(Figure 7-14)** controls the distribution of electricity throughout the IMA system. This unit holds the motor drive module and the DC/DC converter. Both of these are mounted in a heat sink to prevent them from overheating. A fan moves air across the heat sink to keep it and the modules cool. The MDM is comprised of the motor power inverter module, voltage converter module, capacitor, and the U/V/W phase motor current sensors. The latter sensors measure the current into and out of the three stator windings of the motor/generator. The voltage converter and inverter are responsible for the AC to DC and DC to AC changes.

The DC/DC converter reduces some of 144-volt DC from the battery module to 12-volt DC needed to charge a separate 12-volt battery. It also provides the power to operate the 12-volt electrical system. The converter
inside a magnesium housing. This is necessary because during the reduction of the voltage, much heat is generated. If the temperature of the converter becomes too high, the converter's temperature monitoring system will send a signal to the MCM, which in turn will turn off the converter.

Operation. When the ignition switch is turned to the START position, the motor/generator instantaneously spins the engine at 1,000 rpm to start the engine **(Figure 7-15).** Once the engine has started, it runs at all times except during stop-start. The car is fitted with an auxiliary starter motor that is only used to start the engine when the battery module's voltage is very low, when the outside temperature is extremely low, or if there is a problem with the IMA system.

When the driver depresses the accelerator, the PCM sends a signal to the motor control module. The MCM, in turn, sends a signal to the motor drive module. The MDM then sends three-phase AC power to the motor/generator to trigger motor assist **(Figure 7-16).**

As the engine overcomes the load of acceleration, the motor is turned off and the car is powered only by the engine. While the car is cruising at a steady speed, the motor/generator can work as a generator to charge the battery module and power the 12-volt system. The engine will not drive the generator unless there is need for charging. This feature minimizes the work of the engine and therefore maximizes fuel efficiency.

During deceleration, the system automatically switches into the charge mode. The PCM sends a signal to the MCM, which then directs the MDM to turn the motor/generator into a generator. Because the generator is now being driven by the wheels of the car, the car's kinetic energy is changed to electrical energy **(Figure 7-17).** Regenerative braking produces three-phase AC power that is sent to the MDM, where

output of the MDM is also sent to the DC/DC converter and used to charge the 12-volt battery. When the brakes are applied, regeneration is increased, and the batteries are charged at a higher rate. It is important to know that if the driver puts the car into neutral while coming to a stop, there will be no

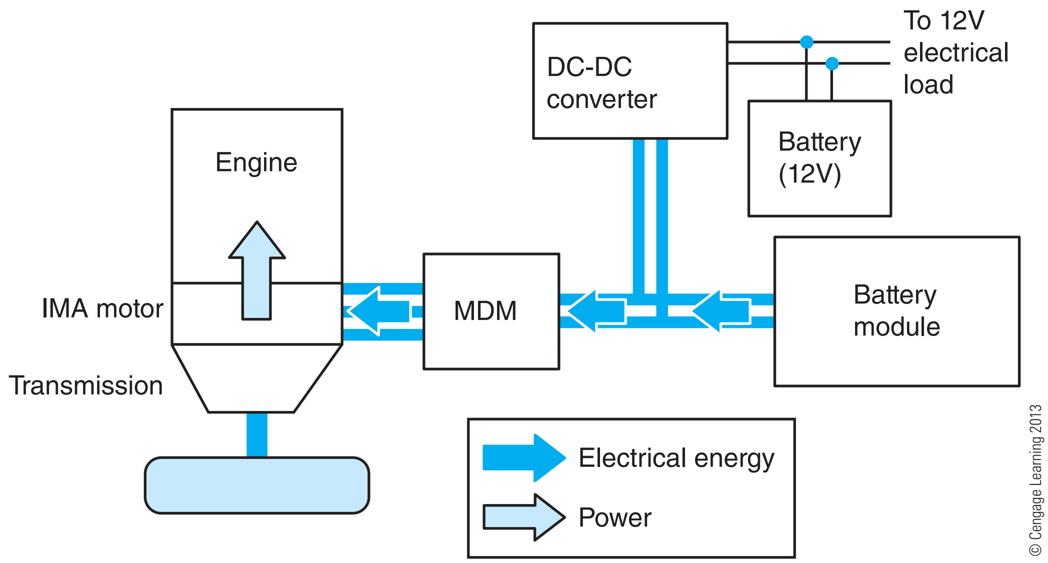


Figure 7-15 The IMA motor, attached directly to the engine's crankshaft, starts the engine under normal conditions. When outside temperature is extremely low, when the battery state of charge is low, or if there is a problem with the IMA system, the conventional starter starts the engine.

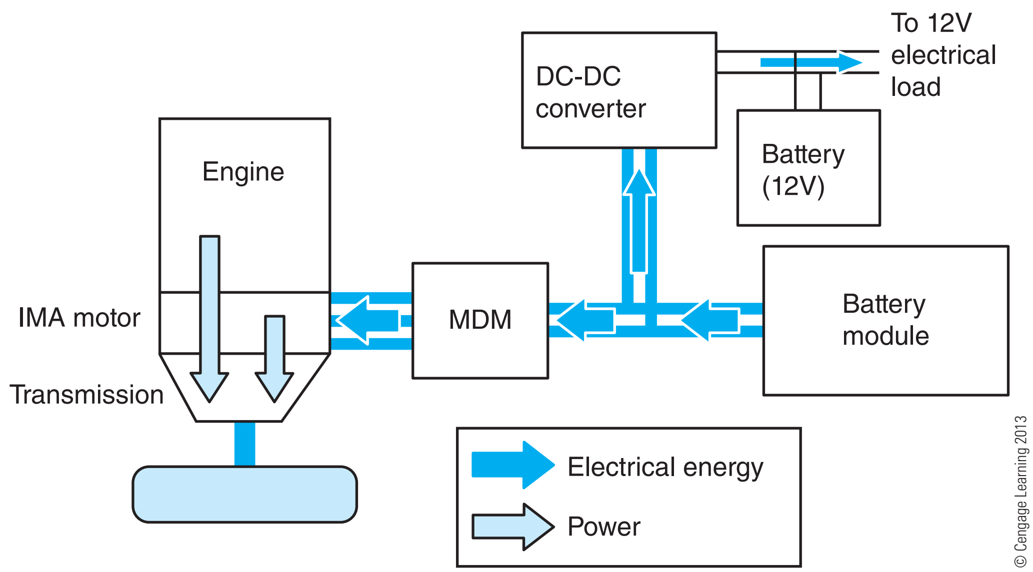


Figure 7-16 When the driver depresses the accelerator, the output of the motor supplements the output of the engine to accelerate the car.

regenerative braking because the wheels can no longer drive the generator.

The stop-start (Honda refers to this feature as idle-stop) mode is initiated when the car is at a stop, the shift
leased, and/or when the brake pedal is held down. During stop-start, the engine is turned off and the green "Auto Stop" light in the instrument panel illuminates. Stop-start does not occur if the voltage of the battery module is low. Also, if the transmission remains in a gear, the engine will not be turned off. This allows the engine to be responsive in heavy or stop-and-go traffic. The engine restarts immediately when the driver releases the brake pedal, a gear is selected, and/or the clutch pedal is depressed.

Electronic Instrument Displays. The Insight is equipped with analog and digital instruments. The instruments display the typical conditions and fuel level for a gasoline engine, and they display the operation of the IMA system and the car's fuel efficiency. On cars equipped with a manual transmission, the instrument

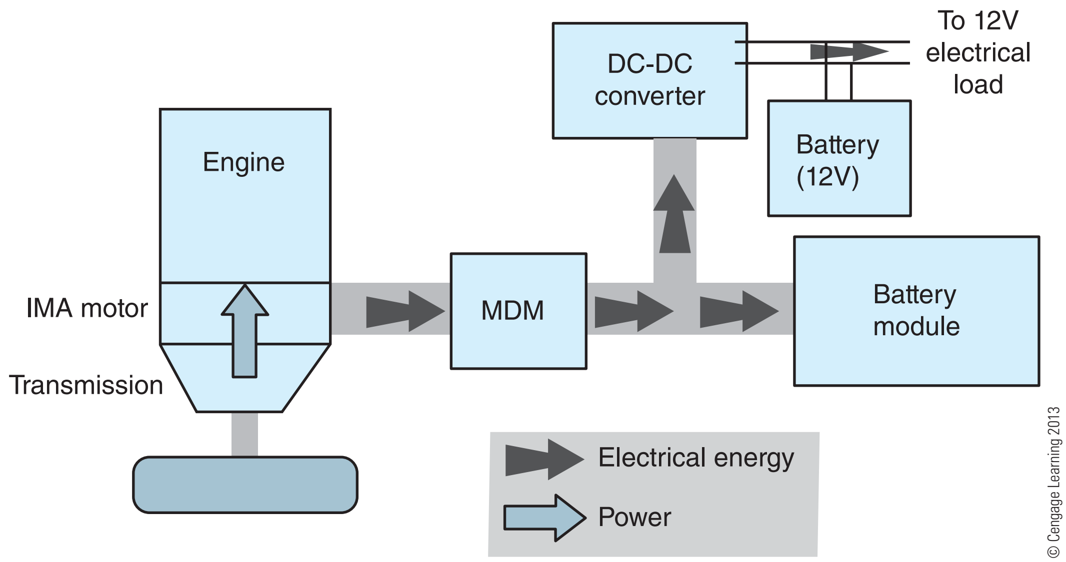


Figure 7-17 During deceleration, the system automatically switches the motor/generator into a generator for regenerative braking.

panel also includes upshift and downshift lights that are triggered by the PCM to inform the driver when it is most economical to shift gears.

The instrument panel is divided into three separate sections. The displays for the gasoline engine are located on the left side of the panel. Included in the engine displays are a tachometer, coolant temperature gauge, and warning lights for oil pressure, PCM-related problems, required maintenance, and problems in the 12-volt system.

The center part of the cluster is a combination odometer/fuel economy meter. This includes a digital speedometer, odometer, and lifetime fuel economy readout. The display can be reconfigured by the driver to show current fuel consumption, the fuel economy for two different trips, and other fuel efficiency indicators.

The right side of the instrument cluster displays the status of the battery and IMA system **(Figure 7-18).** A charge/assist indicator shows when the system's electric motor is assisting the engine. The amount of assist is indicated by amber-colored bars. The number of bars illuminated indicates how much assist is being provided. This same display shows the amount of charge going to the batteries. The amount of recharge is indicated by green-colored bars. When more bars are illuminated, the batteries are being recharged at a higher rate. Also on this side of the cluster is a state-of-charge indicator for the battery module, a fuel gauge, and the shift indicator.

The entire cluster is designed to help the driver achieve maximum fuel economy by minimizing the amount of time there is heavy electrical drain on the battery module. When the engine must drive the generator, additional fuel is used to do this.

Engine. The engine in an Insight was specially designed to provide great fuel economy and reduced

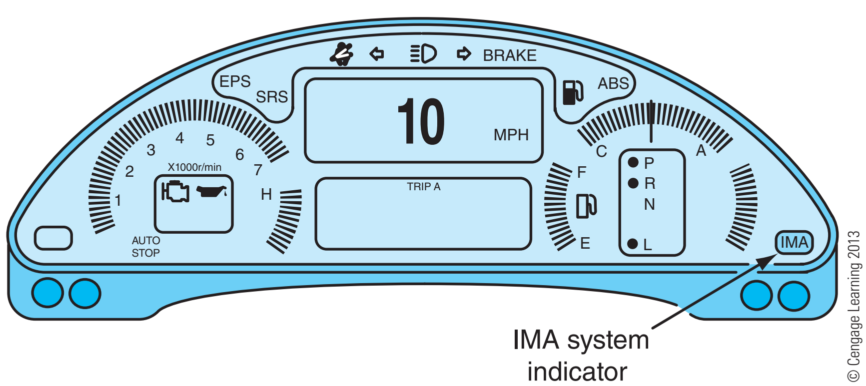


Figure 7-18 The instrument panel in an Insight.

exhaust emissions. The 1.0L, three-cylinder engine incorporated many different technologies to achieve these goals. The engine was very light, weighing only 124 pounds (56 kg), and it produced 67 horsepower at 5,700 rpm. Engine weight was reduced by using aluminum, magnesium, and plastic. The engine also used Honda's **Variable Valve Timing and Lift Control for Economy (VTEC-E)** lean-burn technology, along with several friction-reduction techniques to minimize power losses.

Much of the efficiency of the Insight's engine resulted from the use of the VTEC-E cylinder head and valve train. The VTEC-E system used in the Insight had an expanded stratified charge area within the combustion chamber, advanced fuel-injection mapping, and a **linear air-fuel (LAF) sensor**. The engine relied on Honda's sequential programmed fuel injection and direct ignition systems.

In a VTEC-E engine, there are two intake valves and two exhaust valves in each cylinder. When the engine is running at low speed, only one intake and one exhaust valve are used. When the engine reaches a particular speed, all of the valves are used. This technology allows the engine to run at very lean mixtures when there is a light load on the engine. Lean mixtures provide excellent fuel economy with lower HC and CO emissions.

A VTEC-E engine can burn very lean mixtures at low engine speeds because as the air-fuel mixture enters the combustion chamber through one of the two intake valves, a strong air-fuel swirl is created **(Figure 7-19).** This swirl or vortex of the mixture creates a "stratified" charge. This means the mixture close to the spark plug is richer than the mixture in the rest of the combustion chamber. This richer mixture ignites first, and the heat from that area moves quickly to ignite the rest of the mixture. Very lean mixtures are not easily ignited by the firing of a spark plug. This is why the stratified charge is an important feature of the VTEC engine: the heat created by the ignition of the rich area in the combustion chamber is much higher than the heat generated by a spark plug. As engine speed builds, the other intake valves open to provide more air. In addition, when more power from the engine is needed, the engine, through PCM control, runs at the stoichiometric (14.7:1) ratio or richer.

As part of the design to ignite the lean mixture, Honda
their bore so the ground electrode does not block the incoming air-fuel mixture. The cylinder head has a letter for each spark plug bore and a spark plug with the matching letter must be used in that bore.

One of the problems with running an engine lean is that a normal oxygen sensor will not work. Oxygen sensors are used to monitor the air-fuel mixture so the PCM can control the activity of the fuel injectors to ensure that the desired mixture ratio is maintained. Most normal engines use a zirconia oxygen sensor that can only measure the exhaust's oxygen content when the mixture is very close to stoichiometric. A zirconia oxygen sensor has a piece of zirconia that has one end exposed to the atmosphere and the other end exposed to the exhaust stream. A voltage is generated when the

ent. Because the amount of oxygen in the atmosphere is somewhat constant, the voltage generated by the sensor actually indicates the amount of oxygen in the exhaust. The voltage from an oxygen sensor fluctuates between zero and one volt, depending on the oxygen level.

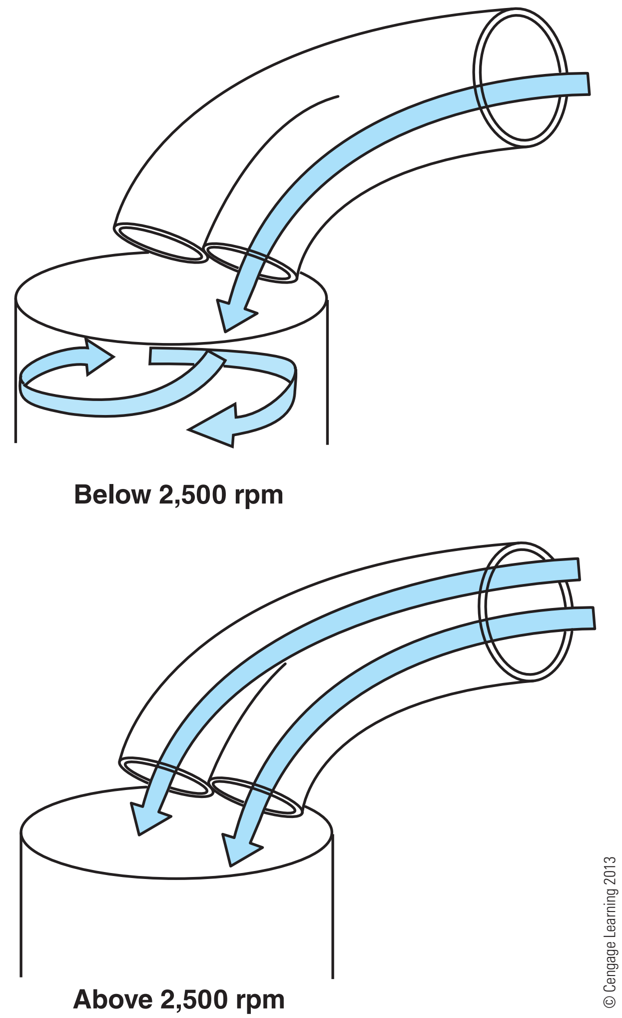


Figure 7-19 A VTEC-E engine can burn very lean mixtures at low engine speeds because as the air-fuel mixture enters the combustion chamber through one of the two intake valves, a strong air-fuel swirl is created that provides for a "stratified" charge.

When the engine is running in the lean-burn mode, the oxygen content of the exhaust is higher than a normal oxygen sensor is capable of measuring. Therefore, to maintain the desired air-fuel ratio, a special oxygen sensor must be used. The Insight uses a LAF sensor, often referred to as a wide band sensor, that can detect the oxygen level in the exhaust during very lean conditions (25:1). Using this type of sensor, the PCM can precisely control the air-fuel mixture, regardless of the operational mode.

The linear air-fuel sensor is located ahead of the three-way catalyst and measures the oxygen in the exhaust. A LAF sensor has two zirconia elements that share a diffusion chamber **(Figure 7-20).** Within the sensor, there is an exhaust flow chamber, atmosphere reference chamber, and a diffusion chamber, plus a heater circuit that allows the sensor to work when the engine is cold. Unlike a non–lean-burn sensor, the voltage can be positive or negative. Positive voltage indicates a lean mixture and negative voltage indicates a rich mixture **(Figure 7-21).** The normal operating

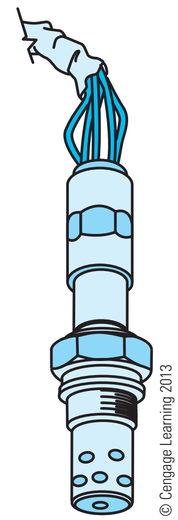


Figure 7-20 A LAF sensor can be identified by its five-wire configuration: (1) heater positive, (2) heater ground, (3) sensor element positive, (4) control element positive, and (5) common ground for sensor and control elements.

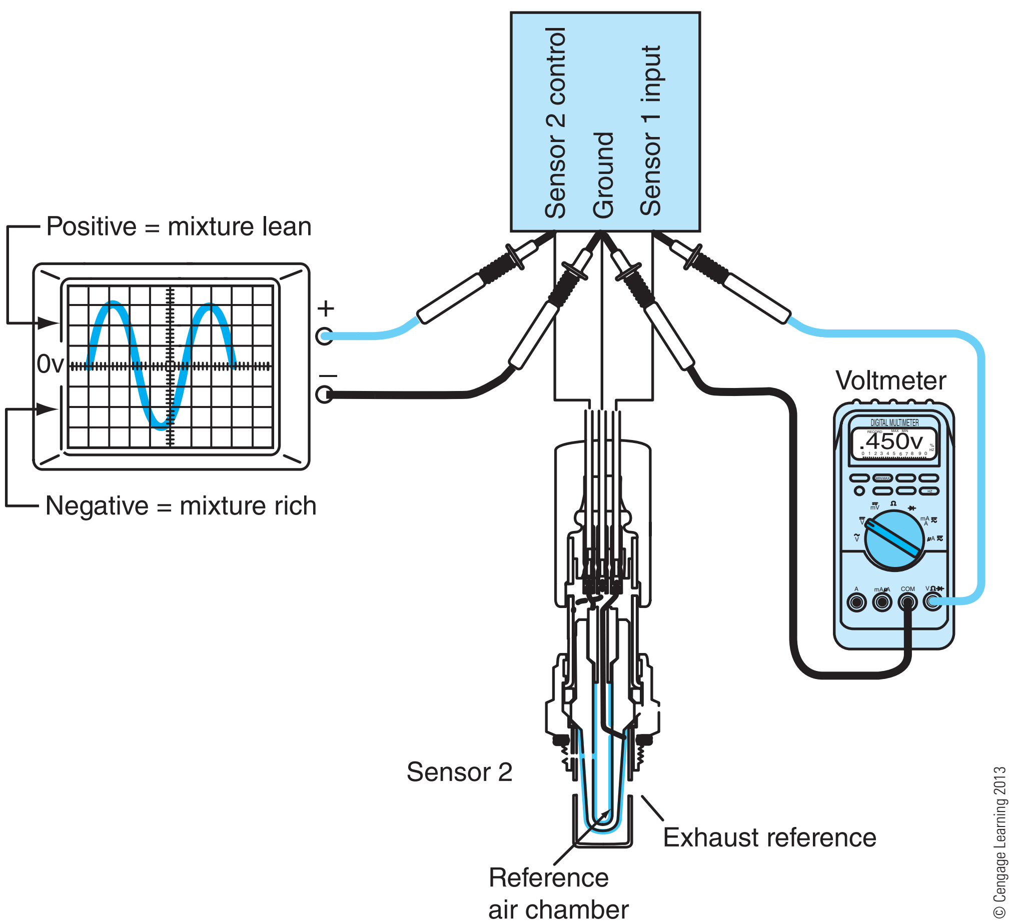


Figure 7-21 Unlike a conventional zirconia oxygen sensor, the voltage from a LAF can be positive or negative. A positive voltage indicates a lean mixture and negative voltage indicates a rich mixture.

voltage range is about 1.5 volts. The zirconia element that is exposed to the exhaust is the sensor element. The diffusion chamber is the space between the two zirconia elements. By applying varying voltages to the control element, the PCM can control the amount of oxygen in the diffusion chamber. Because the diffusion chamber is the reference chamber for the sensor element, this action changes the output of the sensor element. The PCM monitors the output of the sensor element as the oxygen content of the exhaust changes, and it applies voltage to the element to try to maintain the sensor output at 0.45 volts. It then monitors the control voltage to determine the actual air-fuel ratio. The oxygen sensors located to the rear of the catalytic converters are the conventional zirconia type.

The engine in an Insight is equipped with a **nitrogen-oxide-adsorptive catalytic converter**, in addition to a conventional three-way catalytic converter. The nitrogen-oxide-adsorptive converter is necessary to keep NO_x emission levels low. Lean-burn engines have high combustion temperatures and an excessive amount of oxygen in the combustion chamber. Both of these contribute to the formation of NO_x. Conventional three-way catalysts are not very effective in converting NO_x into nitrogen when excess oxygen is present. Lean mixtures require the use of a special catalytic converter. The Insight's nitrogen oxide absorptive catalytic converter uses two NO_x catalyst beds to trap and convert the oxides of nitrogen in the exhaust. The converter attracts NO_x molecules to the surface of the catalyst metals during lean-burn operation. When the engine is running at stoichiometric or richer ratios, the converter combines these NO_x molecules with the hydrocarbons and CO in the exhaust to form water vapor, carbon dioxide, and nitrogen.

The efficiency of the engine in an Insight is further enhanced by the use of many friction-reducing features, such as roller-type rocker arms mounted to a single shaft. The engine also has offset cylinder bores. This feature places the crankshaft slightly away from the center of the cylinders. With offset cylinders, the piston and connecting rod move at a more efficient angle during the power stroke, and friction from piston side loads is reduced. The pistons have a small skirt area and the surface of the skirt has been shot-peened, which improves their ability to hold lubricant that, in turn,

in the cylinder.

The weight of the engine is kept low using a magnesium-alloy oil pan. The oil pan also serves as the engine oil-filter bracket and A/C compressor mount. Further, to reduce weight, plastics are used to make the intake manifold, water pump pulley, and valve cover.

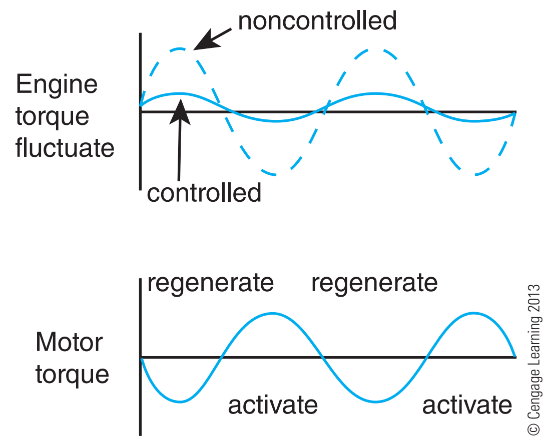


Figure 7-22 The IMA system is equipped with an idle vibration reduction control that minimizes fluctuations in the engine's crankshaft. The motor applies opposite phase torque to the engine when the crankshaft is rotating.

The IMA system is also designed to smooth the operation of the engine. Three-cylinder engines are inherently unbalanced and prone to vibrations. To overcome this problem, the IMA system uses its electric motor to dampen the vibrations. The motor applies a reverse torque to the engine's crankshaft. These reverse torque pulses are precisely in phase but in the opposite direction of the torque fluctuations of the engine **(Figure 7-22).** The reverse torque cancels the vibrations of the engine. This feature requires precise control of the motor/generator as the function of the motor/generator is quickly changed to match the movement of the engine's crankshaft. During a power stroke, the IMA system momentarily switches the motor/generator to the generator mode to help absorb the power pulse. Immediately after the power stroke, the system momentarily switches to the motor mode to speed up the slowing crankshaft.

Transmission. Insights are available with either a manual transmission or a **continuously variable transmission (CVT)**. The five-speed manual transaxle weights just 91 pounds (41.3 kg) and is designed to reduce power loss through friction and to make shifting easy. The CVT (Honda Multimatic) uses computer-controlled drive and driven pulleys and a steel "push"

maximizes power but reduces fuel economy (for acceleration), and *DRIVE,* which reduces power but improves fuel economy (for cruising). The transmission is also equipped with an "anti-rollback brake assist" system that prevents the car from rolling backward when it is moving from a stop on a hill.

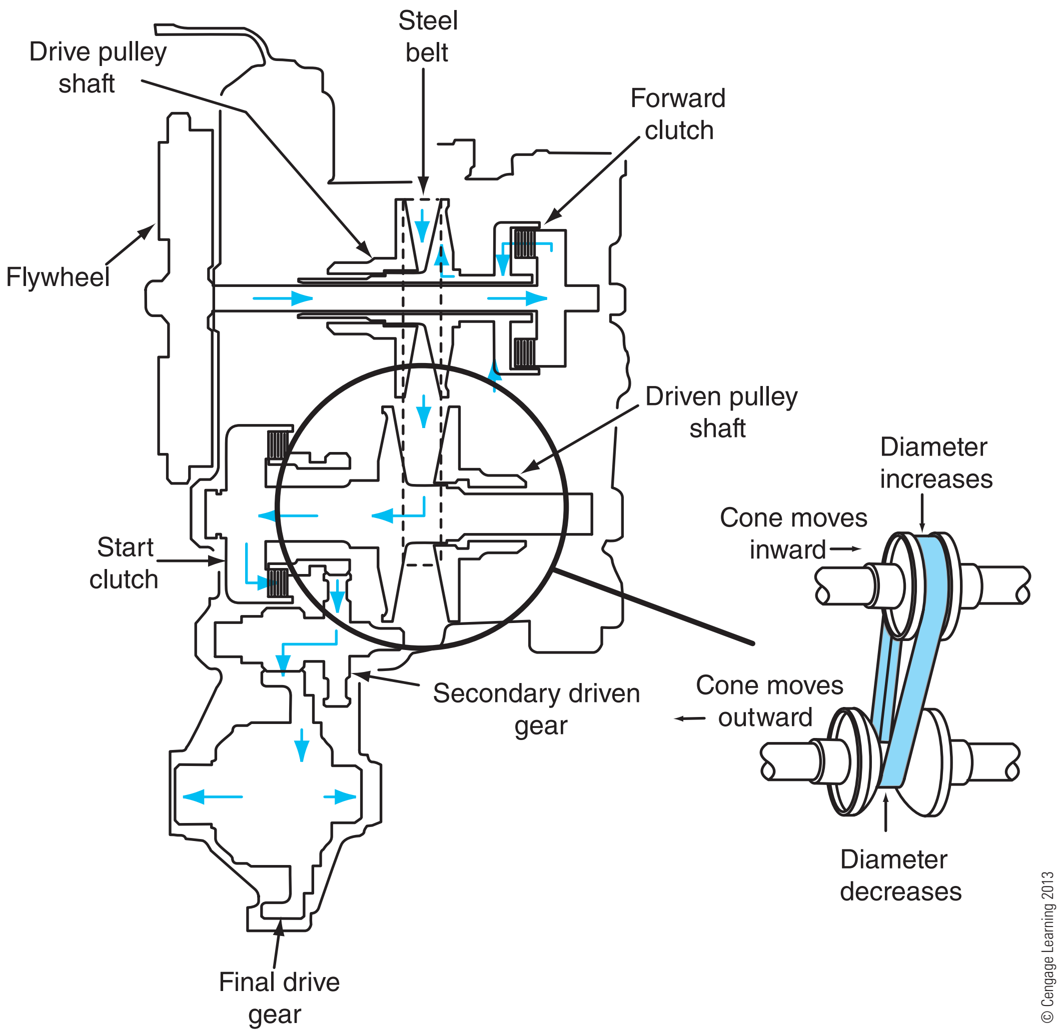


Figure 7-23 The major components in a CVT.

A CVT **(Figure 7-23)** provides varying drive ratios by varying the position of a high-strength steel belt between two metal pulleys. The sides of the pulleys are controlled by hydraulic pressure. One pulley is connected to the output of the engine and the other is connected to the power output side of the transmission. Through various guides within the transmission, the diameter of the pulleys can change, thereby changing the drive to driven ratio of the two pulleys. Because the length of the belt never changes, the effective drive ratio changes. A CVT provides the most suitable gear ratio for any vehicle speed and throttle input.

Honda Civic Assist Hybrid

The 2003 through 2005 Honda Civic Hybrids used the second generation of Honda's IMA system. Compared to the Insight, the Civic was fitted with a larger engine, more powerful electric motor, and refined electronics. Also, many electrical components had been combined, lightened, and reduced in size, to keep the car very fuel efficient. The Civic Hybrid looked very similar to a conventional Civic; however, through minor changes the hybrid model had a lower drag coefficient than a regular Civic. The EPA mileage estimates for a Civic Hybrid with a five-speed manual transmission are 46 mpg in the city and 51 mpg during highway driving. Models equipped with a CVT are rated at 48 mpg for city driving and 47 mpg on the highway.

This assist-type hybrid relies on power from the engine. The engine is a 1.3L, four-cylinder engine. It uses Honda's VTEC and i-DSI technologies. The **i-DSI**

two spark plugs per cylinder to provide for more complete combustion and a lean-burn mode **(Figure 7-24).** The IMA system was an updated version of the system used in the Insight. Although the power output from the electric assist motor was the same, the motor provided more torque.

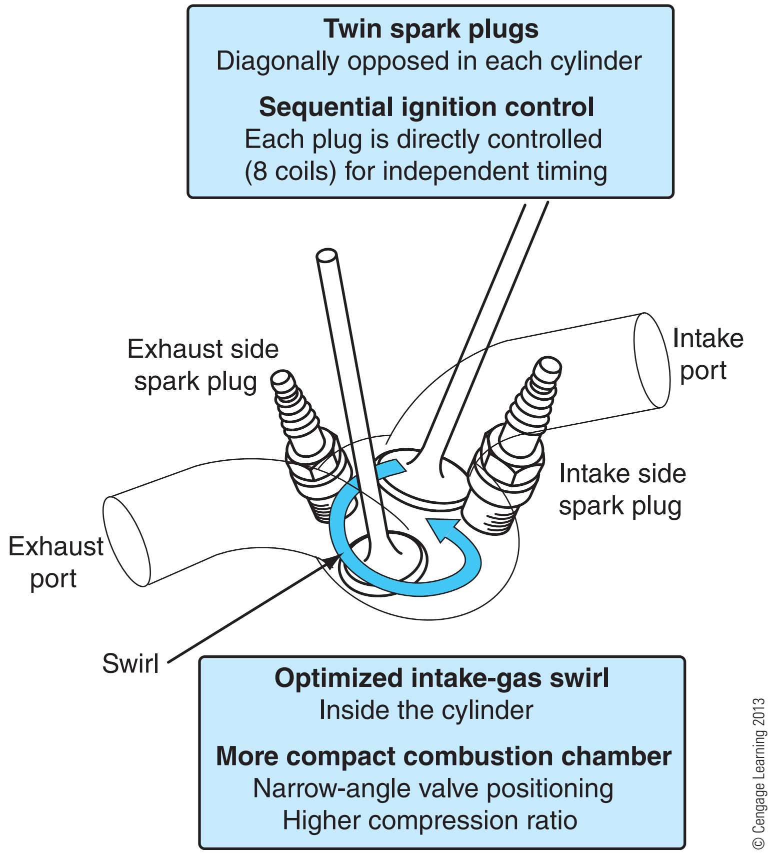


Figure 7-24 The intelligent-Dual & Sequential Ignition (i-DSI) system has eight ignition coils, eight spark plugs that can fire sequentially or simultaneously, and is totally controlled by the PCM.

The operation of the IMA system and its controls were the same as those used in the Insight. Only the components and systems that were unique to the early Civic Hybrids will be discussed in the following.

IMA System. Several items in the IMA system were redesigned to make them more compact and increase their efficiency. The motor/generator's stator windings were wound differently to increase the density of the magnetic flux lines. This change resulted in an increase of 30 percent more torque from the motor **(Figure 7-25).** The torque ratings for the motor **(Figure 7-26)** vary with the transmission. In a manual transmission–equipped car, the motor's maximum torque is 46 ft.-lb torque at 1,000 rpm. When used with a CVT, the torque rating is 36 ft.-lb torque at 1,000 rpm. Each transmission has acceleration characteristics, and the control

assist to match the transmission. Rewinding the stator also increased the generator's ability to produce electricity during regenerative braking.

Electronic Controls. For the Civic Hybrid, Honda made significant changes to the IMA system. These changes resulted in a smaller and lighter unit. In fact, when compared to similar equipment in an Insight, the Civic's IMA system takes up nearly 40 percent less space and weighs about 30 percent less. The functions of the components and the system remain the same.

The Intelligent Processing Unit (IPU) controls the power of the IMA system. The IPU in a Civic was made smaller so that valuable trunk space was not taken up by the unit. The IPU houses the power control unit (PCU), a control unit for the motor, a motor power inverter, a battery module, and a cooling system.

The PCU controls the flow of electricity between the IMA motor and battery pack. The motor control module (MCM) controls the IMA motor, through the motor power inverter. The MCM monitors the state of charge of the battery pack and controls the IPU module fan. The MCM uses inputs of the batteries'

readings to determine the batteries' state of charge. In the Civic, one fan is used to cool the IPU and the batteries. By using one fan, the Civic's cooling system uses less energy and weighs less. The cooling air is drawn into the battery module from the top of the tray behind the rear seat and passes over the heat

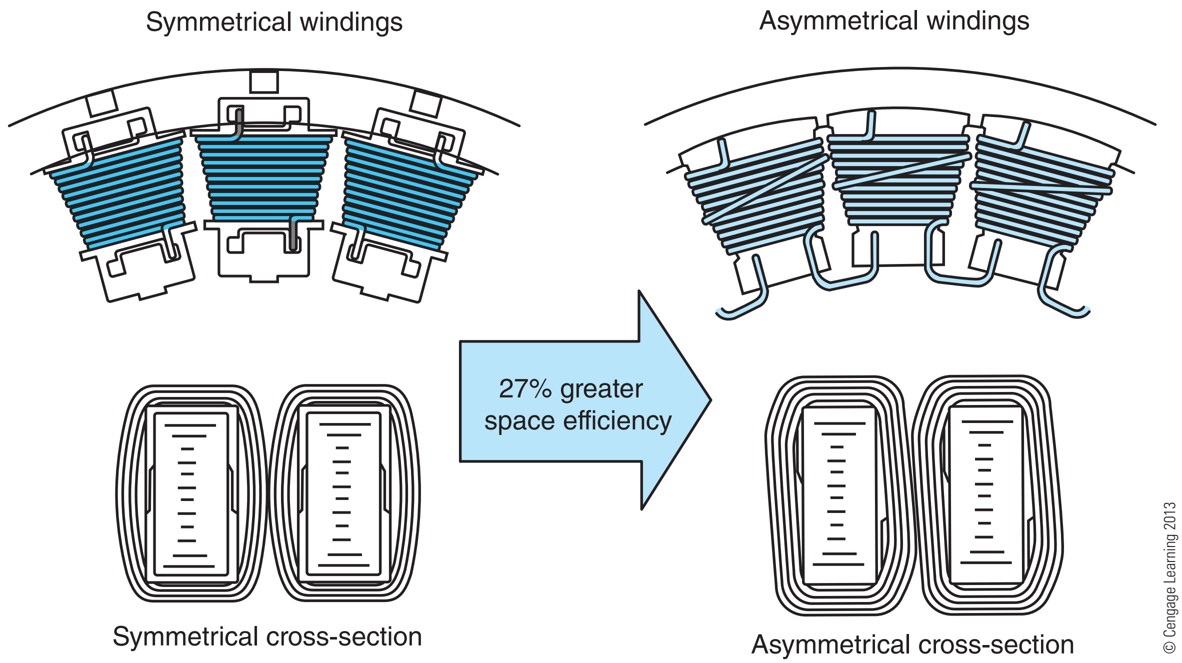


Figure 7-25 The stator windings of the IMA motor in the Civic were wound differently to increase the torque output from the motor.

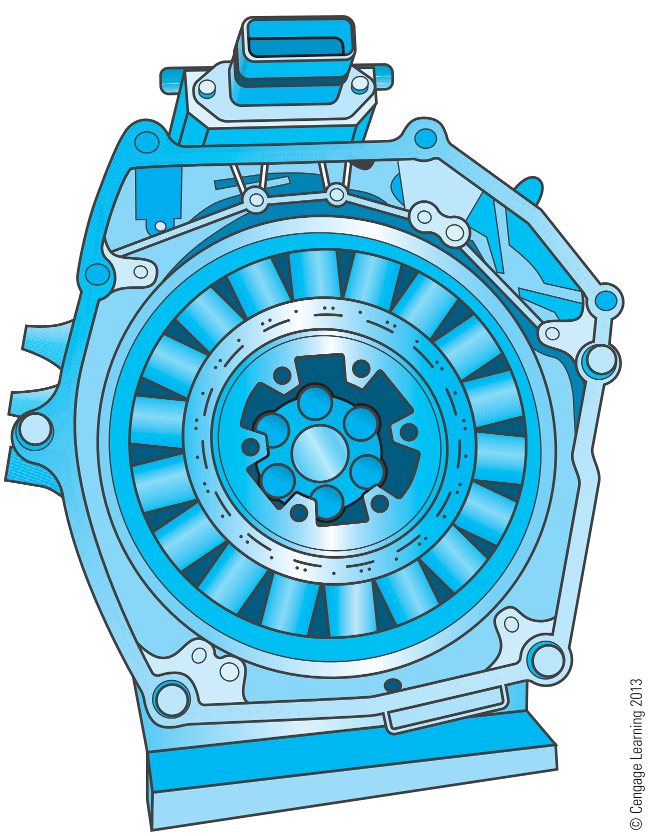


Figure 7-26 The Civic's IMA motor.

sinks or the inverter and DC/DC converter before it is exhausted into the trunk **(Figure 7-27).** The motor power inverter was also redesigned to make it lighter and smaller.

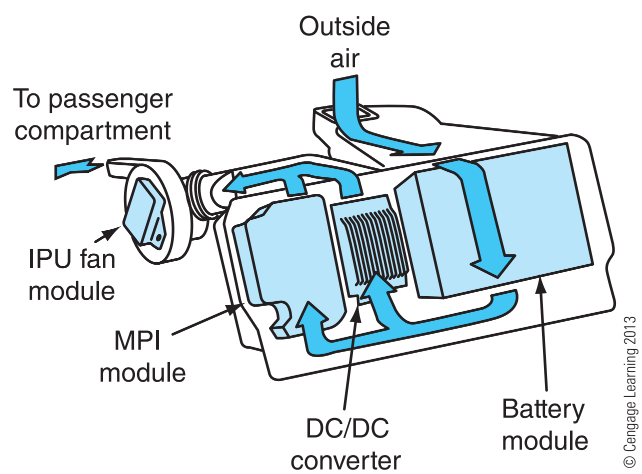


Figure 7-27 The cooling fan assembly for the IPU in a Civic Hybrid.

The battery module is still comprised of twenty 7.2-volt modules and has a nominal output of 144 volts and a capacity of 6.0 amp-hours. However, the battery box has been reduced in size and placed into the IPU. The reduction in size also resulted in a decrease in weight.

Operation. The IMA system functions in the same way as it did in the Insight. The only differences are linked to the stop-start feature, the car's transmission type, and the automatic climate control system. The Civic Hybrid automatically turns off the engine during complete stops under most circumstances. The stop-start

(idle-stop) feature does not work during the first few minutes of engine warmup or if the automatic climate control system is being used in the "air conditioning" mode with the "Economy Mode" not selected.

On cars with a CVT, when the car is moving at more than 9 mph (15 km/h) and the brake pedal is depressed, the engine shuts off. During this time, the auto stop indicator in the instrument panel blinks. If the driver's door is opened during stop-start, the idle-stop indicator blinks and the warning buzzer sounds to remind the driver that stop-start is in operation. The engine restarts when the brake pedal is released and the accelerator is pressed; when the gear selector is placed in the P, R, or L position; or when the control unit senses there is low vacuum in the brake booster.

With a manual transmission, the engine shuts down when the clutch pedal is depressed and the car's speed is 19 mph (30 km/h) or less, when the car is at a stop and the shifter is in neutral with the clutch pedal depressed, or when the brake pedal is depressed and the engine's speed is at 1,000 rpm or less. When the idle-stop system is operating, the auto stop indicator in the instrument panel is illuminated. The engine will restart when the gear shifter is moved into any position other than neutral with the clutch pedal pressed, when the accelerator pedal is pressed while the transmission is in neutral or the clutch pedal is pressed, when the vacuum in the brake booster is low while the transmission is in neutral or the clutch pedal is pressed, or when the IMA battery is low and the transmission is in neutral or the clutch pedal is pressed.

Engine. One of the biggest differences between the powertrain of the Insight and the Civic Hybrid is the engine. Both engines were to be clean and fuel efficient. Because the Civic is larger and is designed to carry a heavier load, the engine is larger. Larger, however, does not mean the engine lacks for advanced systems.

The Civic Hybrid uses a single overhead cam, eight-valve, 1.3L VTEC engine with i-DSI that produces 85 HP at 5,700 rpm and 87 ft.-lb torque at 3,300 rpm. This aluminum-alloy engine had a compression ratio of 10.8:1. The ignition and fuel injection systems provided for a lean-burn mode, and the engine was fitted

verter. To reduce fuel consumption, the engine was equipped with i-DSI, a VTEC Controlled Cylinder Idling System, and many other fuel-saving technologies. Some of these were also used in the Insight, such as offset cylinder bores, low-friction pistons, and roller rocker arms.

The aluminum engine uses thin sleeves for the cylinder walls. The walls' surface is plateau honed, and the pistons are fitted with low-friction piston rings. The engine is also fitted with several lightweight plastic parts, such as the intake manifold and idler pulley.

The engine uses the intelligent dual-point sequential ignition (i-DSI) system that has two ignition coils firing two spark plugs per cylinder. The eight ignition coils are independently controlled by the PCM to respond to engine speed and load, and they can change the timing of the firing of the individual spark plugs, which are located close to the intake port and the exhaust port within the cylinder head. The front spark plugs can be advanced, rear plugs can be retarded, or both plugs can be fired at the same time. These actions depend on the load on the engine and the speed of the engine. Here is a summary of how it works:

- When engine speed is low, the ignition operates in its sequential mode. The spark plug at the intake side has advanced ignition and fires first. Then the plug located near the exhaust port ignites, forcing the flame to grow throughout the mixture in the combustion chamber.
- When engine speed is in its mid-range, the ignition operates in its simultaneous mode; both spark plugs fire at the same time.
- When the throttle is fully opened and the engine's speed is low, the ignition operates in a sequential mode. This combination results in maximum torque from the engine.
- When the throttle is fully opened and the engine's speed is high, the ignition operates in its simultaneous mode.

To improve the regenerative qualities of the IMA system, Honda modified its VTEC system, enabling it to close the intake and exhaust valves on up to three cylinders during deceleration. This system is called the **cylinder idling system**, and it increases the amount of energy captured during regenerative braking.

With the valves closed, the pistons in those cylinders move quite freely. This, in turn, reduces the amount of engine braking or resistance that takes place

chanical resistance of the engine during deceleration, the motor/generator can provide maximum resistance by producing more electricity.

The cylinder idling system actually reverses the role of the standard VTEC system. In conventional VTEC engines, high engine speed and engine oil

pressure are used to lock a pair of rocker arms at each cylinder together to increase horsepower. The system relies on the movement of a hydraulic piston that makes a connection between the two rocker arms, each riding on a differently shaped camshaft lobe and each working a separate valve. When oil pressure is high, both valves in each cylinder open to improve engine breathing. In the cylinder idling system **(Figure 7-28),** low engine speeds and engine oil pressure deactivate the rocker arms. The system also has two rocker arms per valve: a valve lift rocker arm that follows the lobe of the camshaft and a cylinder idle rocker arm that actually opens the valve. The two rocker arms are connected by a hydraulic piston **(Figure 7-29).** When a cylinder is deactivated or idled, hydraulic pressure moves the piston, and the connection between the two

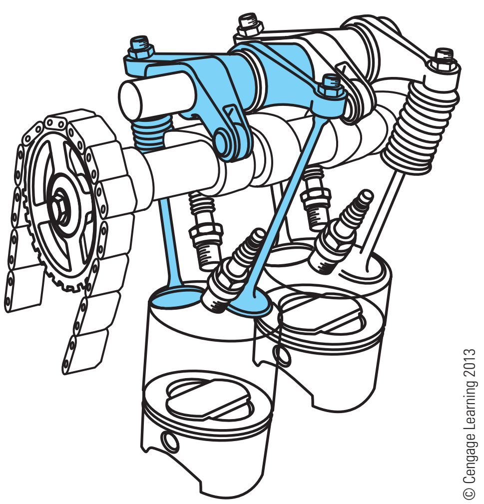


Figure 7-28 The cylinder idling system.

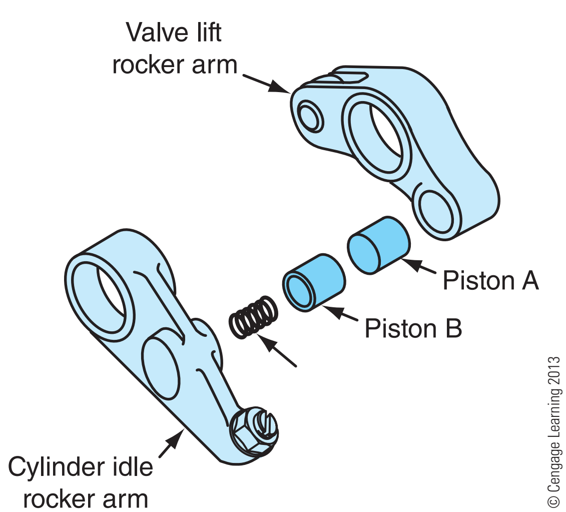


Figure 7-29 A rocker arm assembly for the cylinder idling feature.

rocker arms is gone. This allows the valve lift rocker arm to move along the camshaft lobe without opening the valve.

Transmissions. Civic Hybrids are available with either a five-speed manual transmission or a CVT. The manual transmission is basically the same one used in the Insight except for a few modifications. The primary changes are a larger clutch assembly, different gear ratios, the use of a double-cone synchronizer in both first and second gears, and a redesigned lubrication system that reduces internal friction.

The CVT is also based on the unit used in the Insight. It too was modified for the Civic. Most of these changes were necessary to handle the increased power from the drivetrain and the weight of the vehicle. One notable change is the addition of a creeping aid system that minimizes the amount the car will roll backward during a stop on hills. Other changes include improved hydraulic controls, the use of carbon fiber as the lining material for the starting clutch, and stronger materials used throughout without adding much weight to the unit.

Honda Accord Hybrid

In 2005, Honda released the Accord Hybrid. This car features the third generation of the IMA system. It also incorporates other technologies that result in reduced fuel consumption and emission levels. The changes made to the IMA system include increased motor output, improved battery performance, and greater total system efficiency. The system is used in concert with a 3.0L i-VTEC V6 engine equipped with **Variable Cylinder Management (VCM)**. VCM shuts down three of the engine's six cylinders during certain times, such as cruising and deceleration.

Normally, performance is sacrificed for economy, but the application of hybrid technology in the Accord did not result in this. The combination of the gasoline engine and the IMA system resulted in performance gains as well as in improved fuel economy. The total available output from the combination of power plants is 255 horsepower (nonhybrid Accord V6 sedans have 240 HP) and 232 ft.-lb of torque.

with a 3.0L V6 engine, the acceleration times of the hybrid are quicker by more than 5 percent. At the same time, the fuel economy rating for city driving increased 38 percent, and it increased by 23 percent for highway driving. The hybrid also is categorized as a ULEV.

WARNING *Because the electric motor inside the compressor case is in contact with the oil in the compressor, only the specified oil (Sanden SE-10Y) should be used in the compressor. This oil has electrical insulating qualities that protect you from dangerous electrical shocks. Also, if you use the wrong oil, the air-conditioning unit will be contaminated, and this may result in a need to replace the compressor, condenser, evaporator, and/or all of the refrigerant lines.*

To increase efficiency, Honda equipped the Accord with VCM and the redesigned IMA system. They also used other technologies to reduce power losses and vehicle weight. Air drag was subtly reduced through the addition of a rear spoiler and lightweight aluminum alloy wheels designed to control airflow. Although the hybrid looks like most Accords, these changes result in a drag coefficient of only 0.29. To reduce the weight, the Accord Hybrid is built with a lightweight aluminum hood, aluminum front and rear bumper beams, aluminum rear suspension knuckles, a magnesium engine head cover, and a magnesium intake manifold.

The Accord Hybrid is also equipped with EPS and a dual-scroll "hybrid" air-conditioning compressor **(Figure 7-30).** The air-conditioning system uses two compressors built into one housing; one compressor is driven by the engine and the other is driven by an electric motor powered by the high-voltage battery. When full cooling is needed, the A/C unit relies on both power sources to provide maximum cooling. During normal cooling, the A/C is powered by either the belt-driven compressor or the electric-motor-driven compressor. This allows the A/C system to work at all times, even when the stop-start feature is activated.

Note: The following discussion includes only those features or equipment that has been changed with the new generation of the IMA system. Components and systems that are not mentioned are similar to those used in Insight and Civic hybrids.

IMA System. The IMA system was modified to work with a more powerful gasoline engine, and its overall efficiency has been increased. The system still uses a 144-volt battery pack and an AC synchronous motor. The PCM controls the output of the engine and the

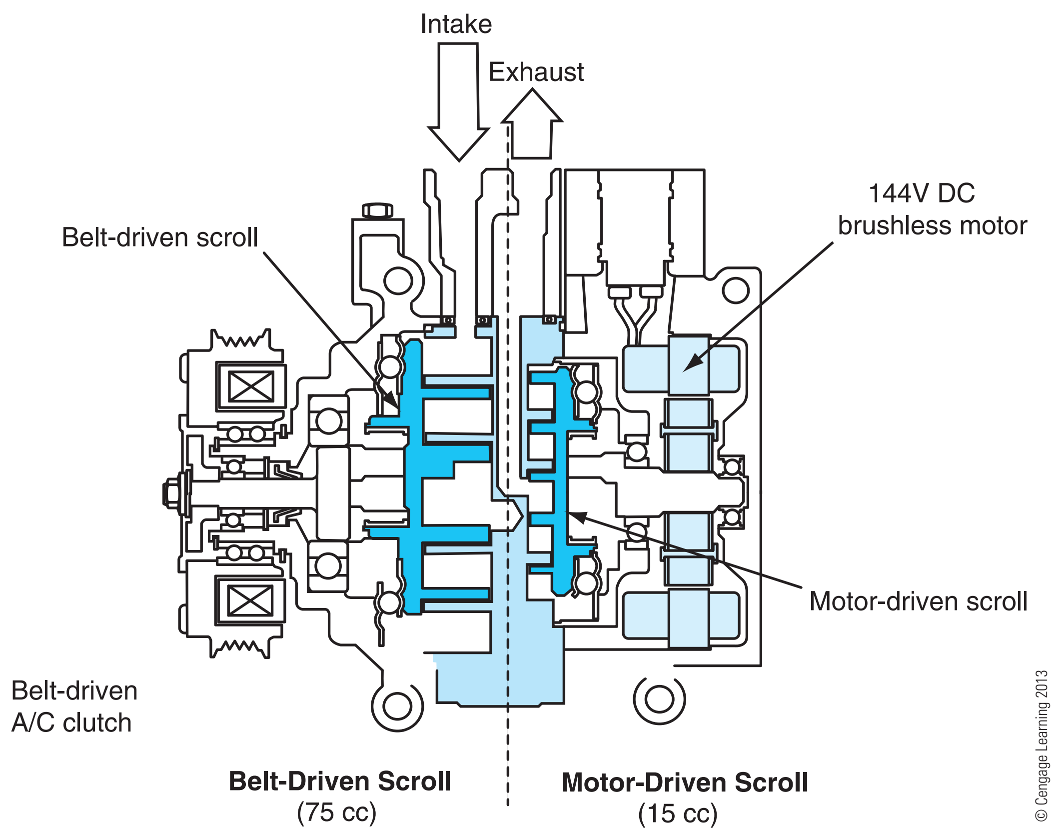


Figure 7-30 The dual scroll "hybrid" air conditioning compressor used in the Accord Hybrid.

electric motor depending on the needs created by the driving conditions.

The PCU, located between the passenger compartment and the trunk, controls the power flow to and from the IMA motor/generator. The motor used in the Accord Hybrid has a redesigned rotor that increases output density and makes the motor more efficient than previous IMA motors. Dimensionally, the new motor is only 0.12 inches (3 mm) thicker than the motor used in the Civic. However, its torque output has been increased by 26 percent during startup, and during driving it can provide more than twice the output of the motor used in the Civic. The total output of the motor is 16.1 HP (12 kW) and 100.4 ft.-lb (136 Nm) of torque.

The redesigned motor can also generate more electricity. During regenerative braking, the motor/generator produces 12 percent more power (14 kW total). This reduces the amount of time the engine must drive the generator to keep the batteries charged.

The IPU is equipped with an integrated cooling system mounted directly on the battery pack's outer box **(Figure 7-31).** Air is pulled, by the cooling fan, into the battery module through the top of the tray behind the rear seats. The air passes over the heat sinks of the inverter, DC/DC converter, and A/C compressor driver before it is exhausted to the outside.

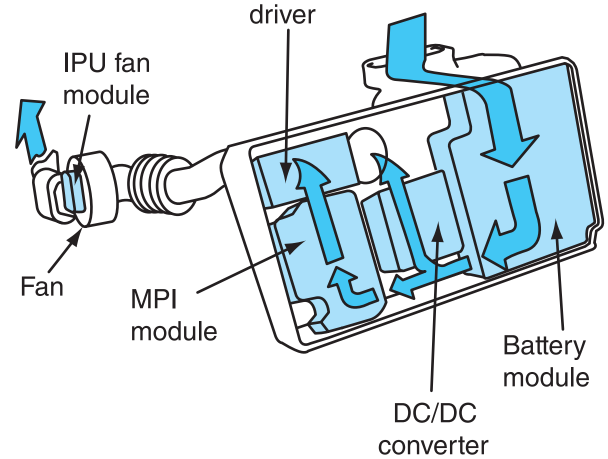


Figure 7-31 The IPU is equipped with a fan. Air is drawn into the battery module from the top of the rear tray, then it is exhausted into the trunk compartment and outside of the vehicle through the MPI module heat sink, the DC-DC converter, and the A/C compressor driver heat sink.

Engine. The engine in the Accord Hybrid is a 3.0L i-VTEC V6. It has the same displacement as other Accord V6s but has been modified to achieve better fuel economy, without sacrificing performance. Without the power assist from the IMA system, the engine provides 240 HP and 217 ft.-lb of torque. With the IMA system, the rated peak power is 255 HP at 6,000 rpm and 232 ft.-lb of torque at 5,000 rpm. This combination results in quicker acceleration times than the nonhybrid models.

Engine modifications include a dual-stage intake manifold **(Figure 7-32)** and a new airflow sensor. The i-VTEC system provides lean-burn and a valve pause system that reduces engine-pumping loss and increases the effectiveness of regenerative braking. The engine is also fitted with a two-axis belt drive with an

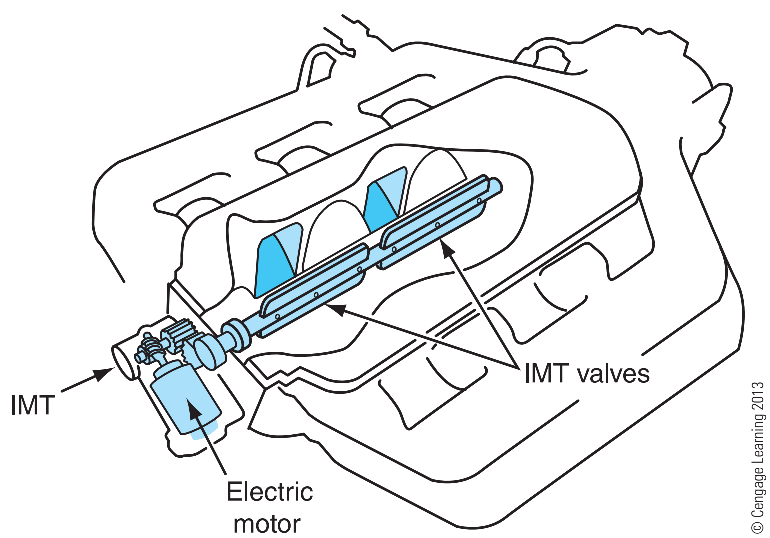


Figure 7-32 Engine power is enhanced by closing and opening the intake manifold tuning (IMT) valve, which changes the effective length of the intake runners. When the valve is closed, there is high torque at low engine speed. When the valve is open, there is high torque at high engine speed.

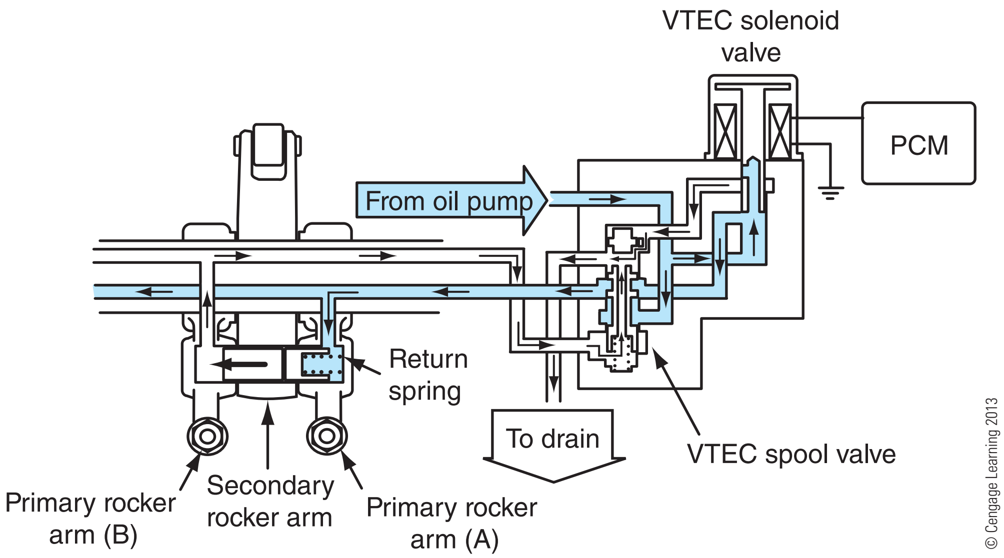


Figure 7-33 During the six-cylinder mode, on the intake side, the spool valve switches oil pressure so that the primary rocker arm moves the switching piston. This causes the piston to slide into the primary rocker arm, locking the rocker arms together. The primary rocker arms are then actuated by the secondary rocker arms.

automatic tensioner designed to prevent power losses due to friction. To keep down the weight of the engine, the engine has an aluminum alloy block with cast-iron cylinder liners, and other parts are made of magnesium.

A major contributor to fuel economy is the VCM system. The system monitors throttle position, vehicle speed, engine speed, transmission gear selection, and other factors to determine if full engine power is required. If full power is not required, the system shuts down the rear bank of three cylinders. This is accomplished by closing the valves and disabling the fuel injectors at those cylinders. The deactivation of the cylinders normally takes place during cruising and deceleration.

When full engine power is needed, the system quickly gets the three idling cylinders back into action. While the cylinders are idling, the VCM system controls the ignition timing and cycles the torque converter lockup clutch to suppress any torque-induced jolting caused by the switch from six- to three-cylinder operation.

The VCM uses a hydraulic circuit with two systems, each capable of providing the hydraulic pressure required to push the synchronizing or locking piston in the required direction **(Figure 7-33).** To deactivate the cylinders,

rocker arms from the deactivated cylinders' valve rocker arms. This action keeps the valves of those cylinders closed. When full engine power is needed, a solenoid-operated hydraulic valve opens and applies pressure to the piston. The piston moves to lock the two rocker arms together. At the same time, the system reinitiates the fuel injection system, and the three cylinders work in harmony with the others.

To reduce the vibrations that result from the deactivation of the three cylinders, the engine is equipped with an **Active Control Engine Mount (ACM)** system **(Figure 7-34).** This system uses sensors monitored by the ECU. The ECU, in turn, directs the engine mounts to move with the vibrations. This stops the vibrations from moving into the passenger compartment. Also, to reduce the noise level of the engine while the cylinders are deactivated, an **Active Noise Control (ANC)** system works in concert with the ACM. The ANC uses microphones in the front and rear of the passenger cabin to monitor the low-frequency noise created by the engine when it is running on only three cylinders. The system creates an equal but opposite noise, which cancels out the noise from the engine. The created noise is sent out through the car's speaker system.

Operation. The engine is normally started with the IMA motor, but if the charge of the IMA batteries is low, an auxiliary 12-volt starter is used. When the driver initially presses on the accelerator, the power from the engine is used to move the car. If hard acceleration is needed, the IMA motor assists the engine while it is

engine when the car is moving up a sharp incline or is moving a heavy load **(Figure 7-35).** When assist is provided, the blue indicator bars in the IMA display will light. If the state of charge of the IMA batteries is below a specified level, the PCM and MCM will not allow assist, regardless of the operating conditions.

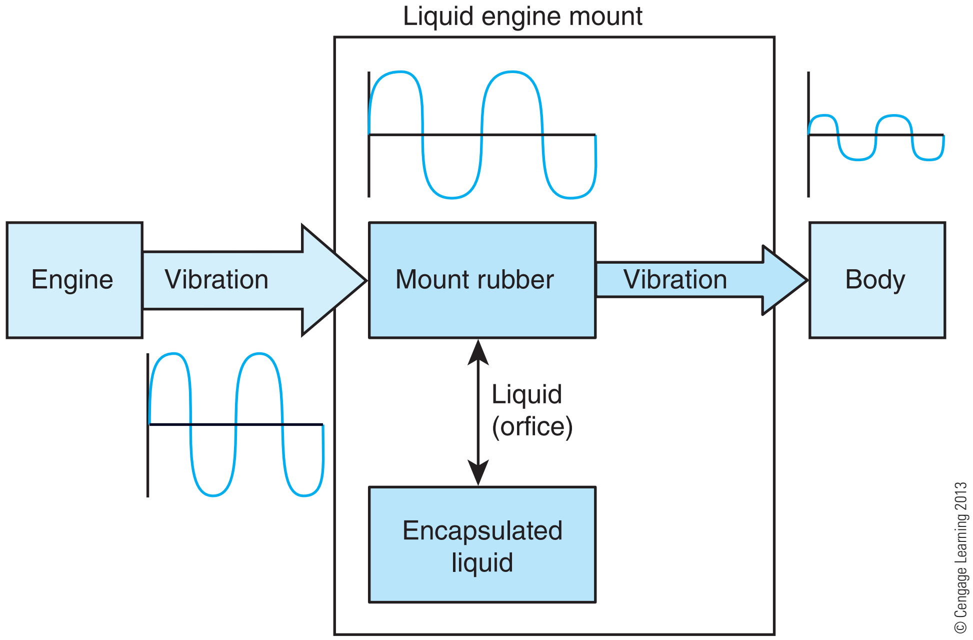


Figure 7-34 The ACM system decreases engine-to-chassis vibration at low rpm and when the engine is in cylinder pause mode. The system includes conventional, liquid-filled engine mounts that absorb vibration and an actuator that cancels engine vibration by producing a counter, or reverse vibration.

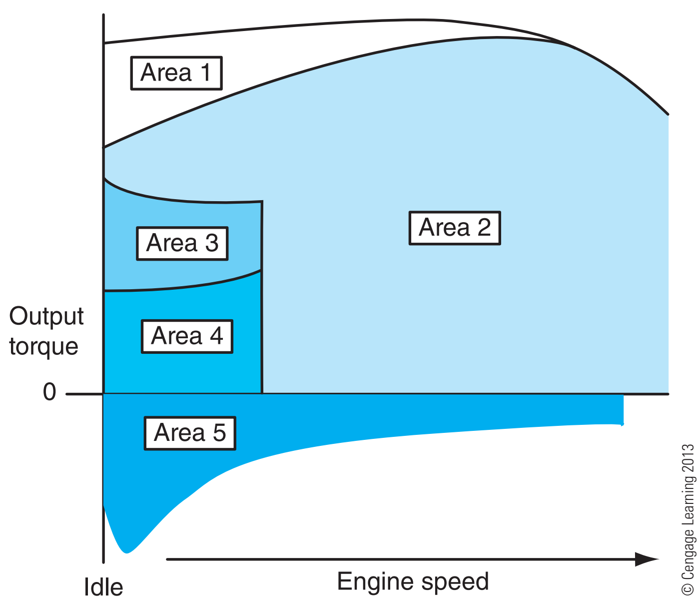


Figure 7-35 Area 1—When maximum output torque is required, the engine is driven by six cylinders with wide open throttle, and the IMA motor assists the engine to increase torque. **Area 2**—At high engine speed except wide open throttle and deceleration, the engine is driven by six cylinders without assist from the IMA motor. **Area 3**—When partial output torque is required at low engine speed, the engine is driven by three cylinders and the IMA motor helps the engine to increase output torque. This control method saves fuel consumption during acceleration. **Area 4**—When low output torque is required at low engine speed, the engine is driven by three cylinders without assist from the IMA motor. This control method saves fuel consumption during cruise and light-load conditions. **Area 5**—During deceleration, the PCM stops the fuel injection to all cylinders, and the IMA motor functions as a generator to charge the IMA battery. The intake and exhaust valves of the rear bank are deactivated by the VCM to reduce mechanical friction and increase the energy for charging.

Also, assist is not available when the battery pack is very cold or very hot.

When the car is driven at high speeds but without the accelerator fully open, the engine runs on six cylinders but is not assisted by the motor. Once the car is cruising at a steady speed and with a light load, the VCM deactivates the rear bank of cylinders. During this time, if slightly more power is needed, the IMA motor will assist the engine as the engine continues to run on three cylinders. When more power is needed, the VCM system will reactivate the cylinders, and the motor assist will stop unless maximum power is needed.

When the driver releases the accelerator to slow the car, the IMA motor, driven by the car's wheels, works as a generator to charge the batteries. The intake and exhaust valves of the rear bank of cylinders are deactivated by the VCM to reduce mechanical friction and to increase the effectiveness of the regenerative braking. During this time, the green bars in the IMA display illuminate to show the amount of electricity being generated. When the battery is fully charged, regeneration is stopped to prevent overcharging of the battery. When the driver presses on the brake pedal to decelerate more rapidly, regenerative braking continues and the VCM system shuts off the fuel injectors in the front bank of the engine.

Like other hybrids, the Accord Hybrid has the stop-start (idle-stop) feature to reduce fuel consumption and emissions. The IMA system temporarily turns off the gasoline engine when the vehicle comes to a stop from speeds over 10 mph. Unlike the Insight and Civic Hybrid, the idle-stop system in an Accord Hybrid will continue to operate even while the car's automatic climate control system is in use. This is because the Accord is fitted with the dual-source A/C compressor. When idle-stop is operating, the auto stop indicator in the instrument panel blinks **(Figure 7-36).** If the driver's door is opened during idle-stop, the indicator blinks and a warning buzzer sounds to remind the driver that auto-stop is in operation. Idle-stop will not operate when the car is first started on an extremely hot day and maximum cooling is required.

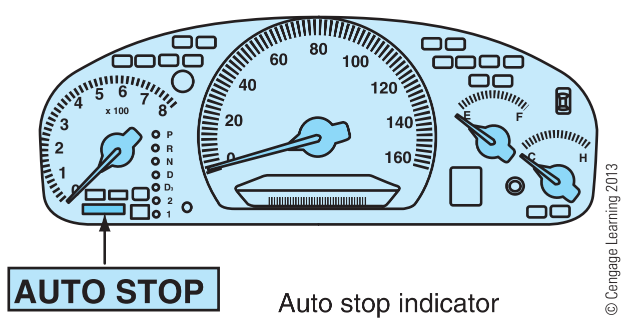


Figure 7-36 When idle-stop is operating, the indicator blinks. If the driver's door is opened during auto idle-stop, the auto stop indicator blinks and the warning buzzer sounds to remind the driver that auto stop is in operation.

Instrumentation. The biggest difference between a conventional Accord and a hybrid Accord is the instrument panel. In hybrid models, the panel displays the level of IMA motor charge or assist, the state of charge of the IMA battery, an "ECO" light to indicate when the VCM is operating in three-cylinder mode, a light to indicate when the idle-stop mode is active, and trip and lifetime fuel economy readouts.

Transmission. The Accord Hybrid is equipped with a five-speed automatic transmission. The transmission is much the same as that used in the conventional Accord but has been modified to work with the IMA system and to provide better performance and fuel economy. The transmission is fitted with different gear ratios, a redesigned lockup torque converter, and an electric oil pump. The electric oil pump maintains consistent pressure within the transmission, whether the engine is running or not. In a conventional transmission, the engine drives the transmission's oil pump, and there is only pressure in the unit when the engine is running. The electric oil pump maintains hydraulic pressure when the engine is not running during idle-stop. The pressure allows the transmission to be responsive immediately after the engine is restarted.

Honda Hybrid Safety Issues

These hybrid systems rely on very high voltages. All of the high-voltage cables are covered in orange sleeves for easy identification, and you should follow the procedures for disarming the high-voltage system before performing any service on or near the high-voltage circuits. There is a main switch on the IPU that is used to disconnect the battery module from the rest of the car. There are three large capacitors in the MDM that will take at least 5 minutes to discharge after the switch is turned off. To disconnect the high-voltage system:

1. Remove the switch cover from the IPU cover **(Figure 7-37** and **Figure 7-38).**

3. Wait at least 5 minutes.
4. Remove the IPU cover.
5. Measure the voltage at the output terminals **(Figure 7-40).** Make sure the voltage is low enough for safe operation before any service is done to the car.

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Figure 7-37 The main power switch for the high-voltage system.

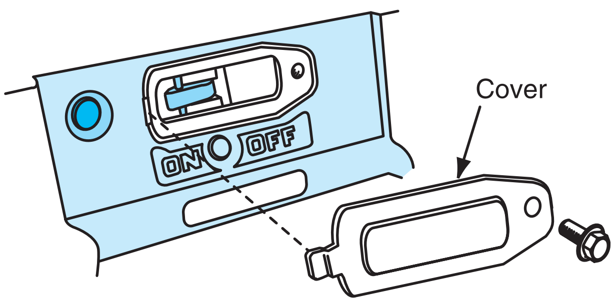

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Figure 7-38 To shut off the high-voltage circuit in a Honda hybrid, turn the ignition switch OFF, remove the rear seat back, and remove the battery module switch lid from the battery module.

The high-voltage circuits are isolated from the car's chassis ground. The car has a ground-fault detection system that can warn the driver if there is a short between the high-voltage circuit and the chassis.

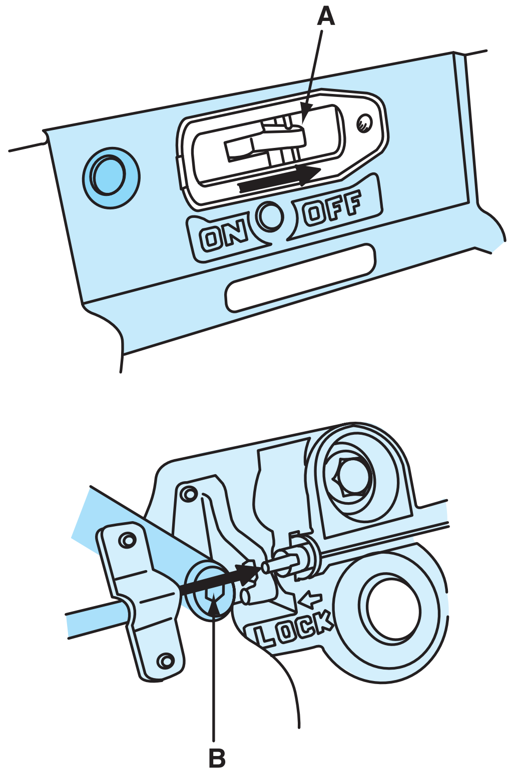

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Figure 7-39 Continue disabling the high-voltage system by turning the battery module switch (A) OFF. Make sure the bolt (B) is showing. Then, wait at least 5 minutes to allow the MDM capacitors to discharge before removing the IPU cover.

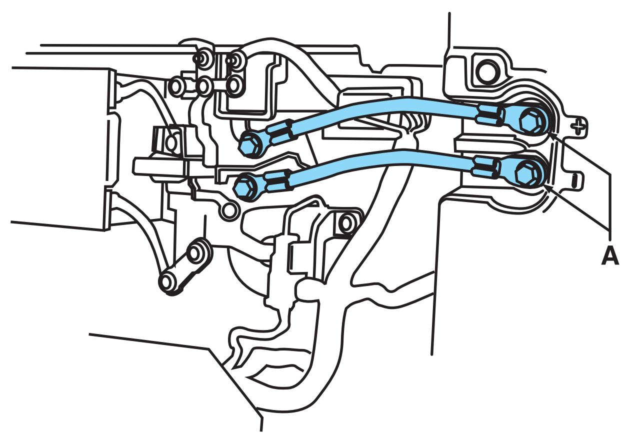

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Figure 7-40 Before doing any service with or near the high-voltage system, measure the voltage at the battery module terminals (A). There should be 30V or less. If more than 30V is present, there is a problem

Note: Throughout Honda's literature, service information, and press releases, the IMA motor is described as a DC brushless type or an AC synchronous type. It cannot be both and it is not. In fact, it is an AC synchronous motor, and many of the controls and sensors indicate this. An explanation for the apparent conflicting information comes from a source within Honda. I include this to prevent confusion and the possibility of a reader deeming the

contents in this chapter to be incorrect. Honda's position is, "The terminology for 'DC brushless' and 'AC synchronous' are both correct when viewed in the proper context. (1) DC brushless refers to the Honda IMA system from a total system standpoint, best described in two parts. A) The initial power source from the battery pack for the electric motor is DC (which is converted into AC via an inverter to power the electric motor). Simply put, DC is used to clearly indicate that the initial power source is DC. The brushless part is used to best describe the long life-cycle advantage of the motor's design. (2) AC Synchronous refers to the electric motor specifically. It is indeed an AC Synchronous design. This terminology is used to describe the electric motor when referencing it on an individual component basis. The best way to summarize this situation is that many terminologies exist for electric motor technology. The dual descriptions provided by Honda are attempting to best explain the technology from a total systems standpoint and from an individual component standpoint, as appropriate." After many discussions with Honda, I was asked how they should describe the motor. I suggested they describe the motor as a brushless AC synchronous motor. That description is accurate and tells the public what Honda wants them to know, and it says what the motor really is.

PORSCHE

It is rather ironic to call the Porsche GT3R a mild hybrid. But, by definition, it is very much a mild assist hybrid. This supercar was designed both to excel on racetracks and to be fuel efficient. The hybrid system is only used to assist a gasoline engine when extra power is needed to overtake another car or pull hard through a curve.

GT3R

The 911 GT3R Hybrid **(Figure 7-41)** does not use conventional hybrid technology; instead, it relies on an electro-mechanical flywheel system. Charged by kinetic energy created under braking and capable of operating at speeds of up to 40,000 rpm, the flywheel

Courtesy of Dr. Ing. h.c.F. Porsche AG

Figure 7-41 A Porsche® 911® GT3®R Hybrid.

can supply electrical energy to a pair of 60-kW motors mounted at the front wheels.

The two motors assist the engine, a 480-HP, naturally aspirated 4.0L flat-six that drives the rear wheels. The energy from the flywheel is never used as the only power to move the car. The flywheel can only provide short bursts of energy to the front motors at the touch of a button. While running endurance races, the hybrid needs to pit for fuel much less often than the competition.

This 400-volt electric-assist system is called a **KERS unit (Kinetic Energy Recovery System)**. The flywheel rotates on a vertical axis and is enclosed within a sealed container mounted on the passenger's floorboard next to the driver **(Figure 7-42).** The flywheel spins in a vacuum at an operational range of 28,000 to 40,000 rpm. To get the flywheel rotating at its maximum speed, and therefore at its highest charge, only a few hard braking events with rapid downshifts are needed.

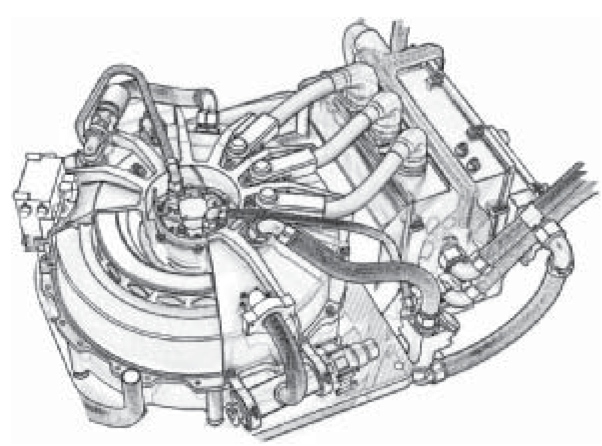

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Figure 7-42 The KERS in the Porsche® GT3®R hybrid.

Review Questions

1. The eAssist from GM is a BAS system that can increase fuel economy by 25 percent. What three functions of this system contribute the most to the improved efficiency?

2. What are the basic components of a belt alternator/starter hybrid system?

3. What are the main reasons that a mild hybrid consumes less fuel than a conventional vehicle?

4. Why would a high-performance hybrid car with about 600 available horsepower be called a mild hybrid?

5. In Honda hybrids, what is the purpose of the DC/DC converter?

6. What are the basic steps that should be followed to disable the high-voltage system in a Honda hybrid?

7. Which of the following statements about the high-voltage circuits in a Honda hybrid is NOT true?

   A. All of the high-voltage cables are covered in orange sleeves for easy identification.

   B. You should always perform the disarming of the high-voltage systems before performing any service work on or near the high-voltage circuits.

   C. There is a main switch on the instrument panel that is used to disconnect the battery module from the rest of the car.

   D. There are three large capacitors in the MDM that will take at least 5 minutes to discharge after the switch is turned off.

8. During deceleration, the eAssist system does three things to increase the amount of energy that can be regenerated. What are they?

9. Which of the following statements about a linear air-fuel (LAF) sensor is NOT true?

   A. The linear air-fuel sensor is located at the outlet of the three-way catalyst.

   B. Within the sensor, there is an exhaust flow chamber, an atmosphere reference chamber, and a diffusion chamber, plus a heater circuit that allows the sensor to work when the engine is cold.

   C. Positive voltage indicates a lean mixture and negative voltage indicates a rich mixture.

   D. The normal operating voltage range is about 1.5 volts.

10. In an Accord Hybrid, which of the following systems relies on microphones to function properly?

    A. VTEC

    B. ACM

    C. ANC

    D. VCM

CHAPTER 8 Power-Split-Type Full Hybrids

Learning Objectives

After reading and studying this chapter, you should be able to:

- Describe the difference between a mild and a full hybrid.
- List and explain the purpose of the basic components used in Toyota's hybrid system.
- Explain why hybrids work well with Atkinson cycle ICEs.
- Describe the basic operation of the two electric motors used in Toyota's hybrids.
- Explain why Toyota uses very high voltage to power the electric motors.
- Describe the purpose of an inverter.
- Describe the basic changes Toyota made to the ICEs used in its hybrid vehicles.
- Explain how Toyota provides four-wheel drive in its hybrid SUVs.
- Describe how Toyota modified the power-split unit for the high-voltage motors used in its SUVs.
- Describe the basic operation of the hybrid system used by Ford Motor Company.
- Explain how Ford provides four-wheel drive in its hybrid SUVs.

Key Terms

Atkinson cycle
battery smart unit
Brake System Control Module (BSCM)
electric motor-assisted power steering (EMPS)
Electric Throttle Control System-intelligent (ETCS-i)
Hybrid Vehicle Control Unit (HV ECU)
planetary carrier
planetary pinions
power-split device
resolver
ring gear
sun gear
System Main Relay (SMR)
Transmission Control Module (TCM)
Variable Valve Timing-intelligent (VVT-i)

INTRODUCTION

Full hybrids (referred to as "strong hybrids" by some) are vehicles that can be powered by their engine, one or motor electric motors, or a combination of these. Some full hybrids are described as having a series-parallel design because the engine is used to drive a generator as well as to power the vehicle **(Figure 8-1).**

Common power-split-type full hybrids include the Toyota Prius, Ford Escape, and Ford Fusions. Ford,

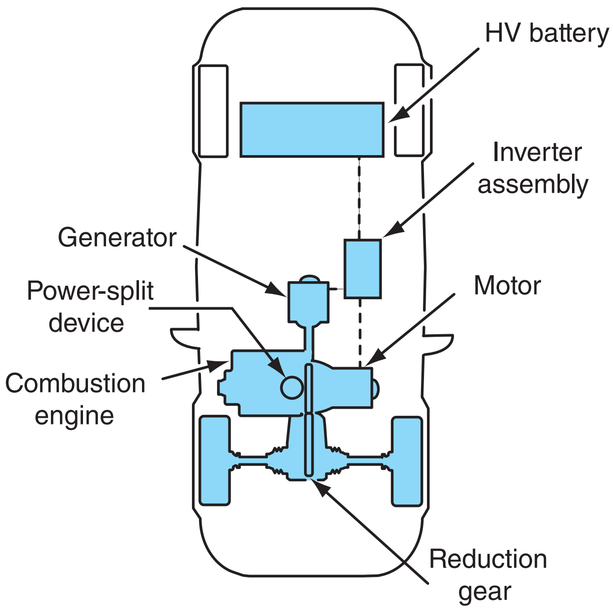

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Figure 8-1 The basic setup for a series-parallel hybrid system.

Toyota, and Lexus also have four-wheel-drive hybrid SUVs.

To function as a full hybrid, the vehicle must be fitted with a powerful electric motor and a high-voltage battery pack. These are necessary to provide the power required to move the vehicle on battery power alone. Full hybrids also require electronic and mechanical devices that allow for seamless switching between the power sources. Full hybrids also have regenerative braking, stop-start capabilities, and a motor that is used to assist the engine.

This chapter will look at the most common full hybrids that use the power-split system to achieve a true series-parallel full hybrid. Other designs are discussed in Chapter 9.

TOYOTA'S HYBRIDS

Toyota introduced the first mass-produced hybrid vehicle in 1997. The hybrid, the Prius, was only available in Japan until the 2000 model year, when it was brought to North America **(Figure 8-2).** Sales of the first-generation Prius were good, but sales increased drastically with the second generation in 2004. Toyota
Lexus (Toyota's premium brand) has introduced several hybrid models.

The original Prius did not look like a regular automobile. Its shape dictated by aerodynamics made it noticeable. Unlike the Honda Insight, which was the only other hybrid at that time, the Prius was a family car that could carry up to five passengers. The second-generation Prius grew up and now provides enough interior space to be classified as a mid-sized vehicle. With the size increase came an increase in power, making it more usable for everyday driving. The fuel economy ratings for the Prius have a combined EPA mileage estimate of 55 mpg. The Prius has also been certified as a SULEV, or Super Ultra Low Emission Vehicle. The Prius is the world's best-selling hybrid. In fact, there is a waiting list of potential buyers.

Courtesy of Dewhurst Photography and Toyota Motor Sales, U.S.A., Inc.

Figure 8-2 A 2001 Toyota Prius.

Toyota's approach to hybridization is based on both the series and parallel designs. The engine can power the vehicle or a motor/generator in the series configuration. Another motor/generator is used to assist the engine, power the vehicle by itself, or charge the batteries. The control of the motor/generators and the engine is one of the keys to Toyota's system. Complex electronics are required to monitor operating and driving conditions and to control the flow to and from the electric motor/generators. Toyota also relies on a power-splitting device that mechanically blends the output from the motors and the engine. This system **(Figure 8-3)** was called the

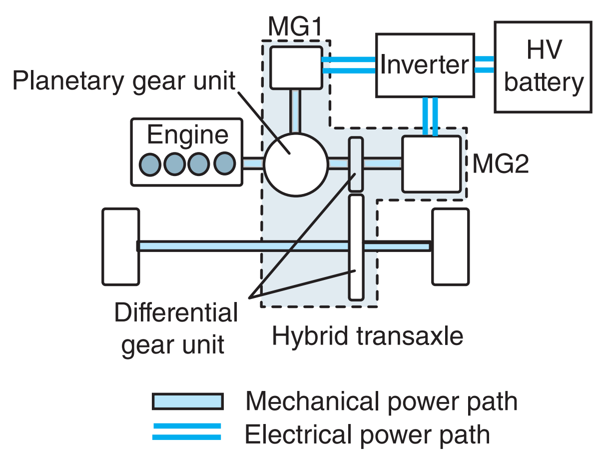

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Figure 8-3 The THS uses a combination of two types of motive forces: an engine and a motor. The THS can be divided into two systems: the series hybrid system and the parallel hybrid system.

Toyota Hybrid System (THS) when it was released, and the newer designs of the THS are called the Hybrid Synergy Drive (HSD) system.

Toyota has applied this technology to the Camry and to its mid-sized SUV (Highlander), and Lexus has many hybrid versions of its cars and SUVs. All use a version of HSD with electric motors and an internal combustion engine (ICE). Four-wheel-drive models of these are also available. These vehicles are also based on the HSD system and have front and rear electric motors in addition to the engine.

Toyota Prius

The first-generation Prius had a fuel-efficient 1.5L, four-cylinder gasoline engine rated at 70 horsepower (52 kW) and a 45-horsepower (33-kW) electric traction motor. A separate motor/generator was used to charge the battery pack and to start the engine; this motor did not contribute power to move the car. During deceleration and braking, the traction motor worked as a generator to provide for regenerative braking.

Power for the second-generation Prius is provided by the same 1.5L, four-cylinder gasoline engine, now rated at 76 horsepower (57 kW), and a 68-horsepower (50-kW) electric motor. This model also has a second motor/generator connected to the engine. With the second generation came a larger car **(Figure 8-4)** and a redesigned version of Toyota's hybrid system. The additional size and more powerful engine did not increase fuel consumption; rather, fuel economy improved. The improvements made to the hybrid system allowed the motor to power the vehicle by itself for longer periods, and the amount of energy captured during regenerative braking was increased. Both of these reduced the amount of time the engine must drive the generator to keep the battery pack charged.

The third generation again brought a more powerful engine and traction motor into the car. The engine is now a 1.8L four-cylinder with Variable Valve Timing with intelligence. It is rated at 98 horsepower

Courtesy of Dewhurst Photography and Toyota Motor Sales, U.S.A., Inc.

Figure 8-4 A 2006 Toyota Prius.

at 5,200 rpm and 105 ft.-lb of torque at 4,000 rpm. The permanent magnet traction motor now can deliver 80 HP (60 kW) and 153 ft.-lb.

This generation has three driver-selected operating modes: EV, Eco, and Power. When the EV mode is selected, the car will drive solely on battery power for up to one-half mile under certain conditions. The Eco mode helps to maximize fuel economy. The Power mode increases the sensitivity of the gas pedal, so the car feels more responsive to throttle position.

The revised HSD systems use a smaller NiMH battery pack with a slightly lower nominal voltage (201.6V). However, the systems can boost the voltage to the motor up to 650V. This additional voltage reduces the required amount of current to power the motor and decreases the amount of electrical energy lost as the motor is powered. If the motor's power (output watts) is held constant, the amount of current drawn by the motor will inversely increase or decrease with a decrease or increase in voltage. Therefore, if the voltage is doubled, the current will be reduced by half. Also, if the current to the motor is held constant and the voltage is increased, the motor's power will be increased.

As current flows through a wire, some of the electrical energy is changed to heat as the electrons move through the wire. The heat is a result of the resistance in the wire. When current is low, less heat is produced, and therefore less energy is lost. According to Joule's law, if the current is reduced by half and circuit resistance remains the same, the amount of energy lost is reduced by 75 percent. This decrease in energy loss increases the efficiency of a hybrid vehicle.

The engine in a Prius drives the wheels and/or a generator only when needed. The primary goal of the HSD is to use electric power as often as possible. The electronics of the system respond to driver inputs and driving conditions and attempt to keep the car operating in its most efficient mode at all times. The engine only runs when extra drive power is needed or when the battery pack needs recharging. The engine is connected to the drive wheels and a generator through the transmission. The transmission houses a single planetary gear assembly, the power-split device. This device controls where the engine's output is directed: to the drive wheels, the generator, or both.

Operation. The basic operation of all generations of the hybrid system is much the same. The THS relies on an engine, a motor/generator that serves as the starter motor and a generator (referred to as MG1, Motor Generator 1), and a traction motor and generator (called the MG2, Motor Generator 2).

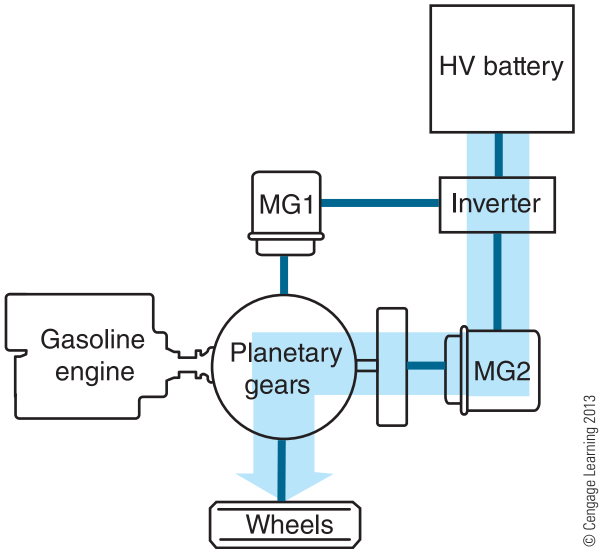

Figure 8-5 During initial acceleration, electrical power from the battery pack to MG2 provides the energy to drive the wheels.

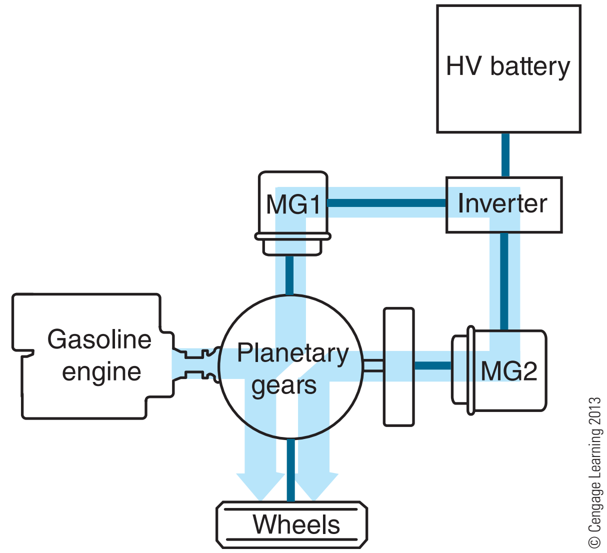

Figure 8-6 While the wheels are being driven by the engine through the planetary gears, MG1 is rotated by the engine to supply voltage to MG2.

This is how the existing "system" works (please keep in mind that this is an evolving technology and things do and will change!): When Drive is selected and the driver releases the brake pedal, the traction motor (MG2) moves the vehicle forward **(Figure 8-5).** The motor is able to supply propulsion power until the battery pack's voltage drops or the driver calls for rapid acceleration. When MG2 is powering the vehicle, the engine is off, and MG1 holds the sun gear in the planetary gear set and does not function as a generator. If battery recharging is needed, the engine starts and drives MG1. When reverse gear is selected, MG2 rotates in a reverse direction. The engine remains off, as does MG1.

In later systems, the battery's state of charge and temperature, engine coolant temperature, and the electrical load determine whether the engine starts when the POWER button is depressed. During conditions that do not meet minimum requirements, the engine is started to drive MG1 to charge the battery.

During normal operating conditions, as vehicle speed increases the engine starts. The power from the engine is split according to the needs of the system. Part of the engine's power drives MG1 to supply energy to MG2, which is working to assist the engine. The
the vehicle. The amount of engine power sent to the generator and drive wheels is controlled by the system. When the vehicle is at a cruising speed, both the engine and MG2 power the vehicle **(Figure 8-6).** If engine power is not needed to maintain the speed, the system will shut down the engine, and the vehicle is powered by electricity alone. If the battery's state of charge gets low, the engine is restarted to drive MG1.

To overcome a heavy load, such as during acceleration, climbing a hill, or passing another vehicle on the highway, both the engine and MG2 power the car. MG2 receives energy from MG1 and the battery pack. This enables the traction motor to work under full power. The engine also works under full power to ensure smooth acceleration and to drive MG1 for maximum electrical generation. Once the car returns to a normal cruising speed, battery power for MG2 is shut off, and battery recharging is provided by MG1, driven by the engine **(Figure 8-7).**

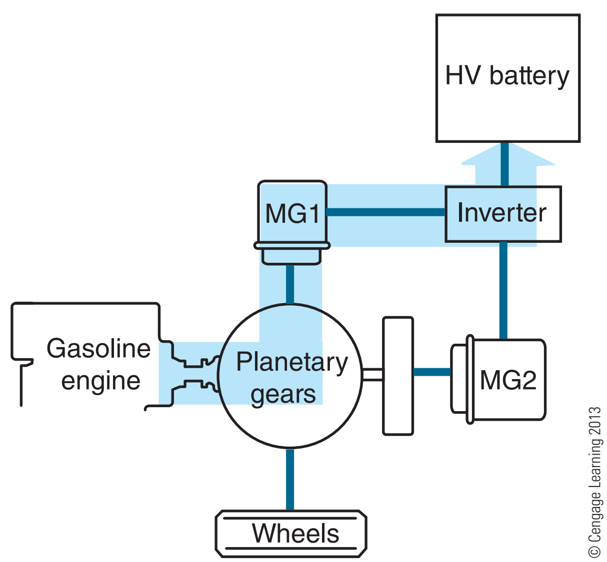

Figure 8-7 To charge the battery pack, MG1 is rotated by the engine through the planetary gears.

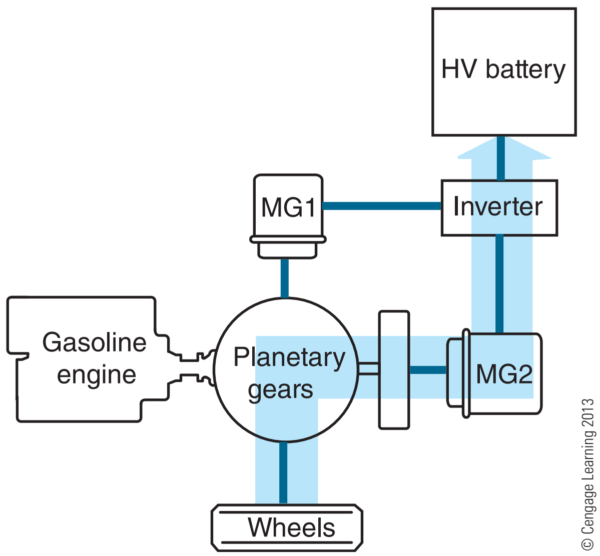

Figure 8-8 When the vehicle is decelerating, the vehicle's kinetic energy is captured by MG2 and is used to charge the battery pack.

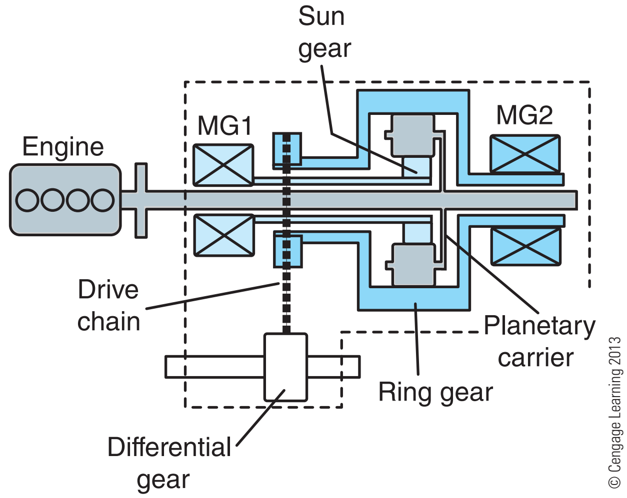

Figure 8-9 The transaxle assembly with MG1, MG2, and the power-split device.

During deceleration or braking, MG2 acts as a high-output generator, driven by the car's wheels **(Figure 8-8).** As soon as the driver lets off the accelerator pedal, the engine is shut down, MG2 becomes a generator, and regenerative braking begins. When the driver presses the brake pedal, most of the initial braking force is actually the force required to turn MG2. The hydraulic brake system supplies the rest of the braking force and brings the car to a halt.

The engine remains off when the car is stopped, unless the battery pack needs recharging. In this case, the engine automatically restarts to drive MG1. However, if the air-conditioning system on a first-generation Prius is set on MAX A/C, the engine will not shut down because the air-conditioning compressor is driven by the engine. More recent models have an electrically operated compressor, and the engine can be shut down without affecting A/C operation. Stop-start in a Prius operates differently than the systems used in mild and assist hybrids. Because the traction motor can power the car by itself, the engine does not restart as soon as the driver releases the brake pedal or depresses the accelerator. The engine in a Prius is only restarted when it is needed to power the vehicle or to drive the generator.

After
and puts the gear selector in the Park position, the engine may run and drive MG1 to recharge the batteries. This activity is determined by the control unit.

Motor/Generators. The main components of the hybrid system include the engine, MG1, MG2, a planetary gear set (**power-split device**), the control unit, an inverter, and the battery pack. The system is capable of instantaneously switching from one power source to another or combining the two. Electronic controls and the power-split device **(Figure 8-9)** channel the outputs of these power sources.

Both the MG1 and the MG2 are permanent magnet AC synchronous motors that can also function as generators **(Figure 8-10).** MG1 starts the engine when engine power is needed. It also is driven as a generator, by the engine, whenever electrical energy is needed to run MG2 or to recharge the battery pack. In addition, when acting as a generator, its speed varies with the charging needs of the system and, therefore, MG1 effectively controls the power-split device.

AC synchronous motors require a sensor to monitor the position of the rotor within the stator. It is necessary to time, or phase, the three-phase AC so it attracts the rotor's magnets and keeps it rotating and producing torque. AC creates a rotating magnetic field in the stator, and the rotor chases that field. The control

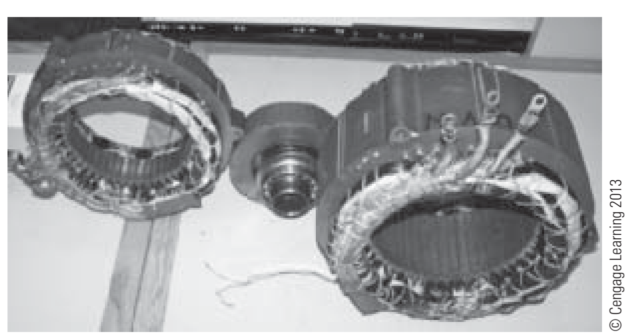

Figure 8-10 The stator assemblies for MG1 and MG2.

system monitors the position and speed of the rotor and controls the frequency of the stator's voltage, which controls the torque and speed of the motor.

Toyota uses a sensor **(Figure 8-11),** called a **resolver**, in MG1 and MG2 to monitor the position

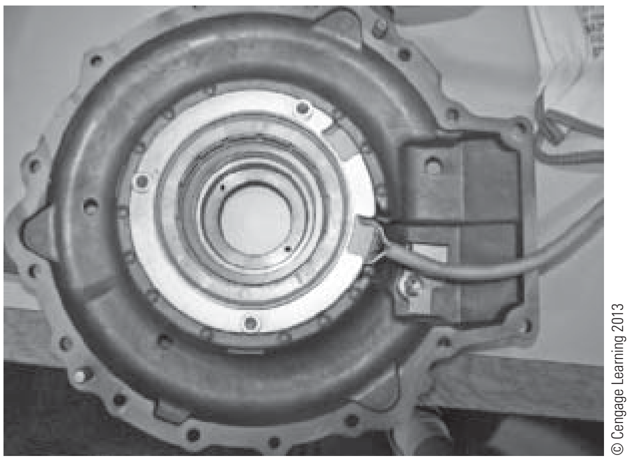

Figure 8-11 A resolver located in each motor precisely detects the magnetic pole position of the rotor and allows the control unit to monitor and control the activity of MG1 and MG2.

of the rotor. The sensor has three individual coil windings: one excitation coil and two detection coils. The detection coils are electrically staggered at 90 degrees. The flow of alternating current into an excitation coil results in a constant frequency through the coil.

This frequency is sent to the detection coils and is altered by the presence of the rotating magnetic field. Because the rotor has an oval shape, the gap between the stator and rotor varies as the rotor rotates. A strengthening and weakening of the magnetic field occurs with the changing gap and alters the frequency at the detection coils. The MG ECU bases the exact position of the rotor on the difference between the frequency values of the detection coils. The MG ECU also calculates the rotational speed of the rotor based on the speed at which the position changes.

Electronic Controls. The ultimate control of the hybrid system is the responsibility of the **Hybrid Vehicle Control Unit (HV ECU)**. This microprocessor receives information from sensors and other processors and in turn sends commands to a variety of actuators and controllers **(Figure 8-12).** In 2004 and newer Prius models, CAN communication is used to link the

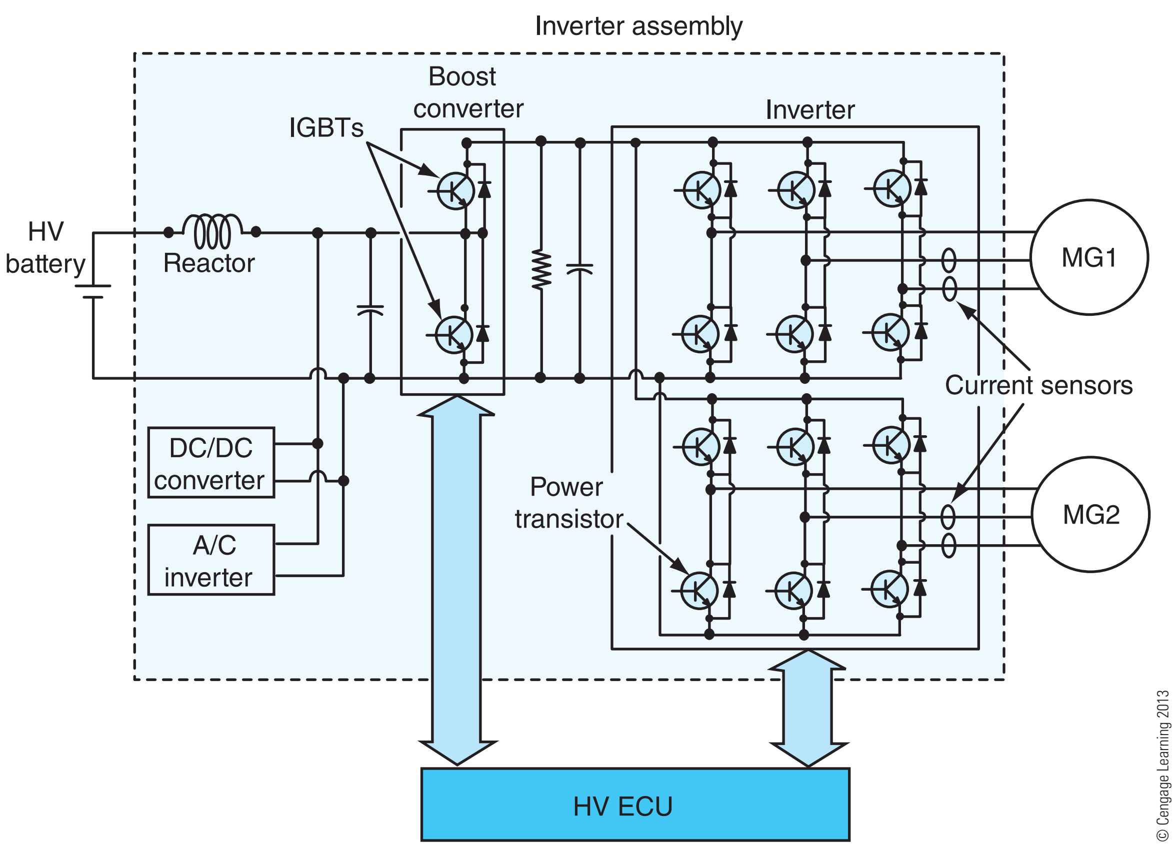

Figure 8-12 An electrical schematic for the hybrid control system.

various microprocessors together. In addition, these late-model cars have a 32-bit CPU rather than a 16-bit unit as used in earlier models. This change increased the processing speed of the control unit.

The control system:

- Controls MG1, MG2, and the engine based on torque demand, vehicle speed, regenerative brake control, and the battery pack's state of charge (SOC). The primary inputs for this calculation are from speed sensors, the shift position, accelerator pedal position, and the skid control ECU that controls regenerative braking.
- Controls the operation of the hybrid transaxle.
- Monitors the SOC and temperature of the battery, MG1, and MG2.
- Monitors the operation of the hybrid system and runs continuous self-diagnostic routines. If a malfunction is detected, the unit stores a diagnostic code and controls the system according to data stored in its memory rather than current conditions (fail-safe), or it may shut down the entire system, depending on the malfunction.
- Sends information and commands to the Engine Control Module (ECM), inverter assembly, battery ECU, and skid control ECU to control the system.

The ECM and skid control ECUs were also updated to 32 bits on late models. The ECM coordinates the engine's activity with the hybrid system. It starts and stops the engine as needed as well as controlling the operation of the engine. The skid control ECU or brake ECU calculates the total amount of braking force needed to stop or slow down the car based on the pressure exerted on the brake master cylinder. This in turn determines how much regenerative braking should take place and how much pressure should be sent to the brakes through the hydraulic system. This information is sent to the HV ECU, which controls the regenerative braking of MG2. The brake ECU also controls the hydraulic brake actuator solenoids and generates pressure at the individual wheel cylinders. The total amount of force applied to the hydraulic brake system is the total required brake force minus the force supplied through regenerative braking. The skid control ECU also controls the operation

lock brake operation, no regenerative braking takes place.

Battery. All models of the Prius rely on NiMH batteries for hybrid operation. They also have an auxiliary battery that serves as the power source for the ECM,

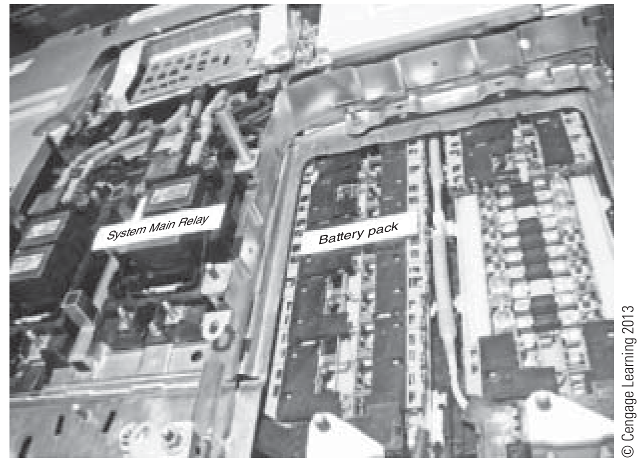

Figure 8-13 The battery module contains the HV battery pack, battery ECU, and the System Main Relay (SMR). The module is positioned behind the rear seat, in the trunk.

lights, and other 12-volt systems. The battery module **(Figure 8-13)** contains the hybrid (HV) battery pack, battery ECU, and three **System Main Relays (SMRs)**. The module is positioned behind the rear seat, in the trunk.

The battery ECU receives information about the HV battery's current SOC, temperature, and voltage from various sensors. This information is then sent to the HV ECU, which controls MG1 to keep the battery pack at the proper charge. The battery ECU also calculates the charging and discharging amperage required to allow MG2 to power the car. This information is also sent to the HV ECU, which sends commands to the ECM to control the engine's output. This continuous loop of information is done to maintain at least a 60 percent SOC at the battery. On late models, the battery ECU is a 32-bit microprocessor.

The battery ECU also monitors the temperature of the batteries during the charge and discharge cycles. The battery ECU also estimates the temperature change that will result from the cycling. Based on this information, it can adjust the battery's cooling fan or, if a malfunction is present, it can slow down or stop charging and discharging to protect the battery. To monitor and calculate battery cooling needs, the bat-

the battery module and a temperature sensor in the air intake for the module.

If the battery ECU determines there is a problem with the battery pack, it will illuminate a warning light on the instrument panel and store the appropriate Diagnostic Trouble Code (DTC) in its memory.

The SMRs connect and disconnect the high-voltage circuit based on commands from the HV ECU. This relay is actually composed of three separate relays and a resistor. Two of the relays (SMR1 and SMR2) are connected to the positive side of the battery pack and the other (SMR3) is in the negative circuit. When the high-voltage circuit is initially turned on, SMR1 and SMR3 are energized by the HV ECU using 12 volts from the auxiliary battery. The resistor is in series with SMR1 and serves to control the amount of current that flows through the relay to eliminate a current surge when the circuit is turned on. Once the circuit is turned on, SMR1 turns off and SMR2 is turned on. This allows full current flow out of the battery pack. When the circuit is shut down, SMR2 and SMR3 are de-energized. If the HV ECU receives a deployment signal from the airbag sensor or an actuation signal from the inverter's circuit breaker sensor, the HV ECU will open the high-voltage circuit by de-energizing the SMR.

A service plug and main high-voltage fuse are inserted in the high-voltage circuit. The fuse protects the circuit by opening if there is excessive current in the circuit. The service plug is used to disconnect or isolate the high-voltage circuit so that service can be performed on the circuit. The service plug is positioned in the middle of the battery modules. When it is removed, the circuit is open.

> **CAUTION** *Always turn OFF the vehicle before removing the service plug. Wear insulating gloves when removing the plug and when working on high-voltage systems. Keep the removed service plug in your pocket to prevent others from installing it while you are servicing the vehicle. After removing the service plug, do not touch the high-voltage connection and terminals for at least 10 minutes. Also, do not operate the power switch with the service plug removed; doing so may damage the HV ECU.*

Individual high-voltage cables **(Figure 8-14)** are used to connect the battery pack to the inverter, the inverter to MG1, the inverter to MG2, and the inverter to the air-conditioning compressor. The cables run from
engine compartment. The high-voltage cables are shielded to reduce electromagnetic interference and are orange in color for easy identification.

Inverter. The inverter controls current flow to and from the motor/generators and the batteries. It is a single unit that contains the inverter, DC/DC converter, boost converter, and air-conditioning inverter.

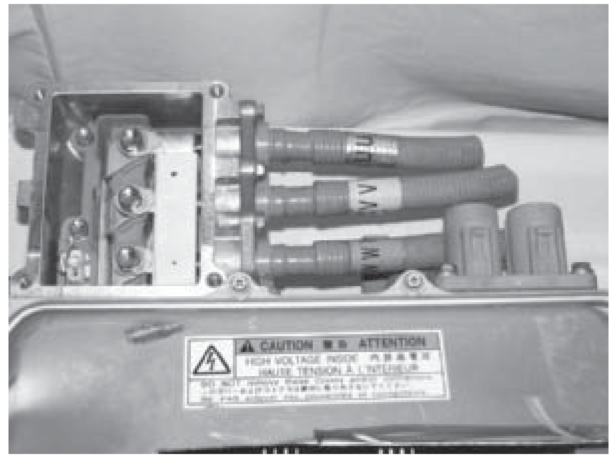

Figure 8-14 Individual high-voltage cables connect the battery pack to the inverter, the inverter to MG1, the inverter to MG2, and the inverter to the air-conditioning compressor.

The inverter **(Figure 8-15)** changes the battery's high-voltage DC into high-voltage AC to power MG1 and MG2. It also rectifies the AC generated by MG1 and MG2 to recharge the battery pack. The inverter is basically a three-phase parallel circuit with each leg containing two power transistors

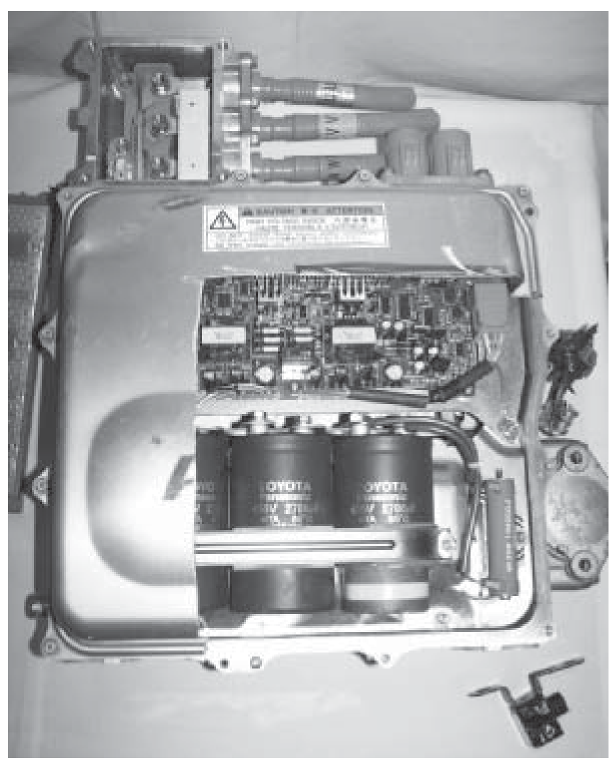

Figure 8-15 A cutaway view of an inverter.

connected in series. The HV ECU controls the power transistors to ensure proper phasing of the AC to the motors. This circuit is connected between the motor/generator and the battery pack. The inverter assembly contains two of these circuits, one for each of the motor/generators.

The DC/DC converter changes the high DC voltage from MG1 and MG2 to 12 volts and sends it to the auxiliary battery. The converter is composed of four transistors, four diodes (to maintain DC), a transformer, and two more diodes. The four transistors and diodes are used to control the high voltage at one side of the transformer. The other diodes rectify the voltage on the output side of the transformer. The voltage of the auxiliary battery is monitored by the converter, which attempts to keep it at a constant level. The voltage of the battery does not, as in conventional vehicles, change with engine speed or electrical load. If a problem occurs in the hybrid system, the HV ECU will stop the operation of the converter.

The late-model Prius has a boost converter that provides high voltage (up to 650 volts) to MG2. This increased voltage increases the power output of the motor. This converter is composed of the boost Integrated Power Module (IPM) that contains two Insulated Gate Bipolar Transistors (IGBTs), a reactor to store the energy, and a signal processor **(Figure 8-16).**

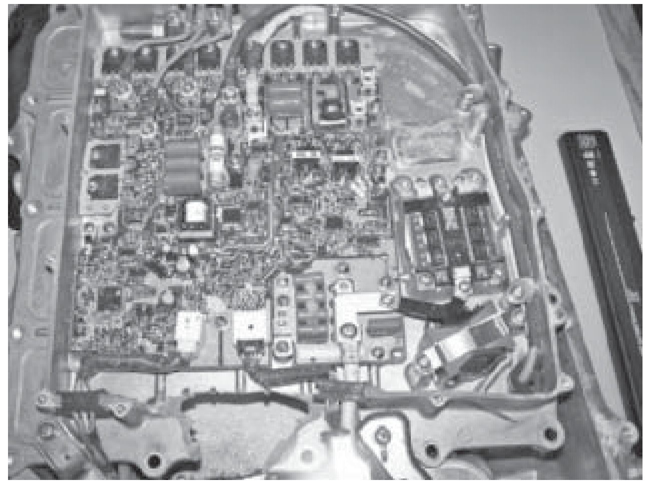

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Figure 8-16 The circuitry inside an inverter.

Engine. The engine is a 1.5L or 1.8L, four-cylinder engine. The horsepower ratings of the engine have increased over time. These increases were largely due to changes that also reduced exhaust emissions. The changes include improved engine controls and the inclusion of a coolant heat storage system **(Figure 8-17).** This system takes hot coolant from the engine and stores it in an insulated tank where it can stay hot for up to three days. When the engine is restarted, an electric water pump circulates the hot coolant through the engine to preheat it. This reduces

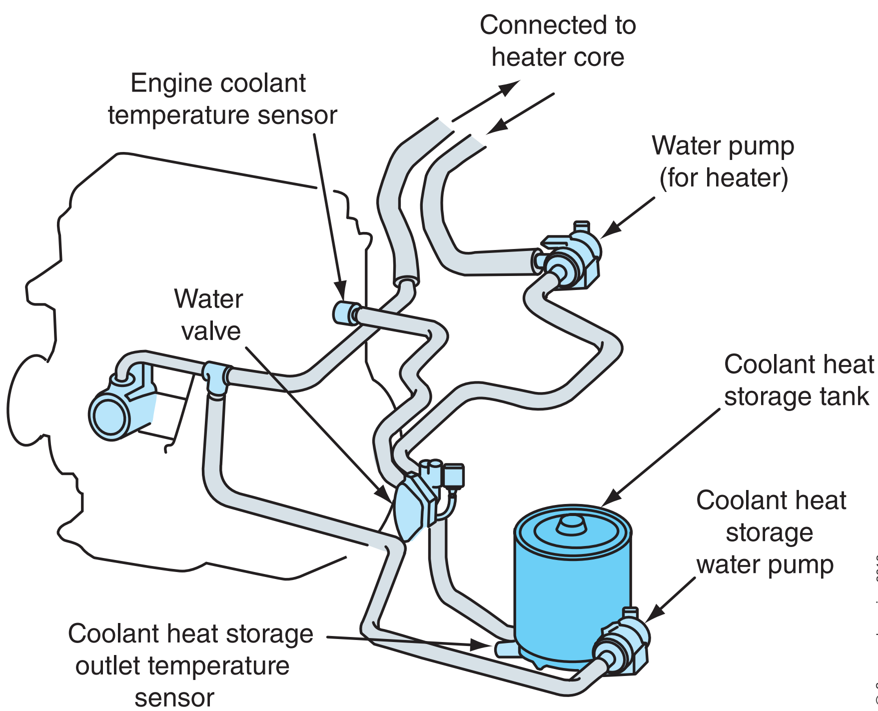

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Figure 8-17 The coolant heat storage system.

the amount of HC emissions normally associated with cold starting.

The engine is based on the Atkinson cycle and is equipped with the **Variable Valve Timing-intelligent (VVT-i)** system and **Electric Throttle Control System-intelligent (ETCS-i)**. In an **Atkinson cycle** engine, the intake valve is kept open well into the compression stroke. The timing of the opening and closing of the intake valves is controlled by the VVT-i system. While the valve is open during the compression stroke, some of the air/fuel mixture is pushed back into the intake manifold. This reduces the volume in the cylinder and effectively reduces the displacement of the engine. Because the allotted time for gas expansion during combustion is longer, fuel consumption is minimized, as are exhaust emissions. The engine runs with normal displacement when the intake valves close earlier. This action provides for more power output. Because the VVT-i system responds to operating conditions, the displacement of the engine changes accordingly.

A "surge tank" is located in the intake manifold to hold the mixture pushed out of the cylinder during the Atkinson compression stroke.

The VVT-i system is controlled by the ECM. With this system, the intake valve can change within a range of 43 degrees. The ECM adjusts valve timing according to engine speed, intake air volume, throttle position, and water temperature. In response to these inputs, the ECM sends commands to the camshaft timing oil control valve.

The VVT-i controller, which is housed at the end of the camshaft, is a housing driven by the crankshaft. The ECM controls the oil pressure sent to the controller. A change in oil pressure changes the position of the camshaft and the timing of the valves. The camshaft timing oil control valve is duty cycled by the ECM to advance or retard intake valve timing. The various valve timing settings are shown in **Figure 8-18.**

The camshaft timing oil control valve selects the path for oil pressure to the VVT-i controller according to signals from the ECM to advance, retard, or hold (keep things the same) the timing. The controller rotates the intake camshaft in response to the oil pressure. An advance in timing results from oil pressure being applied to the timing advance side vane chamber (see

and the oil pressure is applied to the timing retard side vane chamber **(Figure 8-20),** the timing is retarded. The ECM constantly calculates the desired or required valve timing based on the conditions of the car and the engine.

In addition to controlling the VVT-i system, the vehicle's ECM also controls the operation of the fuel injection and ignition systems. The input from many sensors is used to govern the engine in order to provide maximum efficiency. On the 2004 and newer Prius, an air/fuel sensor is placed before the catalytic converter rather than a conventional oxygen sensor.

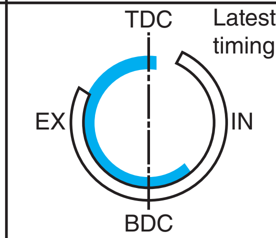
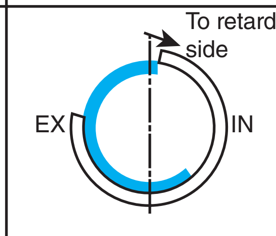
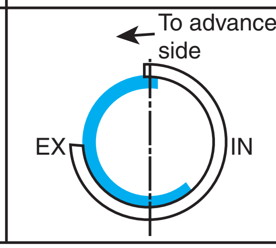
The ETCS-i system controls the position of the throttle plate. There is no mechanical connection between the accelerator pedal and the throttle plate; the connection is made electronically. The ECM calculates the appropriate throttle opening and sends commands to the throttle control motor. The ECM receives inputs from the accelerator pedal position sensor and the HV ECU. The HV ECU monitors current operating conditions and the battery's state of charge to determine the optimal engine speed and sends that information to the ECM.

Transaxle. The power-split device is also called the hybrid transaxle assembly **(Figure 8-21).** The unit functions as a continuously variable transaxle, although it does not use the belts and pulleys normally associated with CVTs. The variability of this transaxle depends on the action of MG1 and the torque supplied by MG2 and/or the engine. The transaxle unit contains:

- Differential assembly
- Reduction unit
- Motor Generator 1 (MG1)
- Motor Generator 2 (MG2)
- Transaxle damper
- Planetary gear set

A conventional differential unit is used to allow for good handling when the car is making a turn. The reduction unit reduces the final drive ratio so that ample torque is available to the drive wheels. The reduction unit is a gear set linked by a chain. MG1, which generates energy and serves as the engine starter, is connected to the planetary gear set. This is also true for MG2, which is also connected to the differential unit by gears or a drive chain. This transaxle does not have a torque converter or clutch. Instead, a damper is used to cushion engine vibration and the power surges that result from the sudden engage-

The planetary gear set provides continuously variable gear ratios and serves as the power-splitting device. The engine, MG1, and MG2 are mechanically connected at the planetary gear set. The gear set can transfer power between the engine, MG1, MG2, drive

Operation State	Range	Valve Timing	Objective	Effect
During Idling	1		Eliminating overlap to reduce blowback to the intake side	Stabilized idling rpm Better fuel economy
At Light Load	2		Decreasing overlap to eliminate blowback to the intake side	Ensured engine stability
At Medium Load	3		Increasing overlap to increase internal EGR for pumping loss elimination	Better fuel economy Improved emission control

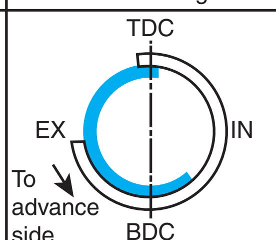
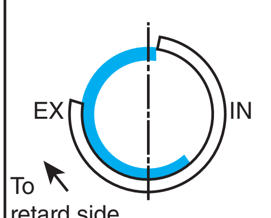
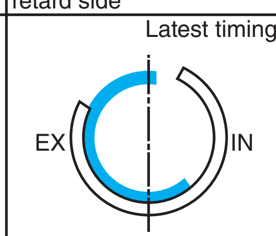
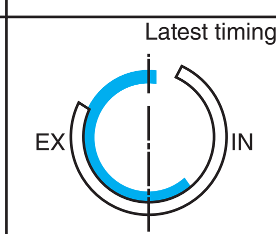
Operation State	Range	Valve Timing	Objective	Effect
In Low-to-Medium Speed Range with Heavy Load	4		Advancing the intake valve close timing for volumetric efficiency improvement	Improved torque in low-to-medium speed range
In High Speed Range with Heavy Load	5		Retarding the intake valve close timing for volumetric efficiency improvement	Improved output
At Low Temperatures	—		Eliminating overlap to prevent blowback to the intake side for reduction of fuel increase at low temperatures, and stabilizing the idling rpm for decreasing fast idle rotation	Stabilized fast idle rpm Better fuel economy
Starting/ Stopping the Engine	—		eliminate blowback to the intake side	Improved startability

Figure 8-18 The various valve timing settings for the VVT-i system.

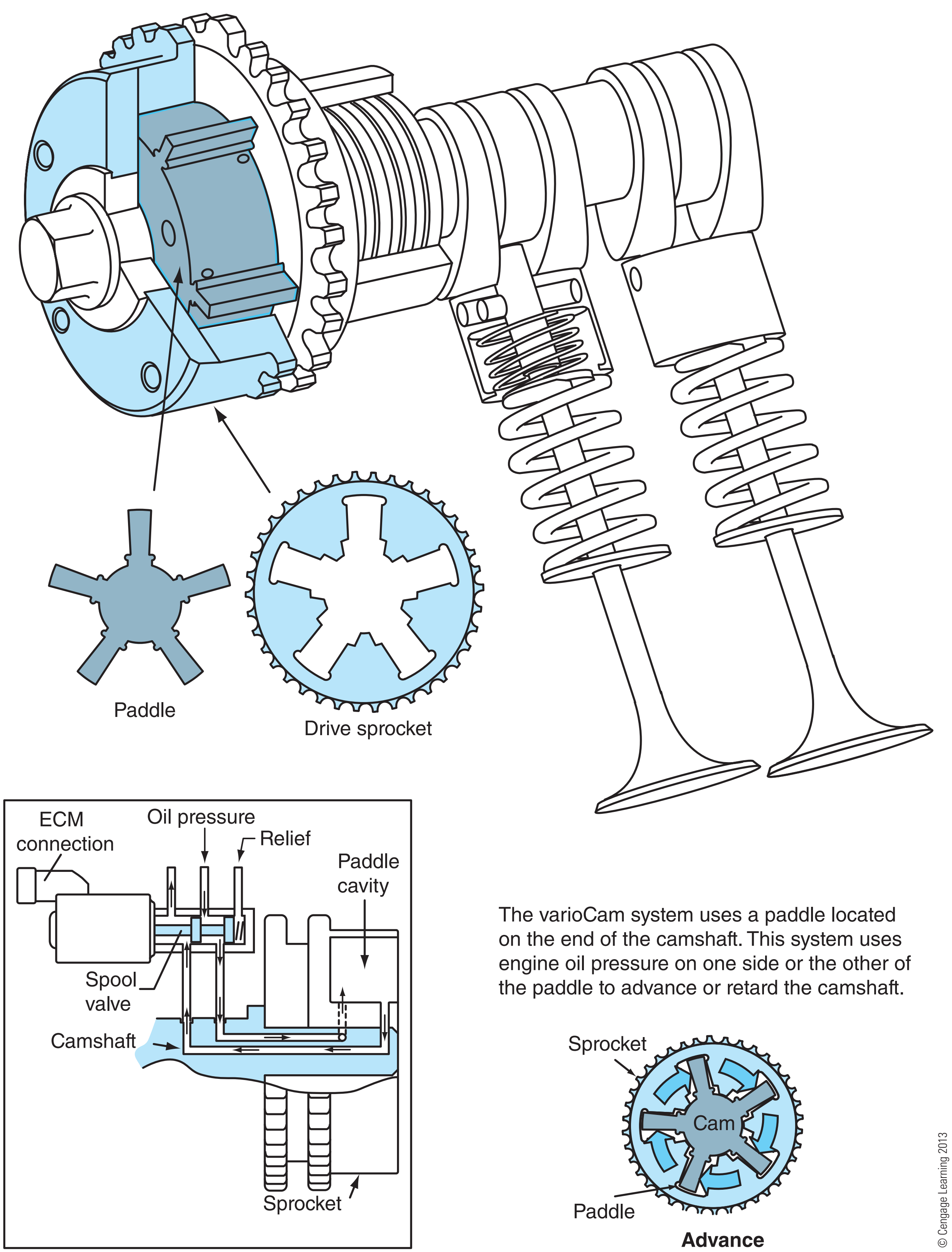


Figure 8-19 The camshaft timing oil control valve is duty cycle controlled by the ECM. When the camshaft timing oil control valve is positioned as shown here, the resultant oil pressure is applied to the timing advance side chamber to advance the camshaft.

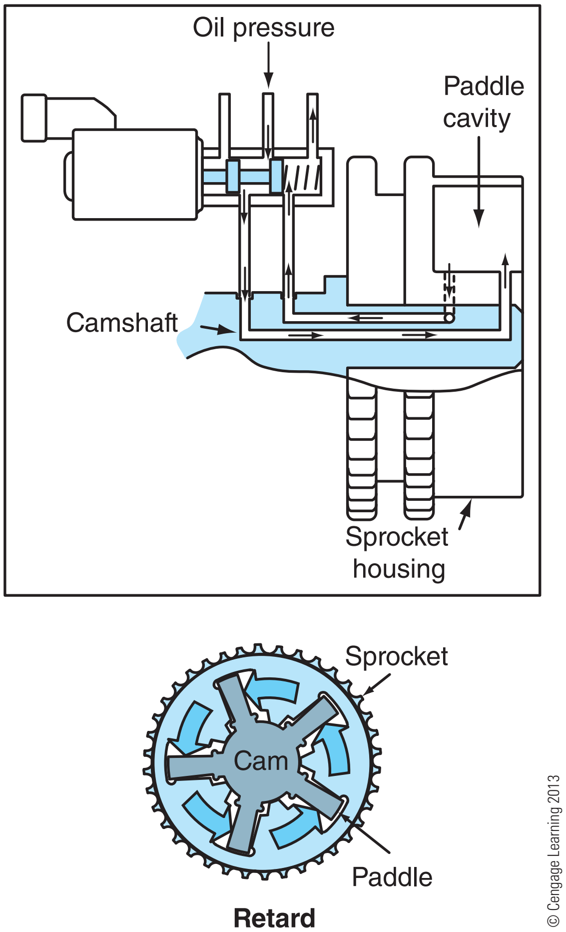


Figure 8-20 When the camshaft timing oil control valve is moved by a retard signal from the ECM, oil pressure is applied to the retard side vane chamber to rotate the camshaft in the timing retard direction.

wheels, and in nearly any combination of these. The unit splits power from the engine to different paths: to drive MG1, to drive the car's wheels, or both. MG2 can drive the wheels or be driven by them.

To understand how this power-split device and transaxle work, a look at the operation of a planetary gear set is necessary. A simple planetary gear set **(Figure 8-22)** has three parts: a sun gear, a carrier with planetary pinions mounted to it, and an internally toothed **ring gear**. The **sun gear** is located in the center of the assembly. It meshes with the teeth of the planetary pinion gears. Planetary pinion gears are small gears fitted into a framework called the **planetary carrier**. The

of the planetary pinion gears (planetary pinion gears are typically called **planetary pinions**). The carrier and pinions are considered one unit—the mid-sized gear member. The planetary pinions surround the sun gear and are surrounded by the ring gear, which is the largest part of the gear set. The ring gear acts like a band to hold the gear set together and provide great strength to the unit.

Each member of a planetary gear set can spin (revolve) or be held at rest. Power transfer through a planetary gear set is only possible when one of the

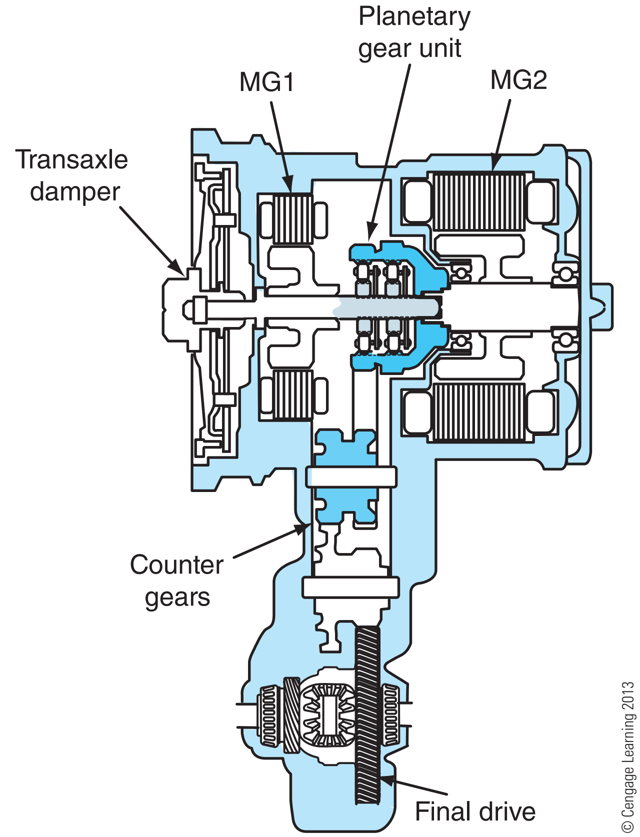


Figure 8-21 The hybrid transaxle in a late-model Prius.

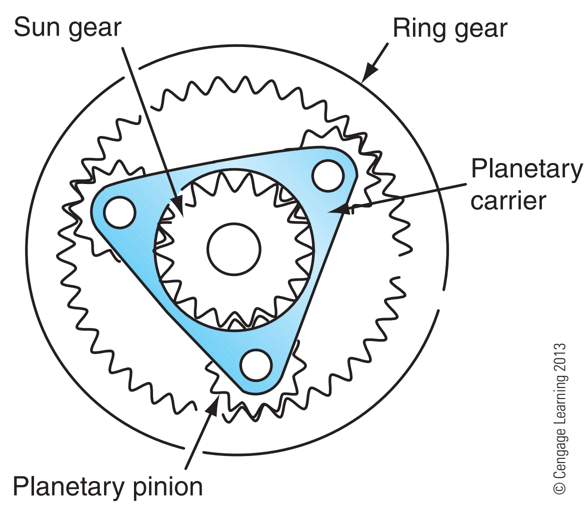


Figure 8-22 The components of a simple planetary gear set.

SUN	CARRIER	RING	SPEED	TORQUE	DIRECTION
Input	Output	Held	Maximum reduction	Maximum increase	Same as input
Held	Output	Input	Minimum reduction	Minimum increase	Same as input
Output	Input	Held	Maximum increase	Maximum reduction	Same as input
Held	Input	Output	Minimum increase	Minimum reduction	Same as input
Input	Held	Output	Reduction	Increase	Opposite of input
Output	Held	Input	Increase	Reduction	Opposite of input

Figure 8-23 The basic laws of reduction in a simple planetary gear set.

members is held at rest, or if two of the members are locked together. Any one of the three members can be used as the driving or input member. Another member might be kept from rotating and thus becomes the held or stationary member. The third member then becomes the driven or output member. Depending on which member is the driver, which is held, and which is driven, either a torque increase or a speed increase is produced by the planetary gear set. Output direction can also be reversed through various combinations. The amount of torque and speed change depends on the size of the gears serving as the input and output. Also, remember that when a combination of gears results in an increase in speed, there will be a corresponding decrease in output torque. Likewise, a decrease in output speed results in an increase in torque. **Figure 8-23** summarizes the results of various gear combinations in a simple planetary gear set.

In the planetary gear set used in the power-split device, the sun gear is attached to MG1. The ring gear is connected to MG2 and the final drive unit in the transaxle. The planetary carrier is connected to the engine's output shaft. The key to understanding how this system splits power is to realize that when there are two sources of input power, they rotate in the same

one can assist the rotation of the other, slow down the rotation of the other, or work together. Also, keep in mind the rotational speed of MG2 largely depends on the power generated by MG1. Therefore, MG1 basically controls the continuously variable transmission function of the transaxle. Here is a summary of the

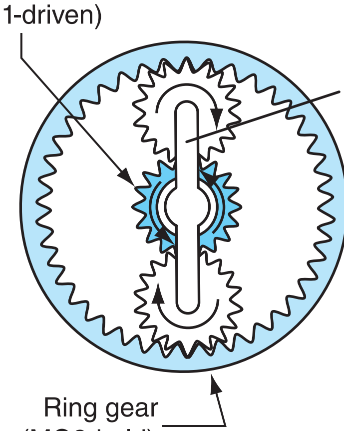


Figure 8-24 Planetary gear action during engine startup.

action of the planetary gear set during different operating conditions:

- To start the engine, MG1 is energized and the sun gear becomes the drive member of the gear set **(Figure 8-24).** Current is sent to MG2 to lock or hold the ring gear. The carrier is driven

  the ring gear to crank the engine at a speed higher than that of the sun gear.
- After the engine is started, MG1 becomes a generator. The ring gear remains locked by MG2 and the carrier now drives the sun gear, which spins MG1.

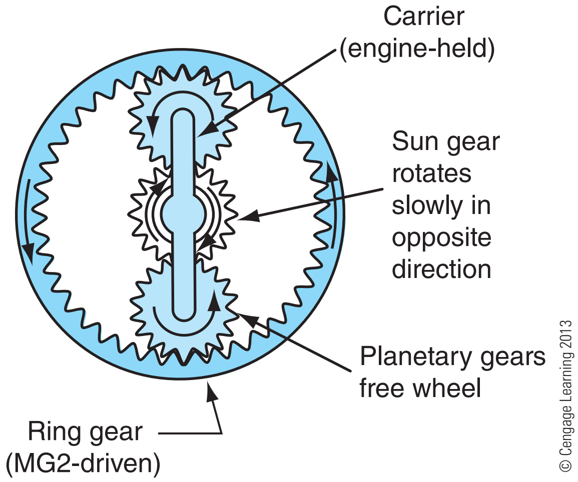


Figure 8-25 Planetary gear action when MG2 is propelling the vehicle.

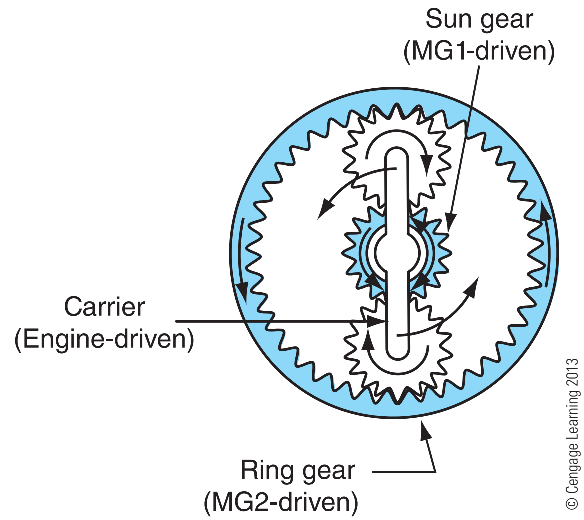


Figure 8-26 Planetary gear action when the engine and MG2 are propelling the vehicle.

- When the car is driven solely by MG2 **(Figure 8-25),** the carrier is held because the engine is not running. The ring gear rotates by the power of MG2 and drives the sun gear in an opposite direction. This causes MG1 to slowly spin in the opposite direction without generating electricity.
- If more drive torque is needed while running with MG2 only, MG1 is activated to start the engine. There are now two inputs to the gear set, the ring gear (MG2) and the sun gear (MG1). The carrier is driven by the sun gear and walks around the inside of the rotating ring gear. This cranks the engine at a faster speed than when the ring gear is held.
- After the engine is started, MG2 continues to rotate the ring gear and the engine rotates the carrier to drive the sun gear and MG1, which is now a generator.
- When the car is operating under light acceleration and the engine is running, some engine power is used to drive the sun gear and MG1, and the rest is rotating the ring gear to move the car **(Figure 8-26).** The energy produced by MG1 is fed to MG2. MG2 is also causing the ring gear to rotate and the power of the engine and MG1 combine to move the vehicle.
- This condition continues until the load on the engine or the condition of the battery changes.

speed cruising, the HV ECU increases the generation ability of MG1, which now supplies more energy to MG2. The increased power at the ring gear allows the engine to do less work while driving the car's wheels and do more work driving the sun gear and MG1.

- During full-throttle acceleration, battery power is sent to MG2, in addition to the power generated by MG1. This additional electrical energy allows MG2 to produce more torque. This torque is added to the high output of the engine at the carrier.
- When the car is decelerating and the transmission is in Drive, the engine is shut off, which effectively holds the carrier **(Figure 8-27).** MG2 is now driven by the wheels and acts as a generator to charge the battery pack. MG1 rotates the sun gear slowly and in the opposite direction, and it does not generate electricity. If the car is decelerating from a high speed, the engine is kept running to prevent damage to the gear set.

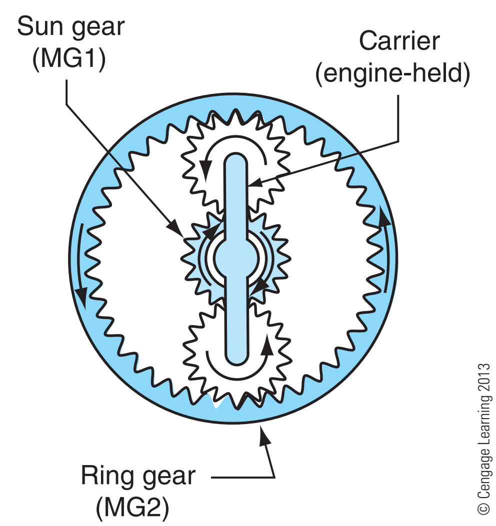


Figure 8-27 Planetary gear action during deceleration and MG2 is driven by the vehicle's wheels.

The engine, however, merely keeps the carrier rotating within the ring gear.

- When the car is decelerating and the transmission is moved into the B range, MG2 acts as a generator to charge the battery pack and to supply energy to MG1. MG1 rotates the engine, which is not running at this time, to offer some engine braking. The engine's valve timing is also altered to provide improved engine braking.
- During normal deceleration with the brake pedal depressed, the engine is off and the skid control ECU calculates the required amount of regenerative brake force and sends a signal to the HV ECU. The HV ECU, in turn, controls the generative action of MG2 to provide a load on the ring gear. This load helps to slow down and stop the car. The hydraulic brake system does the rest of the braking.
- When reverse gear is selected, only MG2 powers the car. MG2 and the ring gear rotate in the reverse direction. Because the engine is not running, the carrier is effectively being held. The sun gear is rotated slowly in its normal rotational directional by MG1 and prevents the ICE from rotating. Therefore, the only load on MG2 is the drive wheels.
- It is important to remember that at any time the car is powered only by MG2, the engine may be started to correct an unsatisfactory condition, such as low battery SOC, high battery temperature, and heavy electrical loads.

Electronic Displays. A Prius has a multi-information display located on the center cluster panel. The display, a 7.0-inch LCD (liquid crystal display) with a pressure-sensitive touch panel, serves many functions. Many of these are typical, but some are unique to hybrid technologies. One of the unique features is the fuel consumption screen, which shows average fuel consumption, current fuel consumption, and the current amount of recovered energy.

Another unique display is the energy monitor screen **(Figure 8-28),** which shows the direction and path of energy flow through the system in real time. By observing this display, drivers can alter their driving to achieve the most efficient operation for the current conditions.

Like other vehicles, the Prius is equipped with a variety of warning lamps and indicators. Here are some of the indicators that are unique to the Prius hybrid:

- READY light—This lamp turns on when the ignition switch is turned to START to indicate that the car is ready to drive.

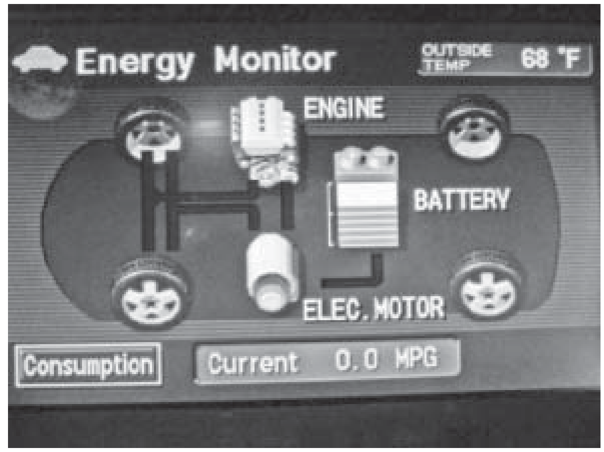


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Figure 8-28 The multi-information display on the instrument panel shows average fuel consumption, current fuel consumption, and the current amount of recovered energy. It also has an energy monitor screen, which shows the direction and path of energy flow through the system.

- Output control warning light—This lamp turns on when the temperature of the HV battery is too high or too low. When this lamp is lit, the system's power output is limited.
- HV battery warning light—This lamp is illuminated when the charge of the HV battery is too low.
- Hybrid system warning light—When the HV ECU detects a problem with MG1, MG2, the inverter assembly, the battery pack, or the ECU itself, this lamp will be lit.
- Malfunction indicator light—This lamp is tied into the engine control system and will be lit when the ECM detects a fault within that control system.
- Discharge warning light—This lamp is tied to the 12-volt system and DC/DC converter. It will illuminate when there is a problem in that circuit.

Electric Motor-Assisted Power Steering System. To reduce fuel consumption and provide power steering when the engine is not running, the Prius uses an **electric motor-assisted power steering (EMPS)** power steering system. Besides providing for appropriate steering ratios according to vehicle speed, this system eliminates the drag on the engine that results from rotating a hydraulic power steering pump. The EMPS provides steering assist when the engine is on and when it is off.

The system relies on a DC motor to add torque to the driver's steering effort, rather than hydraulic pressure. The system is based on a conventional rack-and-pinion steering gear. When the steering wheel is turned, torque is transmitted through the steering column to a torsion bar that links the column to the pinion of the steering gear. The torsion bar twists until the torque and the reaction force equalize. A torque sensor detects the twist of the torsion bar and converts it to an electrical signal that is sent to the EPMS ECU. The ECU then calculates the required amount of assist and controls the electric assist motor accordingly. With this system, the DC motor consumes electrical energy only when power assist is required.

Additional Prius Models. Toyota is set on making different versions of the Prius available. Basically these versions are smaller **(Figure 8-29)** or larger versions of the base model. As an example, the Prius V **(Figure 8-30)** has 50 percent more cargo space than the base model. The wheelbase of the V is 3.1 inches longer, and overall length has been increased by 6.1 inches. It is also taller and wider. The increase in size also increased the car's coefficient of drag, raising it from 0.25 to 0.29. These changes affect the fuel economy ratings as well. The Prius V has an EPA combined estimate of 40 mpg compared to the base Prius's 50 mpg. The powertrain in the Prius V is identical to that found in the base model.

Figure 8-29 A Prius C.

Figure 8-30 A Prius V.

Prius Plug-In

In 2012, Toyota released a plug-in version of the Prius **(Figure 8-31).** It initially was available in a few states, but then available in all states in 2013. The Toyota Prius Plug-in is a mid-sized plug-in hybrid electric vehicle (PHEV). The Prius PHEV is based on the base Prius but is fitted with a 4.4-kWh lithium-ion battery pack. The pack allows the Prius to operate as a pure EV for longer distances and at higher speeds. The estimated all-electric range is 13 miles, which results in an expected total range of 475 miles. The car is also capable of driving up to 62 mph while in the electric mode. The estimated fuel economy while operating as a gasoline-electric hybrid is 72 MPGe.

The battery pack sits under the rear cargo floor and includes a battery charger with 24-foot-long cables. The charger is designed for household current and can be plugged into any wall outlet. A full charge using a 120V AC outlet takes approximately 2.5 to 3.0 hours. The charging cables connect to the charging port, which is located behind a spring-loaded, push-open door on the right-rear fender **(Figure 8-32).** The port has LED lighting to allow for safe nighttime charging. There is also a timer that can be set for start and end charging times. This feature allows the owner to charge when electrical rates are low. A special 240V charger can be installed at the owner's residence. Charging with 240V allows for a full charge in 1½ hours.

The battery pack **(Figure 8-33)** has an internal and three external cooling fans to control heat. The system's

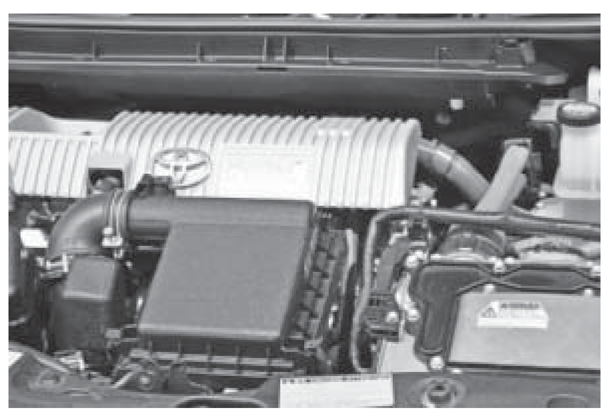

Figure 8-31 Under the hood of a Prius Plug-In hybrid.

Figure 8-32 The charge nozzle inserted into the Prius Plug-In to charge the battery.

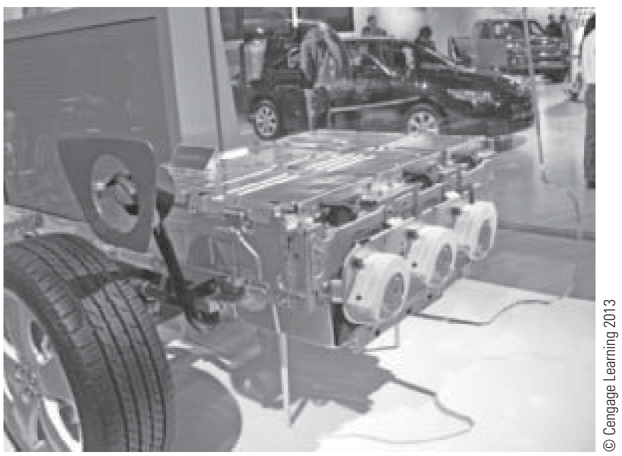

Figure 8-33 The battery module for a Prius Plug-In.

inverter has also been reworked to be compatible with the new battery. The hybrid cooling system also has a larger heat exchanger and higher-capacity electric fans.

The instrument panel in the PHEV has been modified to accommodate the benefits of having a plug-in. There is now an EV Drive Ratio display. This displays the ratio of electric driving distance to total distance traveled. There is also an Eco Savings Record screen that allows drivers to measure their savings by driving a Prius compared to another (driver selected) vehicle.

Other Hybrids from Toyota. Several other hybrid cars are available from Toyota and Lexus (owned by Toyota). Toyota offers a Camry Hybrid, and Lexus has the CT200h, HS250h, GS450h, and the LS750hL. All of these are based on the same architecture as the Prius. However, the base engine, traction motor, and battery have been made more powerful to offset the increased weight of these cars over the Prius. The total power output from these hybrid systems ranges from 187 HP to 438 HP. The power-split devices in the cars with larger ICEs have an additional planetary gear set that operates in the same way as Toyota's hybrid SUVs.

Toyota's Hybrid SUVs

Toyota modified its HSD to work with a high-output, six-cylinder engine to offer a hybrid option on its mid-sized SUVs: the Highlander Hybrid and Lexus RX 450h. Based on the system used in the Prius, this hybrid system was developed to reduce emissions and fuel consumption while increasing the performance of these SUVs. Also, a four-wheel-drive (4WD) option is available **(Figure 8-34).**

These SUVs have the engine and transaxle assembly in front to drive the front wheels. The 4WD models have an additional electric motor and transaxle in the rear to drive the rear wheels. The two motor/generators used to drive the front wheels are still

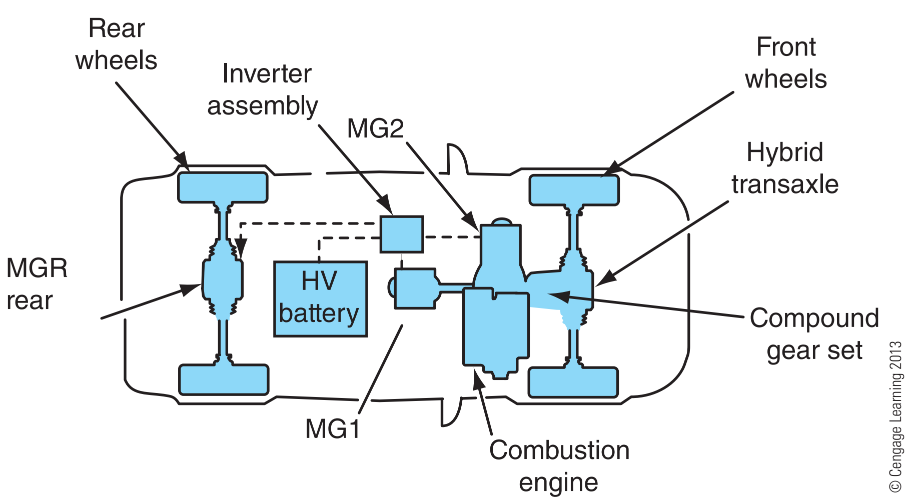

Figure 8-34 The basic layout of the hybrid components in a Toyota four-wheel-drive SUV.

referred to as MG1 and MG2. The motor/generator at the rear on 4WD models is referred to as motor/generator rear (MGR). MG1 is used to start the engine and serve as an engine-driven generator. MG2 and MGR provide power for propulsion and serve as generators during regenerative braking. As in the Prius, the amount of voltage generated by MG1 controls the effective gear ratio of the transaxle.

These SUVs have an MG2 with much more power and are capable of higher rotational speeds. The motor works with a 3.5L V6 engine that has been slightly modified. The combined drive system output (electric motor plus engine output) is nearly 295 horsepower. The redesigned MG2 produces its peak torque (twice the amount available in a Prius) from 0 to 1,500 rpm. The output from the motor, in addition to that of the engine, allows these SUVs to accelerate quicker than their pure ICE-powered cousins. Additionally, these hybrids use less fuel and have a combined EPA fuel economy rating of about 30 miles per gallon.

Along with the new motor, these vehicles have a higher-voltage battery and a variable voltage system that boosts the voltage when extra power is needed. These vehicles have a 288-volt NiMH battery pack and a revised inverter. Inside the inverter is a boost converter that can increase the operating voltage to a maximum voltage of 650 volts.

Like the Prius, the front transaxle is a continuously variable transmission, and it serves as the power-split device. Because of the vehicle's weight, changes have been made to the transaxle. The transaxle still contains the MG1, MG2, planetary gear set (power-split unit), a counter gear set, and the differential unit. However, an additional planetary gear set (the Motor Speed Reduction unit) has been tied to the power-split unit. This gear set reduces the speed of MG2 and thereby increases its torque. This reduction unit is also used in other late-model Toyota and Lexus hybrids.

The 4WD system is capable of responding to operating conditions by varying the distribution of torque between the front and rear axles and by controlling the front and rear electric motors. MGR is incorporated into a rear transaxle assembly that also houses the rear differential.

Operation. The operation of this HSD system is similar to that in the Prius except for 4WD operation and the speed reduction unit in the front transaxle. The latter will be explained in detail with the discussion of the transaxle. The front drive unit is used in both the two-wheel-drive and four-wheel-drive vehicles.

In 4WD models, MGR and MG2 are used to move the vehicle during initial acceleration **(Figure 8-35).** Both motors are powered directly by the battery pack. The engine is not running and MG1 is inactive. However, the engine may start if the control unit senses a need for more drive torque or if the battery's SOC, battery temperature, and/or engine temperature are not within a specified range.

Once the vehicle is operating under a low load and at a constant speed, power to MGR stops and the engine starts to power the vehicle and MG1. The energy from MG1 powers MG2, which works with the engine to keep the vehicle moving.

During hard acceleration, the vehicle is powered by the engine, MG2, and MGR **(Figure 8-36).** The engine's output drives the wheels and MG1. Electrical power for MG2 and MGR comes from the battery pack and MG1. If needed, higher voltages from the boost converter may be sent to MG2 and MGR.

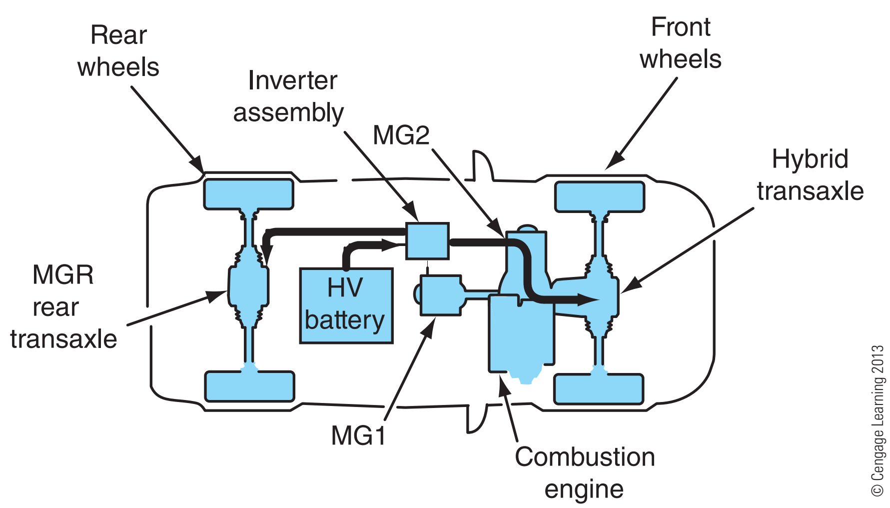

Figure 8-35 When the vehicle accelerates from a standstill, it is powered only by MG2 and MGR. The engine is off and MG1 is not generating electricity.

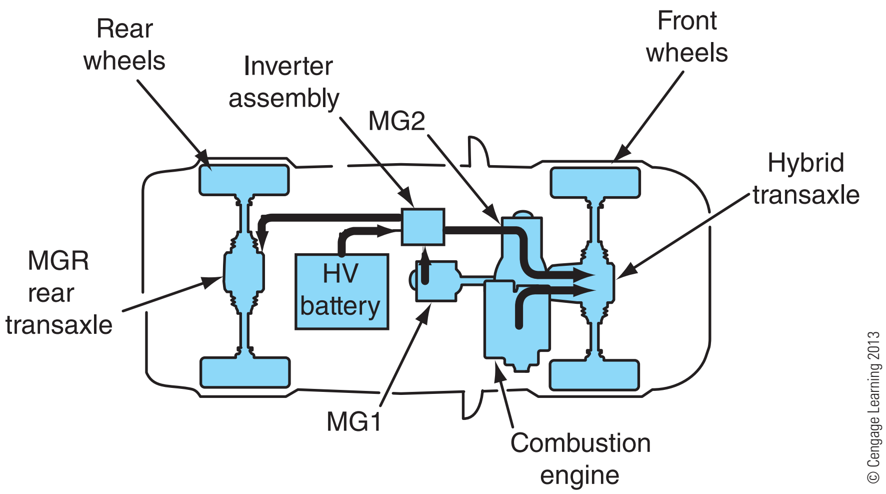

Figure 8-36 During full-throttle acceleration, the vehicle is powered by the engine, MG2, and MGR. Electrical power for MG2 and MGR comes from the battery pack and MG1.

During deceleration, the system calculates the torque distribution at the front and rear axles. Based on this calculation, it controls the regenerative capability of MG2 and MGR. This prevents any "push-pull" that can result if one axle is braking or slowing more than the other.

Torque distribution is constantly being monitored by the skid control ECU. If the system detects any variance in wheel or axle speeds, which normally occur on slippery roads or while cornering at high speeds, adjustments are immediately made to rectify the situation. These adjustments affect the power output of the engine, MG2, and MGR.

When the vehicle is driven in reverse, MG1 and the engine are shut down and the vehicle is powered by battery power to MG2 and MGR.

Motor/Generators. The three motors used in the HSD system are AC synchronous motors. As in the Prius, MG1 is primarily used as a generator. Power from MG1 is used to charge the batteries and supply power to the A/C compressor, power-steering motor, and the water pump. MG1 is also used to start the engine.

MG2 has a maximum output rating of 167 HP (123 kW) at 4,500 rpm and a torque rating of 247 ft.-lb at 0 to 1,500 rpm. MG2 is the main traction motor and drives the front wheels, by itself or with the engine. MG2

eration and braking.

The electric 4WD-i system uses the MGR to power the rear wheels of the vehicle. MGR has a maximum output of 68 HP (50 kW) at 4,610 to 5,120 rpm and a maximum torque rating of 96 ft.-lb at 0 to 610 rpm. The final drive ratio in the rear transaxle is very low. This provides a large amount of torque to the rear wheels. Of course, the amount of torque produced by MGR depends on the voltage it receives. The source of its voltage can be the battery pack and/or MG1. During deceleration, MGR acts as a generator.

The operation of the motors is controlled by a motor/generator ECU through commands from the HV ECU (referred to now as the THS ECU). The MG ECU is linked to the Intelligent Power Module (IPM) and switches its six IGBTs to turn the various MGs on or off and to change their operation from a motor to a generator and vice versa. The MG ECU receives input from each of the motors' resolvers to determine the speed of the unit's rotor and its exact position within the stator.

The motors are also fitted with a temperature sensor. The THS ECU monitors the temperature of each and will alter the power to them if there is evidence of overheating.

Electronic Controls. The THS ECU is the main control unit for the hybrid system and is very similar to the one used in the Prius. The same basic systems and operating conditions are monitored by the ECU. However, the THS ECU in the SUVs, especially those equipped with 4WD, has additional systems to control **(Figure 8-37).**

The THS ECU receives information from a variety

used to calculate how much power is required from the motors and engine to meet current driving conditions. The primary inputs used for this calculation are from the shift position sensor, motor resolvers, accelerator pedal position sensor, vehicle speed sensor, battery smart unit, skid control ECU, and EPS ECU. Based on

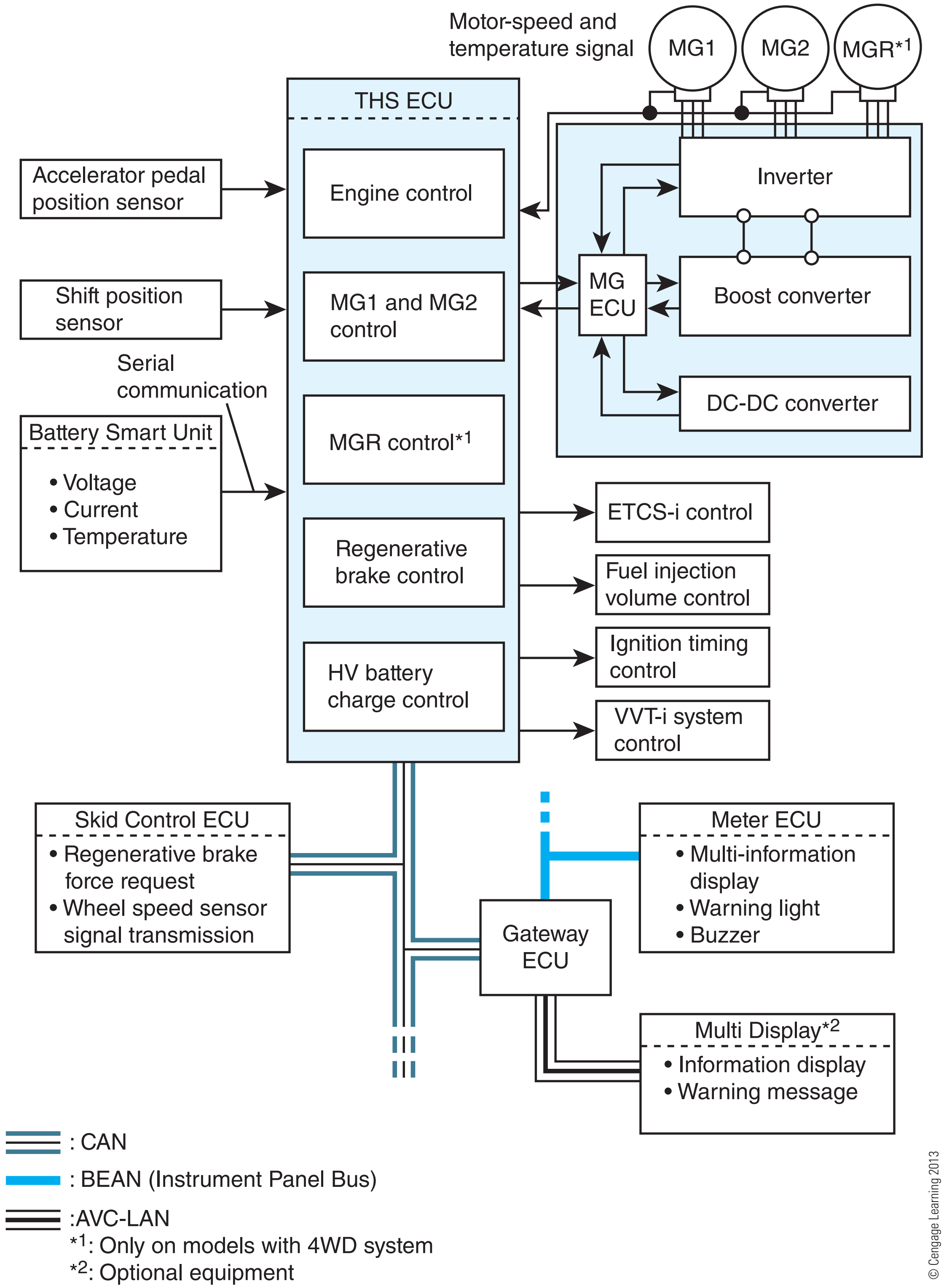

Figure 8-37 The basic configuration of the THS II system with the four-wheel-drive option.

the calculations, the THS ECU sends the appropriate commands to the MG ECU, inverter, and skid control ECU to control the powertrain. The THS ECU also sends commands to the ETCS-i, fuel injection, ignition, and VVT-i systems.

The THS ECU constantly monitors the SOC and temperature of the battery pack. When the SOC is below a specific level, the THS ECU orders the engine to rotate MG1 faster. If the engine is not running and the SOC is too low, the engine will start and drive MG1.

A temperature sensor in the battery module sends information regarding current battery temperature. Based on this input, the THS ECU controls the operation of the cooling fans in the battery module. If the SOC is low, or the temperature of the battery, MG1, MG2, or MGR is too high, the THS ECU will decrease the motors' output until the undesirable condition is corrected.

The THS ECU also monitors the speed of each wheel to determine if any slippage is occurring. Slippage is evident by any sudden speed change. The ECU calculates the amount of slippage and controls the operation of MG2 to reduce it. If one axle is turning faster than the other, the rotational speed of MG2 will increase. It may increase enough to damage the planetary gear set. Because the drive axles are connected directly to MG2, which is directly connected to the sun gear in the planetary gear set, slippage can cause the sun gear to attempt to rotate too fast for the rest of the gear set. Also, this overspeed condition may cause MG1 to generate an excessive amount of electricity. To prevent these things from occurring, if the THS ECU detects slippage it will immediately apply a brake force to the spinning axle. If one of the drive wheels is slipping, the THS ECU will send a command to the skid control ECU to apply the brake at the wheel that is slipping.

The THS ECU monitors the entire system and memorizes all conditions and operating parameters that are outside a specified range. Depending on the type and severity of the problem, the THS ECU will illuminate or blink the MIL, the master warning light, or the HV battery warning light. The THS ECU will assign a DTC to the problem and keep it in memory for diagnosis. If the THS ECU detects a nonworking sensor or control unit, it will ignore the inputs from that source and operate on data stored in its memory. This is the fail-safe mode of operation.

The **battery smart unit** constantly monitors the voltage, current flow, and temperature of the batteries. It also has a leak-detection circuit that watches for excessive current drain. Serial communication is used to transfer the digital signals from the battery smart unit to the THS ECU.

The skid control ECU determines how much regenerative force, during deceleration, should be applied

calculation is based on the pressure applied to the brake master cylinder and the brake pedal. The ECU also calculates the amount of brake force that should be applied by the hydraulic brake system. On 4WD systems, the skid control ECU also monitors the torque distribution between the front and rear drive axles.

The hybrid system is also linked to the cruise control ECU. Information from the cruise control switch and vehicle speed sensor is sent to the cruise control ECU, which in turn, sends information to the THS ECU. The THS ECU regulates the motor/generators and engine to provide for the selected speed with a minimum use of fuel.

Battery. The battery pack **(Figure 8-38)** is composed of 30 modules of eight 1.2-volt NiMH cells connected in series by a bus bar. The nominal voltage is 288 volts. The battery pack supplies power for MG1, MG2, and MGR according to the commands of the THS ECU. It is also recharged by MG1 and MGR through the commands of the same control unit.

Changes to the previous battery pack include a rubber damper at the mounting point of the SMRs to reduce vibrations. An electrical connection is made between every 10 cells to minimize internal resistance, and there is a more efficient cooling system. The battery module is divided into three separate units and relies on a cooling fan for each unit to keep them within the desired temperature range. The fans pull in air from the passenger compartment. There are eight temperature sensors located within the battery module; when the THS ECU detects an increase in battery

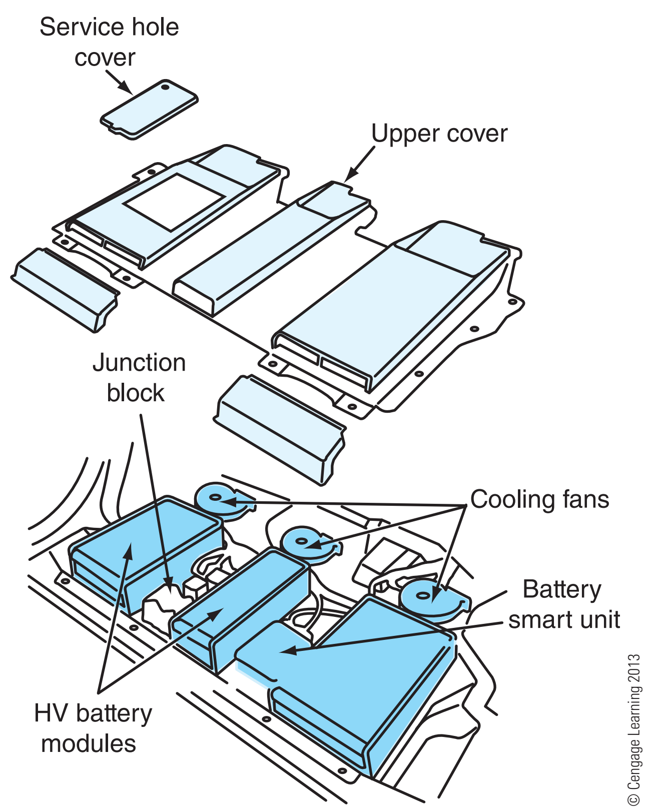

Figure 8-38 The main components of the high-voltage battery pack.

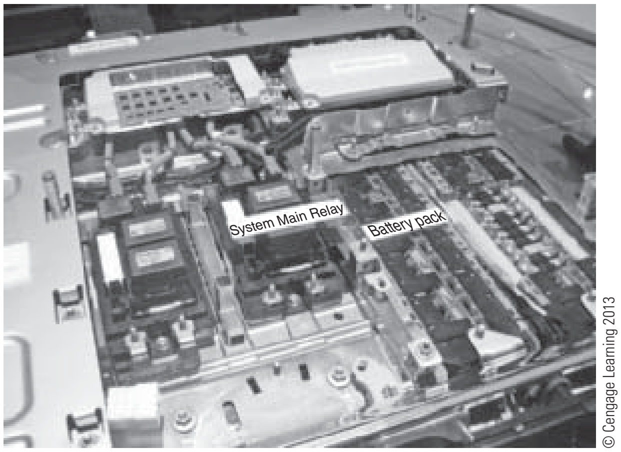

Figure 8-39 Inside the battery pack.

temperature, it duty cycles the appropriate cooling fan to bring the temperature down **(Figure 8-39).**

Inverter. The inverter includes a boost converter that can deliver up to 650 volts to the motor/generators **(Figure 8-40).** The inverter assembly also contains the MG ECU, the inverter, and the DC-DC converter. The inverter converts the direct current from the battery pack into an alternating current for MG1, MG2, and MGR. When the motor/generators are operating as generators, the inverter converts the generated AC voltage to DC before sending it to the battery pack. The inverter also directly sends the AC generated by MG1 to MG2 and MGR.

The MG ECU ultimately controls the inverter, boost converter, and DC-DC converter through commands received from the THS ECU. These commands control the operation of the inverter's power transistors. The transistors, in turn, control the phasing of the motors and their output. If the THS ECU detects a problem in the high-voltage circuit or if the transmission is placed in neutral, the inverter is turned off to stop the operation of the motor/generators.

The boost converter is also controlled by the THS ECU through the MG ECU. It can boost the nominal voltage of the battery (288 DC volts) to 650 DC volts. After the voltage has been increased, it passes through the inverter and is changed to AC voltage for the motors. The opposite is true when the motor/generators are acting as generators. During this time, the generators can generate as much as 650 AC volts. This output is passed through the inverter and changed to DC. The DC output from the inverter is dropped to 288 volts by the boost converter, and this voltage is sent to the battery pack.

The boost converter contains a boost Integrated Power Module (IPM) that uses IGBTs to control the circuit and a reactor to store the higher voltage. The action of the boost converter is similar to that of an ignition coil. Composed of two parallel coil windings, one side is energized by battery voltage and the other winding is the output. When the magnetic field on the input side collapses, a higher voltage is induced in the output coil. As in an ignition coil, the amount of time current flows through the battery's winding before the field collapses determines the amount of voltage that is induced in the output winding. The longer that current flows through the input winding, the more voltage is induced in the output coil. The output coil is connected to a capacitor, called the reactor, that stores the higher voltage until it is sent to the motor/generators. The IGBTs are duty cycled and control the current to the boost converter.

The DC-DC converter changes a portion of the high voltage to a much lower voltage to charge the

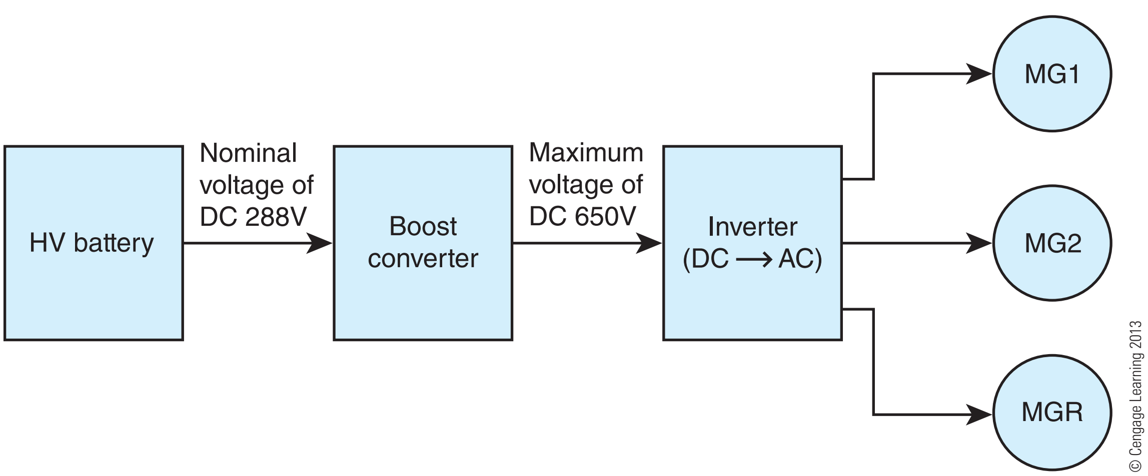

Figure 8-40 The control system uses a boost converter to allow for a variable voltage to and from the motor/generators.

auxiliary battery. This voltage is used to power some accessories and safety items.

The inverter assembly, MG1, and MG2 are kept within a specified temperature by a cooling system. In the SUVs, the radiator for the inverter and motors is part of the engine's radiator, but is totally isolated from it.

Engine. The engine is a 24-valve, dual overhead cam, V6 engine equipped with many accessories that are normally belt driven, but here are electrically operated to reduce power loss and to allow these items to operate when the engine is not running.

Transaxle. The front transaxle assembly now has a speed reduction unit **(Figure 8-41).** This unit is a planetary gear set coupled to the power-split planetary gear set. This compound gear set has a common or shared ring gear that drives the vehicle's wheels. The sun gear of the power-split unit is driven by MG1, and the carrier is driven by the engine. In the reduction gear set, the carrier is held and the sun gear is driven by MG2. Because the sun gear is driving a larger gear, the ring gear, its output speed is reduced and its torque output is increased proportionally. High torque is available because MG2 can rotate at very high speeds. As in the Prius, the rotational speed of MG1 essentially controls the overall gear ratio of the transaxle.

The torque of the engine and MG2 moves from their designated gears to the common ring gear to the final drive gear and differential unit.

The transaxle has three distinct shafts: a main shaft that turns with MG1, MG2, and the compound gear unit; a shaft for the counter-driven gear and final gear; and a third shaft for the differential. Because a clutch or torque converter is not used, a coil spring damper is used to absorb torque shocks from the engine and from the initiation of MG2 to the driveline.

MGR uses its own transaxle assembly to rotate the drive wheels. Unlike conventional 4WD vehicles, there is no physical connection between the front and rear axles. The aluminum housing of the rear transaxle contains the MGR, a counter drive gear, counter-driven gear, and a differential. The unit has three shafts: MGR and the counter drive gear are located on the main shaft (MGR drives the counter drive gear), the counter-driven gear and the differential drive pinion gear are located on the second shaft, and the third shaft holds the differential.

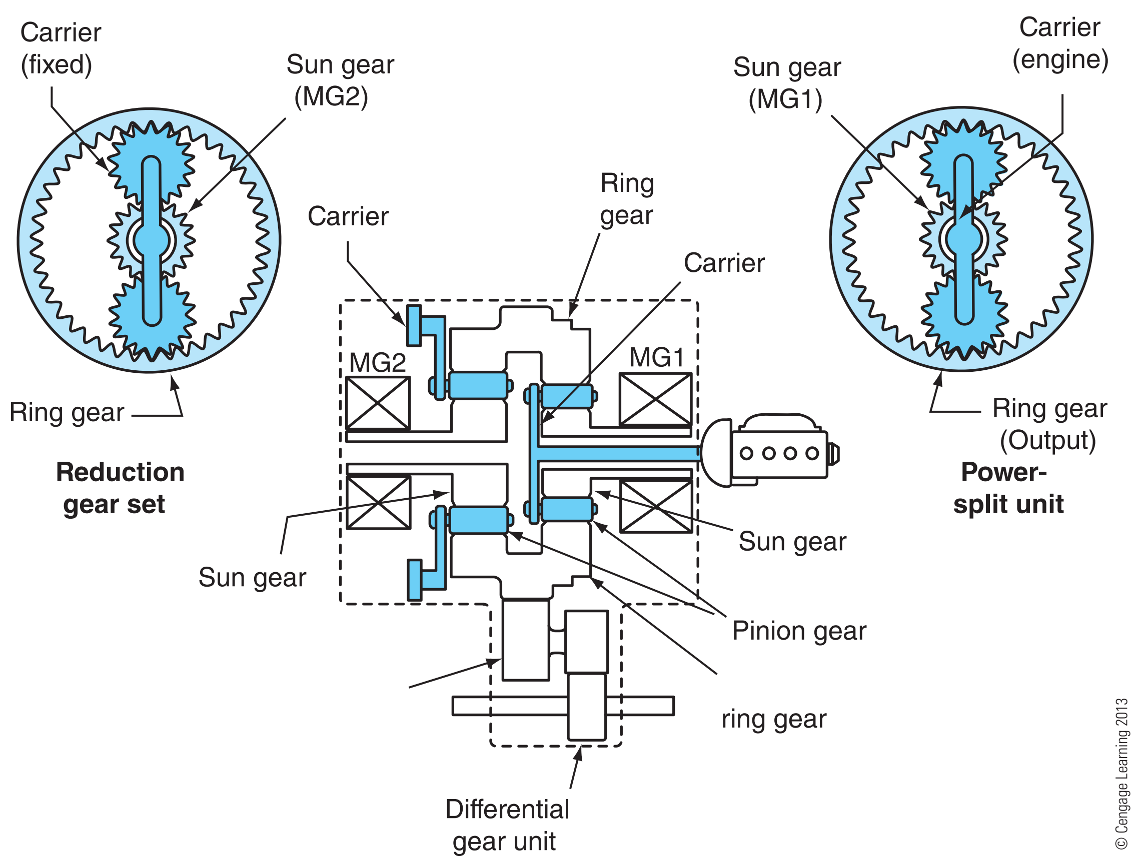

Figure 8-41 The hybrid transaxle with a compound planetary gear set to accommodate larger engines.

FORD HYBRIDS

In 2004, Ford released the Escape hybrid. This was the first hybrid SUV, and the first hybrid vehicle built in North America. Sales of the hybrids went very well, although they were limited simply because of a shortage of batteries for the vehicles. The Ford Escape SUV **(Figure 8-42)** received many accolades and looked nearly identical to the nonhybrid Escape. The major differences in appearance are badges or external markings that say it is a hybrid **(Figure 8-43)** and a barely noticeable vent near the rear quarter window on the driver's side of the vehicle. This vent is for the battery's temperature-management system. The standard Escape Hybrid is front-wheel drive, and an Intelligent 4WD system is optional. This option made the Escape the first 4WD hybrid.

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Figure 8-42 A Ford Escape.

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Figure 8-43 The vent at the rear side window is one of the clues that a Ford Escape may be a hybrid.

In 2006, Ford released a hybrid version of the Escape's cousin, the Mercury Mariner. The Mariner Hybrid is a Ford Escape Hybrid with Mercury luxury items, badges, and styling.

These SUVs are full hybrids and feature a CV transmission and stop-start technology, as well as the ability to be powered solely by battery power. They have a towing capability of up to 1,000 pounds (454 kg), the same tow rating as a regular four-cylinder Escape or Mariner. The hybrid package is condensed to minimize its required space, so these small SUVs offer much practicality, in addition to good fuel economy and low emissions.

In 2010, Ford released a hybrid edition of its mid-sized car, the Fusion **(Figure 8-44).** Creating a hybrid system for the Fusion led to many changes in the system used in the Escape. However, all of those developments are now used in the Escape. In 2012 the Escape had an EPA combined fuel economy of 32 mpg and the Fusion was rated at 39 mpg. The Fusion also has a total driving range of over 600 miles.

The hybrid system is based on a four-cylinder engine and two electric motors. The combined power output from the engine and the traction motor is the equivalent of 191 horsepower (142 kW). The main components and systems of these hybrids are **(Figure 8-45):**

- **Gasoline engine:** The 2.5L, dual overhead cam (DOHC) four-cylinder engine uses the Atkinson cycle and advanced engine control systems.
- **Electric motors:** Two separate electric motor/generators are used. One of these, a 28-kW (equivalent to 38 HP) motor, is primarily used as a generator but also serves as the starter motor for the engine and controls the activity of the transaxle. The other motor/generator has a

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Figure 8-44 A Ford Fusion.

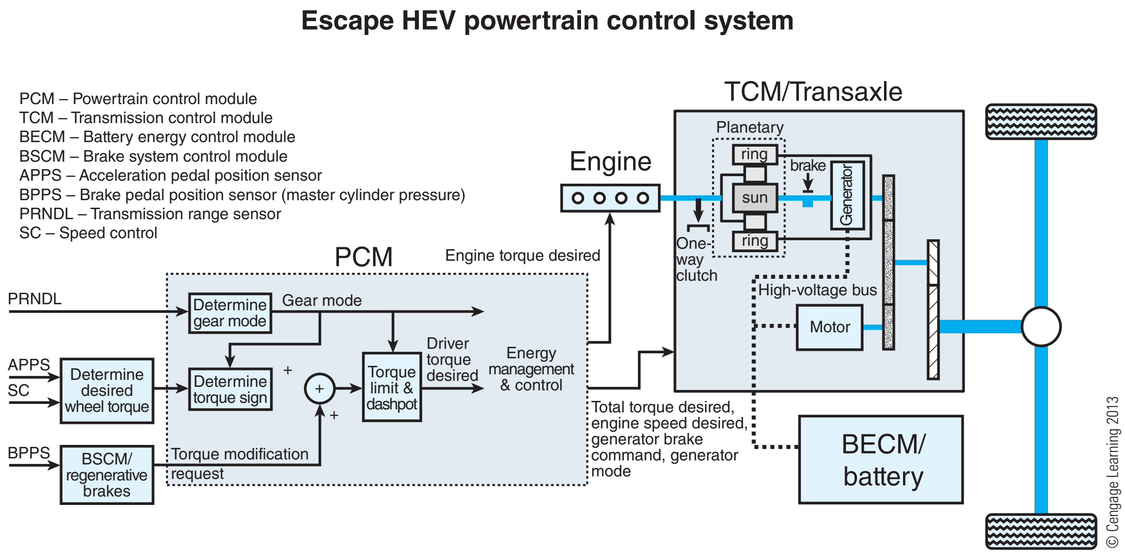

Figure 8-45 Layout of the Ford Escape hybrid powertrain.

peak power of 74 kW (equivalent to 106 HP). This motor is used to propel the vehicle during low-speed and low-load conditions and to assist the engine during hard acceleration, heavy loads, and/or during high-speed driving.

- **Battery pack:** The sealed NiMH battery pack is rated at 275 volts and has 208 D-sized cells **(Figure 8-46).** The battery pack supplies the power for the two motors.
- **Regenerative braking:** Through intelligent controls, deceleration and braking are accomplished through regenerative braking and a conventional hydraulic brake system.
- **Electronically Controlled Continuously Variable Transmission (eCVT):** Based on a single planetary gear set, the transaxle controls the direction of power from the engine and motors.

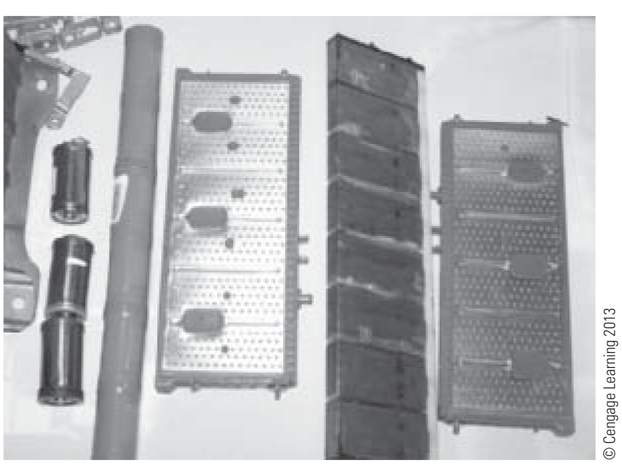

Figure 8-46 The main components that make the HV battery.

- **Vehicle System Controller (VSC):** The vehicle system controller is the primary electronic control unit. Based on information from several other control units and inputs, it controls the charging, drive assist, and engine starting functions of the system according to current conditions. The VSC is part of the Powertrain Control Module (PCM).

These vehicles are also equipped with an electro-hydraulic brake-by-wire system and an electric power steering system. They also offer an optional 110-volt, 150-watt AC auxiliary outlet. They are equipped with standard instrumentation but have an additional gauge that monitors the economics of the current operating mode and driving style.

Operation

The basic components and operation of Ford's hybrid system are very similar to what is found in Toyota hybrids. This has led many to conclude that Ford is simply buying the system from Toyota. This is not true. This is unfortunate because Ford's system is its own, and Ford is not getting the credit deserved for its engineering. The concept of using two electric motors to create a transaxle suitable for hybrid technology was first exposed by an American engineer

the planetary gear set Henry Ford used in the original Model T.

Going forth with the basic idea of using a planetary gear set as a power-split device, Toyota entered into a partnership with a Japanese transmission design and manufacturing company, Aisin, in 1986 to develop a

hybrid transmission with two electric motors. These companies continued to work together for about six years (when their contract expired), and then Toyota decided to continue development of the transaxle on its own. The result was the transaxle it introduced in the Prius. In the meantime, Volvo joined forces with Aisin and continued to develop the transaxle. Shortly after that, Ford purchased Volvo and the technology. Because of the basic roots, the Toyota and Ford power-split units are quite similar. Due to the similarities and to avoid legal problems, Ford licensed some of the technology from Toyota and Toyota licensed some technology from Ford. Toyota holds over 150 patents on the technology, and Ford has received more than 100 patents on its design.

The bottom line is simply, Aisin supplies the transmission used in the Ford hybrids **(Figure 8-47)** and Toyota makes its own. Toyota does not supply hybrid components to Ford. Both Ford and Toyota state that Ford received no technical assistance from Toyota during the development of the hybrid system.

These are series-parallel hybrid vehicles. Ford divides the operation of the hybrid system into three different modes: positive split, negative split, and electric modes. During the positive-split (series) mode, the engine is running and driving the generator, to recharge the battery or directly power the traction motor. The system is in this mode whenever the battery needs to be charged or when the vehicle is operating under moderate loads and at low speeds.

During the negative-split (parallel) mode, the engine is running, as is the traction motor. The output of the traction motor tends to reduce the speed of the engine through the action of the planetary gear set. The engine's output is, however, supplemented by the power from the traction motor. During this mode, the traction motor can function as a motor or a generator, depending on the current operating conditions and the demands of the driver.

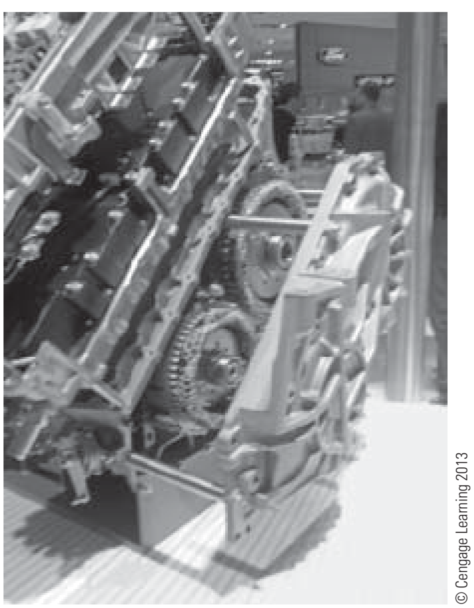

Figure 8-47 The hybrid drive system integrated with an inverter.

In the electric mode, the engine is off and the vehicle is propelled solely by battery power. This is the mode of operation when the battery is fully charged and during slow acceleration and low speeds, as well as when the reverse gear is selected by the driver. The hybrids are capable of reaching about 47 mph on pure electric power.

Ford's hybrid technology includes stop-start and relies on a nontraction motor to start the engine, to control the action of the planetary gear set, and to serve as a generator when the engine is running. This motor is claimed to be able to start the engine within 400 milliseconds (0.4 seconds). The engine is shut down when the vehicle is stopping or slowing down, unless the air-conditioning system's demands are high or the battery needs to be recharged. Electric assist steering allows for power-assisted steering even when the engine is off. When the vehicle is slowing down or stopping, the system checks the battery's SOC and makes sure there is enough power available for the restart. If there is low power, the engine continues to run in order to drive the generator and charge the battery pack. If the battery has a decent charge, the engine stops running and the electric traction motor (powered solely by the battery) moves the vehicle for initial acceleration after the stop.

The engine can restart immediately after the driver depresses the accelerator or when the electric motor cannot continue to efficiently move the vehicle. The driver has no control over this; the system simply decides what is best for the situation. When operating at low load, low speed, the propulsion power comes from the electric traction motor. This means there are zero exhaust emissions and no fuel is consumed. When the load or vehicle speed increases, the engine starts, and more power is available to accelerate or overtake the load at the drive wheels.

Like other hybrids, these vehicles have regenerative braking. They are equipped with an electro-

wheels and an antilock brake system. When the driver releases pressure on the accelerator pedal, the electronic controls change the electrical path to the traction motor so that it operates as a generator. When the brake pedal is depressed, the control unit calculates the required braking force based on the pressure on the brake pedal

and the vehicle's speed. The control unit then controls the amount of braking supplied by the motor/generator and the hydraulic brake system. The motor/generator can provide most of the braking force during less-than-panic stops.

Electronic Components

The individual cells in the battery pack are contained in a stainless-steel case **(Figure 8-48)** and are welded together in groups to form separate modules. Each cell has a voltage of about 1.3 volts; therefore, the battery pack has a nominal voltage of 275V. The battery pack has a rated capacity of 5.5 amp-hours. To control the temperature of the batteries, the pack is equipped with a thermal management system that operates an electric heater and a forced-air cooling system to keep the battery pack's temperature within a specified range **(Figure 8-49).**

Figure 8-48 The battery pack is located behind the rear seat.

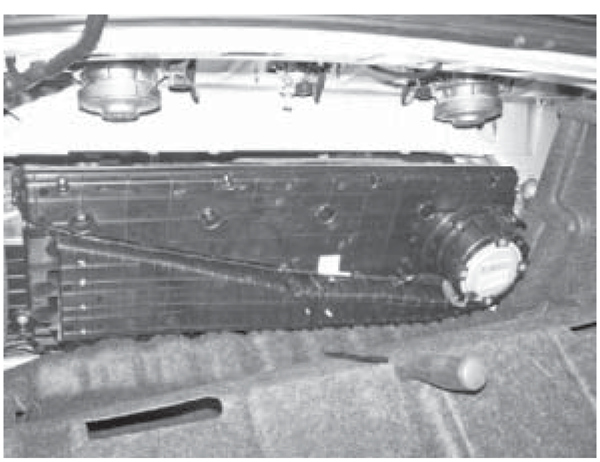

Figure 8-49 This is part of the cooling and vent system for the HV battery in a Fusion.

There is also a lead-acid 12-volt battery, located under the hood, to provide power for the various 12-volt systems of the vehicle. This battery is recharged by the DC-DC converter, also located under the hood.

Two inertia-type switches, one in the front and the other in the rear, can disconnect the high-voltage system if the vehicle is in an accident. Also, all high-voltage wires, harnesses, and connectors are wrapped in orange-colored insulation or are colored orange and have a warning label. The high-voltage cables are routed under the vehicle from the battery pack to the motors in the front transaxle and from the transaxle to the DC-DC converter.

Motor/Generators. The operation of the two motors is ultimately controlled by the master control unit (the VSC), through inputs concerning speed and rotor position. The nontraction motor is powered by the battery pack, while the traction motor **(Figure 8-50)** can be powered by the battery pack and/or the other motor/generator.

Electronic Controls. The control system is composed of several different modules, which control the operation of the system. These modules use CAN communications and have diagnostic capabilities. The PCM monitors the activity of the system and has direct control of the engine's operation. The VSC **(Figure 8-51)** communicates with the other modules and receives inputs from the gear selector sensor, the accelerator pedal position sensor, the brake pedal position sensor, and many other inputs. Plus, it receives as many as 50,000 signals each second regarding the temperature and SOC of the battery pack. Based on this information, the VSC manages the charging of the battery pack, controls the stop-start function, and controls the operation of the traction motor/generator.

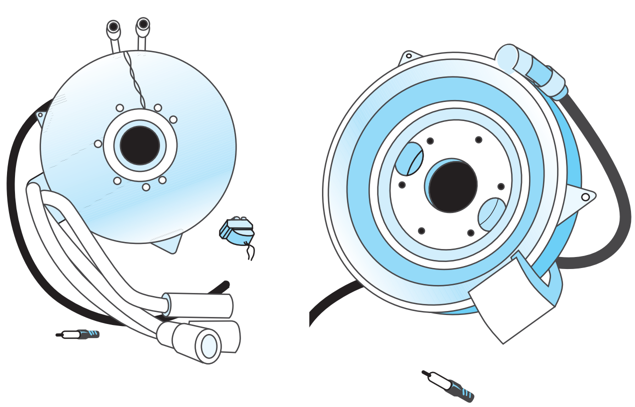

Figure 8-50 The rotor and stator assemblies of the traction motor.

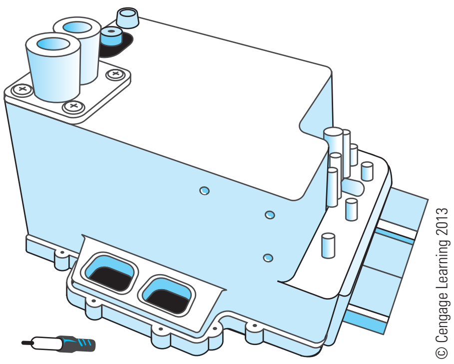

Figure 8-51 The vehicle system controller.

Through commands from the VSC, the **Transmission Control Module (TCM)** directly controls the operation of the motor/generators, and therefore controls the operation of the transaxle. This module is housed inside the transmission case.

The Battery Energy Control Module (BECM) is housed in the battery pack and controls the activity of the battery pack. It receives commands from the VSC and sends feedback to the VSC to verify that the hybrid components are operating within the parameters set for the current condition of the battery. The battery pack is divided into modules. The voltage of each of the modules is constantly monitored, as is the current flow to and from them. There are eight temperature sensors in each unit to help the BECM keep the battery pack within a specified temperature range. If the temperature is outside that range or if the voltage and current flow are outside their range, the BECM will order the PCM to set a fault code, and the system will move to a default setting or shut down.

The **Brake System Control Module (BSCM)** calculates the required brake force to slow down or stop the vehicle. Based on this calculation, it controls the regenerative braking and the hydraulic brake system.

The instrument panel is equipped with gauges that allow the driver to monitor the activity of the hybrid system **(Figure 8-52),** as well the current SOC of the battery pack.

Figure 8-52 The instrument cluster in a Ford Fusion Hybrid.

The electric-assist power-steering control module relies on a variety of inputs, one of which measures the amount the steering wheel is turned and how much effort is exerted on the wheel. Based on these inputs, the control module calculates the amount of assist required and controls a small motor in the steering linkage to provide the desired amount of assist.

Heating and A/C Systems

The A/C has two parallel refrigerant loops, one for the passenger compartment and the other for the HV battery. Both loops are connected to the same compressor and their own shutoff valve. The system can cool the two zones independently. Late-model vehicles have a high-voltage electric compressor.

Early models rely on an engine-driven compressor. Since cooling the battery always has precedence over passenger comfort, the engine may turn on just to run the A/C. It is important to note that the A/C unit will not run unless the engine is running. When the driver selects the MAX A/C or defrost modes, the engine will run continuously and will not shut down during normal stop-start conditions.

These vehicles have a PCM-controlled helper heater pump. This pump is located in series with the heater hose leading to the heater core. The pump is activated when the engine is off, such as during stop-start. This allows for some heat when the engine is not running.

The HV battery has its own cooling circuit, in addition to the designated A/C system. Air constantly passes through the pack. The air inlet for the battery's cooling system is in the left rear quarter windows and the outlet is below the inlet and behind the bumper. There is an air inlet filter in the battery cooling system that should be changed every year or 15,000 miles.

The motor electronics (M/E) cooling system is completely separate from the engine's cooling system. The M/E cooling system cools the transaxle, motors, and the DC/DC converter. The system uses a PCM-controlled 12V coolant pump mounted near the bottom of the radiator to move the coolant through the system. The M/E system has a separate degas bottle that is part of an assembly that also includes the engine cooling system's degas bottle.

Engine

These hybrids are equipped with a 2.5L, aluminum, four-cylinder, DOHC, 16-valve, Atkinson cycle engine **(Figure 8-53).** The engine is also equipped with electronic throttle control and sequential multiport electronic fuel injection. The rated output from the engine is 155 HP at 6,000 rpm and 136 ft.-lb of torque

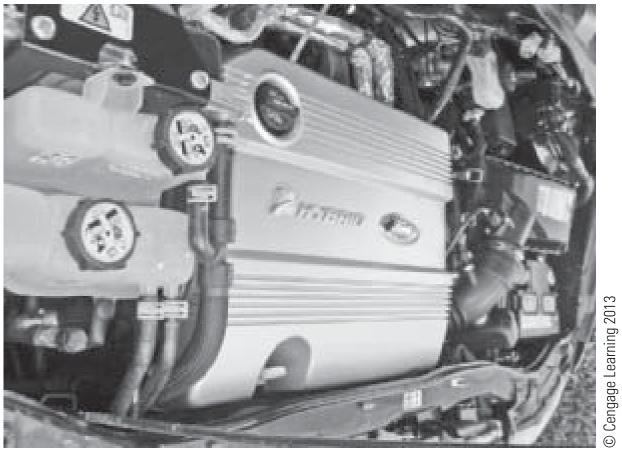

Figure 8-53 The inverter assembly hides the view of the gasoline engine.

at 4,500 rpm. This is less than the output of Ford's conventional 2.5L engine because the hybrid utilizes the Atkinson cycle. The decrease in power output is negated by the assist from the electric motor. The combined output of the gasoline engine and the electric traction motor is 177 horsepower.

The engine uses the Atkinson cycle because it is more fuel efficient than a conventional four-stroke cycle engine. Atkinson cycle engines are often described as five-cycle engines. The five cycles are typically called intake, backflow, compression, power (expansion), and exhaust. During the backflow cycle, the mixture moves back into the intake manifold to reduce pumping losses. Pumping losses represent the power lost when the engine rotates during periods of high vacuum. Because the intake valve closes after the piston begins its compression stroke, some of the incoming air/fuel mixture is pushed back into the intake manifold, which reduces the effective volume or displacement of the cylinder and provides an instant charge of mixture for the next cylinder in the firing order.

These engines have a high static compression ratio but operate at a low compression ratio. This is due to the loss of compressed gases into the intake manifold. These engines also perform best with low-octane fuel, something that is not characteristic of high-compression engines. The Atkinson cycle allows the engine to operate more efficiently, but sacrifices are made in the total output of the engine.

The engine and the transaxle are mounted by conventional mounts plus a controllable liquid-type mount. The purpose of this mount is to reduce noise, vibration, and harshness when the engine is at idle and during the stop-start mode. The mount assembly includes the mount, a vacuum reservoir, a solenoid-type control valve, and some vacuum hoses.

When the engine is running at its idle speed, the PCM will command the control valve to turn on. This allows the vacuum to open a second path inside the mount. This new flow path changes the responsiveness of the mount.

Transaxle

Ford's hybrids are equipped with an electronically controlled, continuously variable transmission (eCVT). Based on a simple planetary gear set, like the Toyota's, the overall gear ratios are determined by the motor/generator. Ford's transaxle is different in construction from that found in the Prius. In a Ford transaxle, the traction motor is not directly connected to the ring gear of the gear set. Rather it is connected to the transfer gear assembly **(Figure 8-54).** The transfer gear assembly is composed of three gears, one connected to the ring gear of the planetary set, a counter gear, and the drive gear of the traction motor.

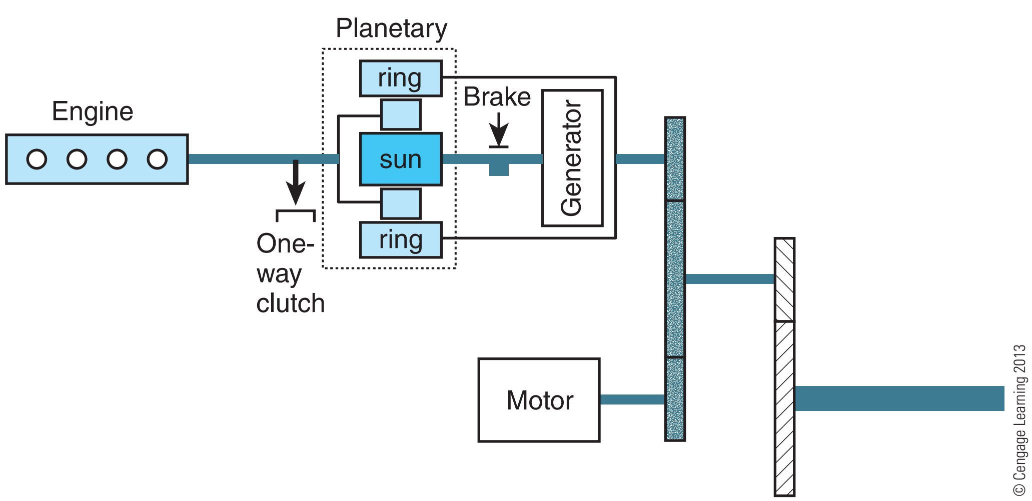

Figure 8-54 In a Ford hybrid transaxle, the traction motor is connected to the transfer gear assembly.

The effective gear ratios are determined by the speed of the members in the planetary gear set. This means the speed of the motor/generator, engine, and traction motor determine the torque that moves to the final drive unit in the transaxle. All three of these power plants are controlled by the VSC through the TCM. Based on commands from the VSC and information from a variety of inputs, the TCM calculates the amount of torque required for the current operating conditions. A motor/generator control unit then sends commands to the inverter. The inverter, in turn, sends phased AC to the stator of the motors. The timing of the phased AC is critical to the operation of the motors, as is the amount of voltage applied to each stator winding.

Angle sensors (resolvers) at the motors' stator track the position of the rotor within the stator. The signals from the resolvers also are used for the calculation of rotor speed. These calculations are shared with other control modules through CAN communications. The TCM, through these sensors, monitors the activity of the inverter and constantly checks for open circuit, excessive current, and out-of-phase cycling. The TCM also monitors the temperature of the inverter and transaxle fluid.

Four-Wheel Drive (4WD)

Unlike the Toyotas with 4WD, the Escape and Mariner do not have a separate motor to drive the rear wheels. Rather, these wheels are driven in a conventional way with a transfer case, rear driveshaft, and a rear axle assembly. This 4WD system is fully automatic and has a computer-controlled clutch that engages the rear axle when traction and power at the rear are needed. Based on inputs from sensors located at each wheel and the accelerator pedal, the system calculates how much torque should be sent to the rear wheels. By monitoring these inputs, the control unit can predict and react to wheel slippage. It can also make adjustments to torque distribution when the vehicle is making a tight turn; this eliminates any driveline shudder that can occur when a 4WD vehicle is making a turn.

Lincoln MKZ. This Lincoln hybrid is based on the Fusion hybrid, and most of the mechanicals are the same with some upgrades. The hybrid system is rated at 41 mpg in the city and 36 mpg on the highway. Power is provided by a 2.5L Atkinson-cycle four-cylinder, 156 HP engine and a 40-horsepower electric motor. The combination results in 191 net horsepower. It is capable of all-electric driving up to 47 mph for short periods. The car is also equipped with Ford's SmartGauge with an interactive technology, called EcoGuide. This system provides real-time information to help a driver achieve maximum fuel efficiency.

Review Questions

1. Describe the basic construction of a simple planetary gear set.

2. Which of the following statements about the Atkinson cycle are NOT true?

   A. The Atkinson cycle allows the effective displacement of the engine to change according to need.

   B. In an Atkinson cycle engine, the intake valve is kept open well into the compression stroke.

   C. The delay in intake valve closing reduces the power output of the engine and decreases its emissions.

   D. During the Atkinson stroke, some unburned air/fuel mixture is pushed into the exhaust manifold.

3.

4. Describe the evolution of the power-split drive technology used in Ford Motor Company's vehicles.

5. Why is an Atkinson cycle engine more efficient than a conventional four-cycle engine?

6. Compare the power-split unit found in a Prius to that found in a Ford Escape hybrid.

7. Which of the following units provides the increased voltage in Toyota's latest hybrid system?

   A. HV battery
   B. Inverter
   C. Boost converter
   D. Resolver

8. In a Toyota Prius, what members of the planetary gear set are connected to the motor/generators and the engine?

9. The ECM for the Variable Valve Timing-intelligent (VVT-i) system looks at several inputs when calculating the proper valve timing for the conditions. Name three of the more important inputs.

10. Which of the following statements about the motor/generators used in the Toyota Prius is NOT true?

    A. MG1 controls the action of the planetary gear set in the power-split device.
    B. MG1 is used to start the ICE.
    C. Only MG2 is used to supplement the power from the engine.
    D. Both MG1 and MG2 are used during regenerative braking.

CHAPTER

9 Other Full Hybrid Designs

Learning Objectives

After reading and studying this chapter, you should be able to:

- Describe the changes Honda made to change their assist-type hybrids to full hybrids.
- Describe the basic operation of the electronic controls for Honda's full hybrids.
- Identify the changes Honda made to produce a plug-in hybrid.
- Describe how a Hyundai ISAD system operates differently than other similar systems.
- Identify other full hybrid vehicles that use an ISAD system.
- Describe the purpose of the various clutches used in some ISAD systems.
- Describe the operation of the two-mode hybrid system.
- Describe the major differences between the powertrains of a BMW X6 ActiveHybrid and the BMW 7 series ActiveHybrid.

Key Terms

transmission-mounted electrical device (TMED)

two-mode hybrid system

INTRODUCTION

Keep in mind, full hybrids are vehicles that can be powered by their engine, by one or more electric motors, or by a combination of these. Most full hybrids are described as having a series-parallel design because the engine is used to drive a generator as well as to power

This chapter will look at the most common full hybrids that do not rely on the power-split technique. Most manufacturers are relying on ISAD or a motor in the transmission architecture.

MODELS USING AN ISAD

This section will focus on the full hybrid vehicles that are based on the ISAD design, including the current hybrids from Honda, Audi, BMW, Kia, Porsche, and Volkswagen. The flywheel/alternator/starter assembly replaces the starter and generator used on a con-

integrated starter alternator damper (ISAD). In most applications, the ISAD is positioned between the engine and the transmission, although it can also be mounted to the side of the transmission.

HONDA CIVIC FULL HYBRID

Late-model Civic Hybrids have a more powerful electric traction motor and are classified as full hybrids. However, by design, the car is seldom powered by the electric motor only. The engine used in this hybrid is the same as that used in previous nonhybrid models except that it has been modified to include the i-VTEC system and other efficiency-increasing technologies **(Figure 9-1).** Also, this hybrid is only available with a continuously variable transmission **(Figure 9-2).**

The engine also is capable of full (all) cylinder deactivation to allow the engine to rotate without producing power and act as a brake during regeneration. The output from the engine is now 93 HP at 6,000 rpm compared to 85 HP at 5,700 rpm in the previous mild hybrids. The engine torque output has also been increased from 87 ft.-lb at 3,300 rpm to 89 ft.-lb at 4,500 rpm. The engine and electric motor have a combined maximum output rating of 110 HP at 5,500 rpm and 127 ft.-lb of torque at 1,000 to 3,500 rpm. Besides the increase in output, note that the system now provides its peak torque at a lower engine speed.

The IMA motor for the system remains between the engine and the transaxle. However, its power output has been increased to 23 horsepower (17 kW) at 1,546 to 3,000 rpm from 15 at 4,000 rpm and can provide up to 78 ft.-lb at 500 to 1,546 rpm of additional torque. This new motor **(Figure 9-3)** enables the Civic to be powered solely by the electric motor. Although the motor is less powerful than other hybrid traction motors, it helps the Civic to obtain an EPA estimated fuel economy rating of 44/44 mpg city/highway, and the vehicle is rated as an AT-PZEV by CARB.

used in previous models, but it has reconfigured permanent magnets in the rotor, and the rotor and stator rely on flat wires, which increases the density of the magnetic field around the wires. The generative capabilities have also been increased with this redesigned motor.

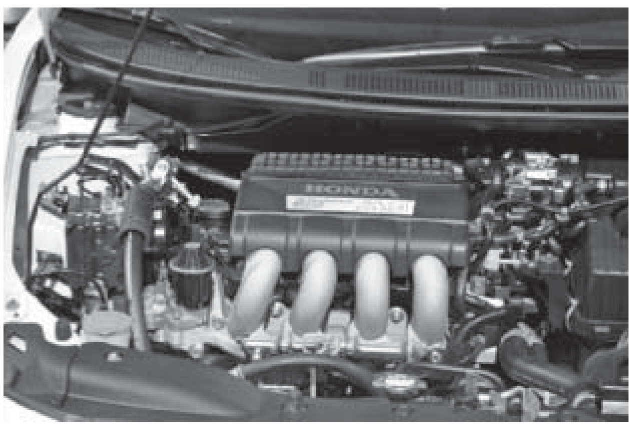

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Figure 9-1 The engine and IMA of a full hybrid Honda Civic.

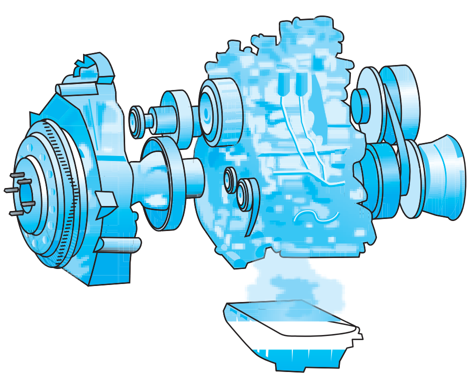

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Figure 9-2 The new Civic Hybrids are equipped with a CVT.

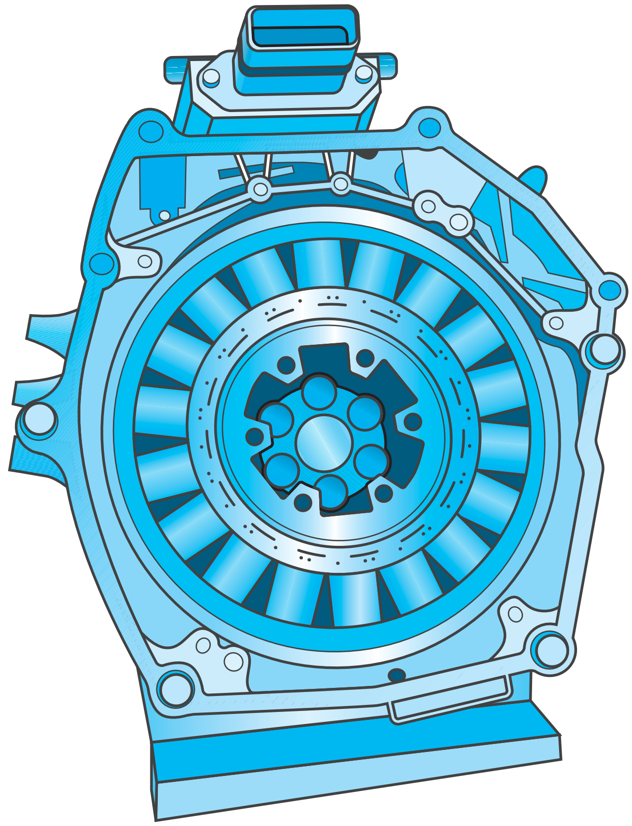

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Figure 9-3 The new IMA motor produces 23 horsepower.

Electronic Controls

This Civic also has a redesigned Intelligent Power Unit (IPU). The new IPU **(Figure 9-4),** which is the control center for the IMA system, is smaller and weighs less than the previous designs. Perhaps the biggest change is the use of a lithium-ion (Li-Ion) battery rather than a nickel-metal hydride (NiMH) unit. The output of the battery pack has also been increased to 20 kW at 144V. The operating voltage range for the motor has also changed to 108 to 172 volts. Switching to the Li-Ion battery reduced the battery's weight by more than 20 lb.

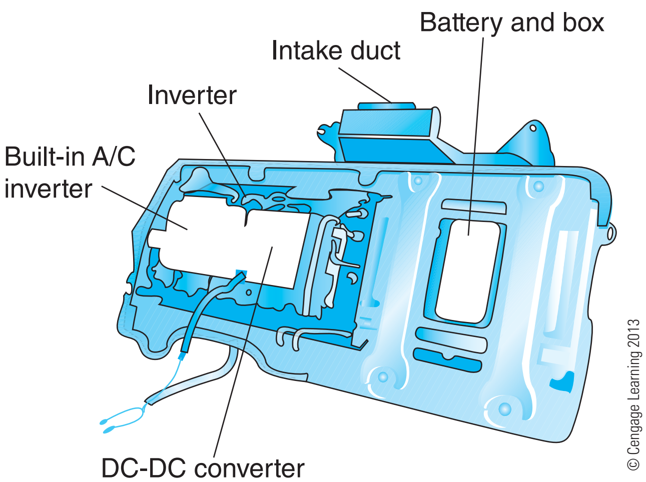

Figure 9-4 The IPU is the control center for the IMA system.

The construction of the battery module is much like that in earlier Honda hybrids. Each cell can store 3.6V, and 10 cells are assembled into a module. Therefore each module stores 36V. There are four such modules. Each module has a control unit that monitors voltage and temperature to determine the condition of the module. The data from each module is sent to the motor control module (MCM), which controls the actual discharge and charge rates of the battery pack **(Figure 9-5).** The MCM does this by sending signals to the motor power inverter (MPI).

The switch to Li-Ion batteries necessitated a revised battery module fitted with temperature sensors and a cooling system that relies on the A/C system, outside air, and a cooling fan. This airflow also cools the inverter, the motor control module, the DC-DC

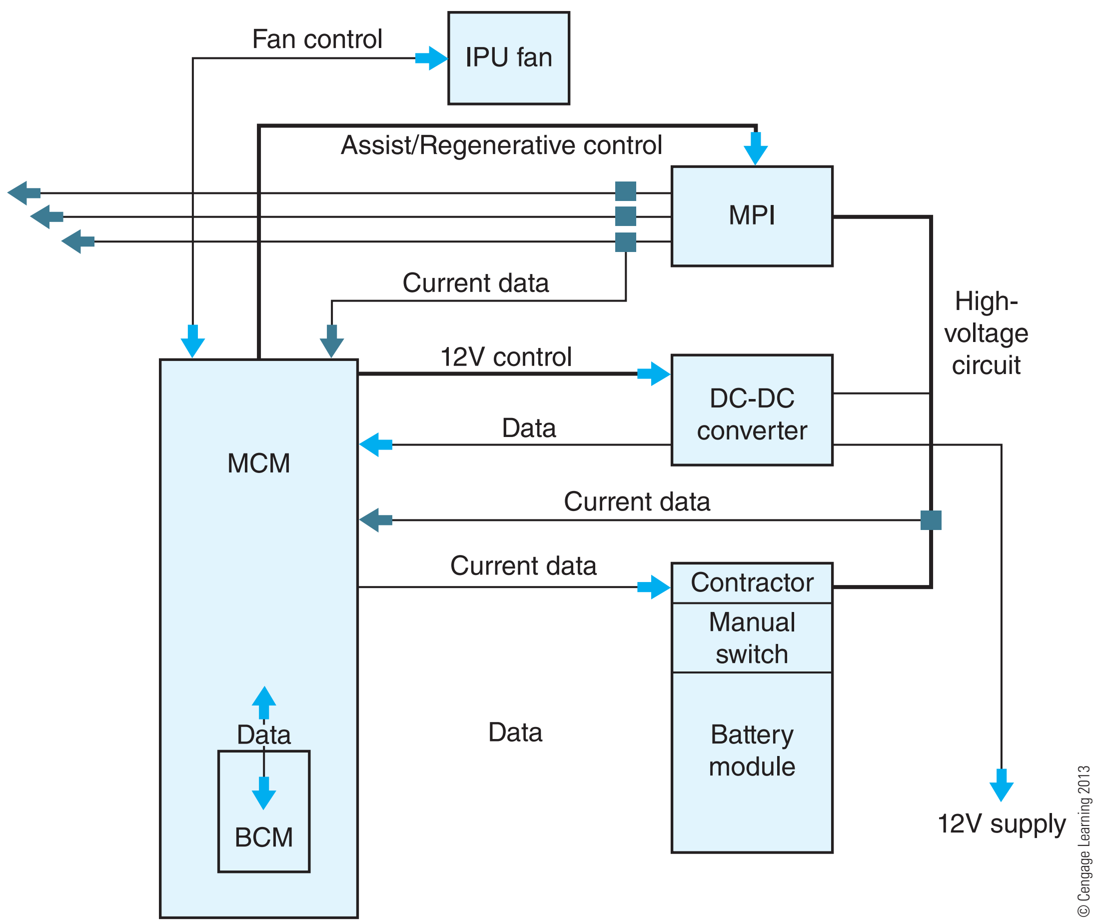

Figure 9-5 The basic control circuit for an IMA system.

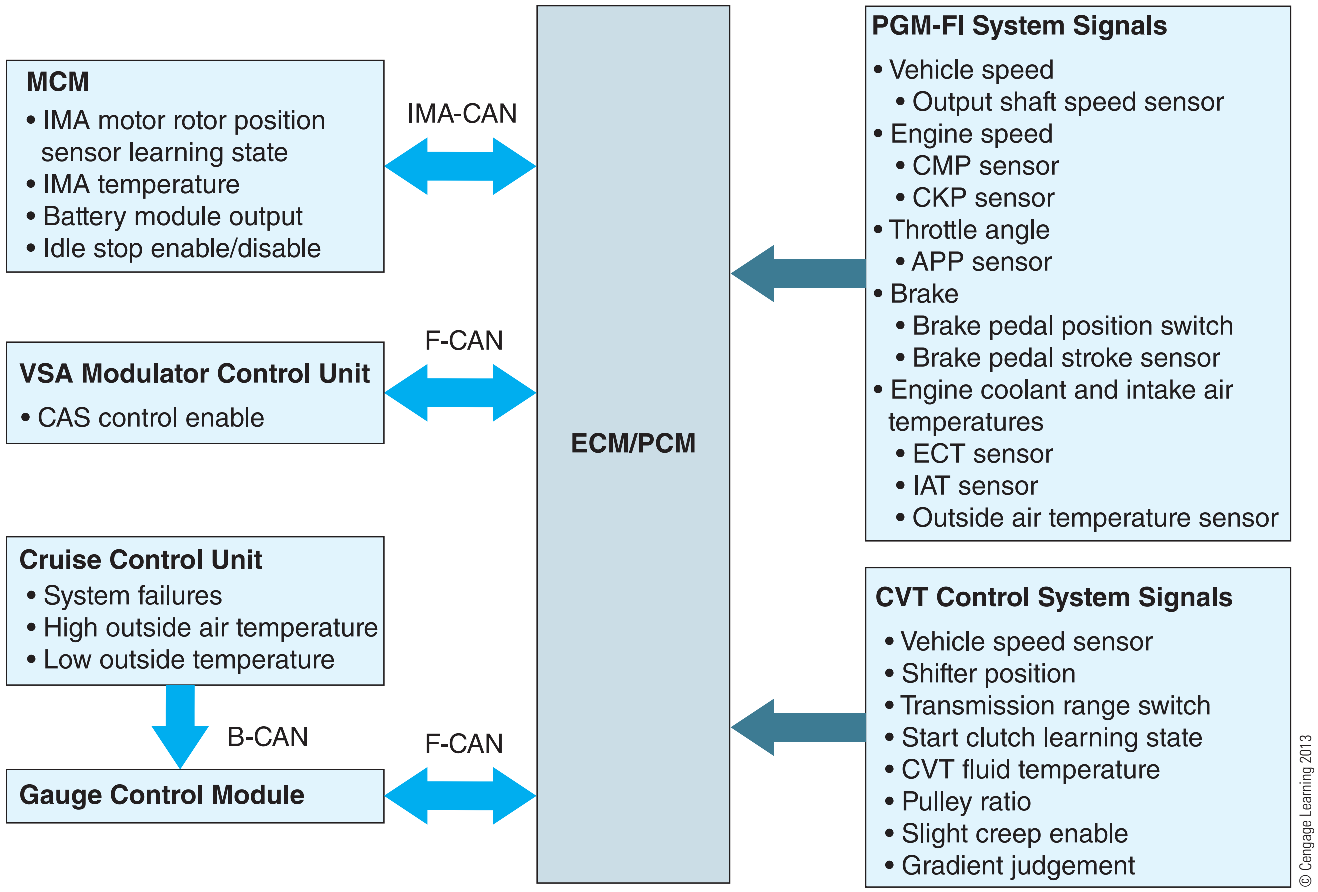

Figure 9-6 A look at how all of the components and sensors influence the performance of a full hybrid Honda.

converter, and the heat sink for the air conditioning compressor driver. A junction board, which consists of the contactors, a bypass resistor, and a battery current sensor, is mounted on the battery module. The junction board distributes the high voltage for system operation.

The MCM, which is part of the IPU, continuously receives information from the Battery Condition Monitor (BCM). The BCM monitors the voltage, temperature, and current in and out of the battery to calculate the battery's SOC. The SOC is then sent to the PCM, which in turn sends commands to the inverter within the motor control module. If the battery's SOC is lower than a specified amount, the PCM will prevent the electric motor from working.

The MCM also converts the motor to a generator and vice versa. This new Honda hybrid has a revised regenerative

module calculates the amount of brake force required for safe slowing down and stopping. The control module attempts to maximize the amount of power generated by regenerative braking by minimizing the amount of brake force supplied by the hydraulic brake system.

The entire powertrain is monitored and controlled by the PCM through various CAN lines and sensors to ensure the best efficiency and driveability **(Figure 9-6).**

Engine

The engine used in this latest model of the Civic Hybrid is much the same as that used in previous models. It is a single overhead cam, eight-valve, 1.5L i-VTEC engine with i-DSI. This aluminum alloy engine is equipped with ignition and fuel injection systems that provide for a lean-burn mode. Both the intake and exhaust systems have been refined to increase airflow. The engine is also manufactured with many features to reduce friction and, therefore, fuel usage, such as plateau-honed cylinder walls, offset

arms. The engine also uses a very lightweight oil (0W-20) to reduce friction.

The i-DSI system uses two ignition coils firing two spark plugs per cylinder to ensure complete combustion for economy and power. The eight ignition coils are independently controlled by the PCM in response

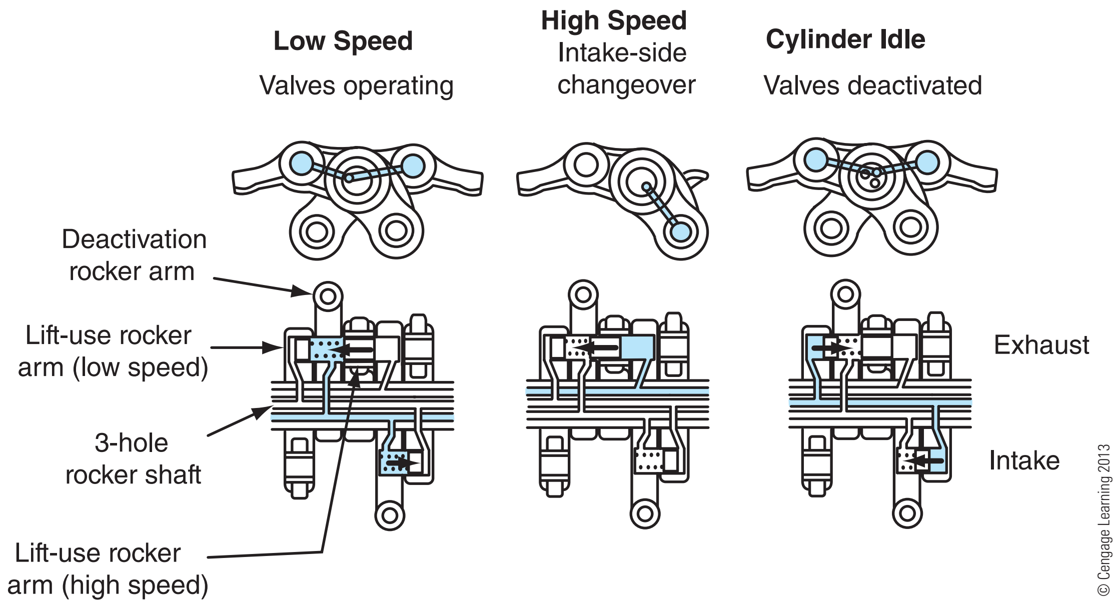

Figure 9-7 The action of the three-stage i-VTEC system.

to engine speed and load and can change individual spark plug firing times.

The engine is equipped with an electronically controlled throttle plate and a Variable Cylinder Management (VCM) system, which is a three-stage i-VTEC system that increases power output by varying cam timing and allows for deactivation of all four cylinders to reduce pumping losses during deceleration. The latter increases the system's ability to generate electricity during deceleration.

This Civic Hybrid is also equipped with the dual-scroll hybrid air conditioning system found in the Accord Hybrids. These compressors are actually two compressors built into a single unit. One is driven by the engine and the other is driven by an electric motor. The compressors can work independently or together, depending on the temperature inside the passenger cabin and the SOC of the battery pack.

Three-Stage i-VTEC with VCM. The three-stage i-VTEC valve control system **(Figure 9-7)** provides normal and high-output valve timing, plus cylinder idling at all cylinders. Earlier Civic Hybrids had a two-stage VTEC system that provided normal valve timing and cylinder idling at three of the four cylinders. With the three-stage

the valves can change according to engine speed and driver demands. At high speeds, the system extends valve opening time for improved performance. The VCM system allows for deactivation of all systems during deceleration. It is claimed that this deactivation reduces pumping losses by 66 percent and improves the regenerative ability by 1.7 times because the engine now provides very little engine braking during deceleration. This effect is accomplished by the generator.

The three stages of the VTEC system are accomplished through hydraulic pressure and an advanced rocker arm design. A pin moves inside the rocker arm shaft to engage or disengage a rocker arm. There are three separate oil passages leading to the pin. As the pressure moves through a passage, the pressure moves the pin. The pressure and the passage for the pressure are controlled by a spool valve that is controlled by the PCM.

Operation

The system operates much like previous generations of the IMA hybrid system, except the vehicle can now operate solely by battery power for a short period of time at initial startup **(Figure 9-8).** The car is equipped with a conventional 12V starter that is only used when the HV battery has a low state of charge, when the ambient temperature is low, and when there is an IMA fault. During all other startups, the IMA starts the engine. The 12V battery is recharged through the DC/DC converter.

down the engine during idle times if the battery does not need charging. When the engine is off but the system is turned on, the auto stop indicator blinks. If the driver's door is opened during auto idle stop, the auto stop indicator blinks and the warning buzzer sounds. The engine will not shut off if the engine is

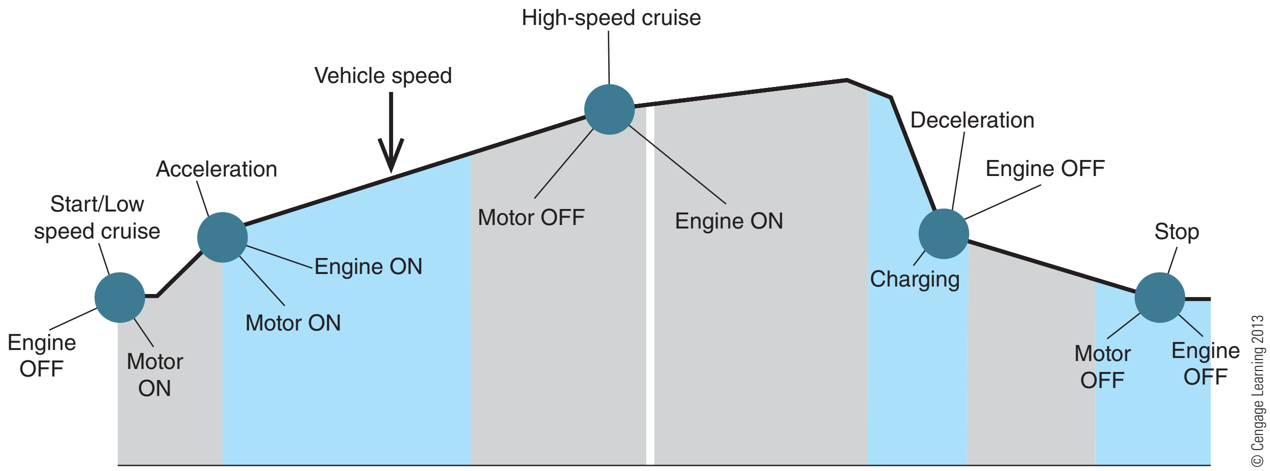

Figure 9-8 The operation of the IMA system during different driving conditions.

cold, the pressure on the brake pedal is low, the A/C system is running, the battery's SOC is low, or if the vehicle did not reach a speed of over 10 mph during the last drive cycle. The latter allows for battery charging during a traffic jam.

When the brake pedal is released and the accelerator pedal depressed, the vehicle moves by both electric and ICE power. The engine at this time is running in the economy mode with the valves opening by the low lift camshaft profile. During slow acceleration, the motor is turned off and the vehicle moves only by the engine, which is still operating in the economy mode.

When the driver is maintaining a very low cruising speed, the cylinders in the engine are deactivated and the motor powers the car by itself. During this time, the engine's rocker arms are not opening the valves. If the battery needs charging during this time, the engine will continue to run.

During acceleration from a low speed, the engine starts and runs in the economy mode. The motor is also running and supplements the power output of the engine. If the battery pack's temperature is outside the specified range, the motor will not run, and the vehicle is powered solely by the ICE. Once a cruising speed has been established, the motor turns off and the vehicle is propelled solely by the engine. During heavy acceleration, the engine runs in its high-output mode and

During deceleration, the motor begins to work as a generator, and the valves in the engine close and remain closed, which allows for maximum regenerative braking and reduces fuel consumption. If the battery is fully charged, the system causes the hydraulic brake system to do all of the slowing down and braking. The activity of the regenerative braking system is totally dependent on the charge needs of the battery pack. Once the vehicle is stopped, the engine shuts down until the brake pedal is released.

Insight and CR-Z

Honda has two other hybrids that can be considered full hybrids, although they seldom operate in an all-electric mode: the Insight and the CR-Z. They both use the same IMA system, but because they are intended for different markets, they have some differences. The current Insight is not a remake of Honda's original hybrid. Instead it is now totally redesigned and is a five-passenger vehicle.

The Insight **(Figure 9-9)** hybrid has a 1.3L, four-cylinder gasoline engine and a 13 HP (10 kW) permanent magnet AC synchronous electric motor. Combined they provide 98 HP at 5,800 rpm and 123 ft.-lb of torque at 1,000 to 1,700 rpm. The battery is an NiMH with an output of 100.8V and 5.75 ampere hours. Together they have an EPA-estimated city/highway/combined fuel economy rating of 41/44/42

Figure 9-9 A redesigned Honda Insight.

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Figure 9-10 A Honda CR-Z hybrid.

miles per gallon. The power sources are connected to a CVT.

The CR-Z (Compact Renaissance Zero) is a two-passenger "sporty" hybrid. It is rated by CARB as an AT PZEV, which is the lowest emissions rating for a vehicle with a gasoline engine. The CR-Z is unique in that it offers a six-speed manual transmission, in addition to a CVT. This was the first hybrid to offer a manual transmission. The CR-Z **(Figure 9-10)** has a 1.5L, four-cylinder engine and the typical IMA system that has a combined output of 122 HP and 128 ft.-lb of torque with the manual transmission and 123 ft.-lb with the CVT. This version of IMA is identical to that used in the Insight, a 13-HP electric motor powered by 84 1.2-volt NiMH cells.

With the CVT, the EPA estimates the fuel economy to be 36 mpg in the city and 39 mpg on the highway. The manual transmission models are rated at 31 mpg in the city and 37 mpg on the highway.

The engine allows for variable intake-valve duration and lift, plus it will close one intake valve at low engine speeds. The engine will operate with three valves per cylinder until the engine reaches 2,300 rpm, and then the engine goes back to four-valves-per-cylinder operation. These changes allow the engine to run more efficiently at the very bottom of its power band.

The standard six-speed manual transmission has a hill assist that temporarily prevents the car from rolling backward during initial acceleration. When previously at a stop, if the driver lets up on the brake pedal, the hill start assist will maintain brake pressure for about 1.5 seconds to prevent the car from unintentionally rolling backward. Brake pressure is released once the throttle is opened and engine torque increases.

Both

"Eco Assist." Eco Assist gives the driver feedback on how to improve fuel efficiency through changes to driving style. The Eco Assist display shows such things as the Eco Display that displays feedback during braking and acceleration. The display is one of the screens in the multi-information display. It displays the driver's improvement in fuel economy by "growing" five plant icons, one leaf at a time, based on fuel-efficient driving. This guide has three progressive efficiency stages: the first stage can grow two leaves on each of the five plants; the second stage can grow four leaves on each plant; the third stage can grow a blossom on each plant. Other displays in the Eco Assist include real-time driving information, an Eco score, lifetime points, Eco stages, and an Eco driving record.

In the CR-Z, a digital speedometer floats in the middle of an analog tachometer in the center ring of the instrument display. A ring between the tachometer and speedometer helps the driver get the best possible gas mileage. The system also has three driver-selected modes, like the Civic and Insight: Normal, Hybrid, and Sport. Normal mode allows for standard settings of the steering, engine, motor assist, and air conditioning systems. The ring in the instrument panel is green, which is where maximum fuel economy can be achieved. During acceleration, the ring changes to blue; this is the hybrid mode. In this mode, the IMA assist works to maximize fuel efficiency, and the air conditioning system is programmed to reduce its drag on the engine. The colored ring moves between blue and green, depending on the force on and position of the throttle pedal. The ring turns to blue when there is a wide throttle opening. In the sport mode, the ring becomes red.

Accord and Civic Plug-In Hybrids

Honda also uses lithium-ion batteries in its new two-motor plug-in hybrid systems. Both the Civic and Accord received this technology first, and Honda says the technology will be used in more models in the near future. This system uses one traction motor for propulsion and the other as a generator/motor for recharging the battery pack. The traction motor, rated at 161 HP (120 kW), works with a 2.0L, i-VTEC four-cylinder, Atkinson cycle engine mated to an electric continuously variable transmission (E-CVT).

In the all-electric mode, the car is powered by a 6-kWh lithium-ion battery and 161-HP (120-kW) electric motor that can provide an all-electric range of 10 to 15 miles and a top speed of 62 mph. Honda claims the battery pack can recharge in less than four

The plug-in system **(Figure 9-11)** can operate in three modes: all-electric, hybrid, or engine direct-drive. During initial operation and when traveling at low speeds, the car will operate in the all-electric mode. At startup and low speeds, the electric motors will drive the car. During acceleration the car will

Figure 9-11 A plug-in Honda Civic.

move into hybrid mode, using both the ICE and the electric motors. Once the car is traveling at high speeds, the system switches to allow only the ICE to propel the car.

AUDI, PORSCHE, AND VOLKSWAGEN HYBRIDS

The basic system used in the Porsche Cayenne, Porsche Panamera **(Figure 9-12),** and Volkswagen Touareg **(Figure 9-13)** hybrids is very similar. The

Figure 9-12 Porsche® Panamera® hybrid.

Figure 9-13 A Volkswagen Touareg hybrid.

Figure 9-14 The Audi supercharged V6 that is used in the Porsche® Cayenne®, Porsche® Panamera®, and Volkswagen Touareg hybrids.

main difference between the various models is defined by the vehicle's intended purpose and the body style. All are equipped with an Audi direct-injected, supercharged 3.0L V6 engine **(Figure 9-14)** rated at 333 HP and 324 ft.-lb of torque. An electric motor with a maximum power output of 47 HP and 99 ft.-lb is placed between the engine and an eight-speed automatic transmission. The engine and motor offer a maximum combined output of 380 HP and 428 ft.-lb of torque at 1,100 rpm. They are rated as super-low ULEVII vehicles by CARB.

Energy for the electric motor comes from a 288V, 1.7-kWh NiMH battery pack. With this battery pack, the vehicles can be driven up to 30 mph and for about 1.2 miles in all-electric mode. The vehicles are equipped with a clutch between the electric motor and the engine. The driver can press the "E Power" button on the center console, which prevents the engine from starting and allows the vehicle to operate in pure electric mode. This action decouples the engine from the rest of the powertrain as the electric motor receives energy from the battery to maintain the vehicle's speed. This feature only works when the vehicle is traveling less than 53 mph and for about 1 mile. After that the engine starts and propels the vehicle.

The vehicles also have a coasting feature that disengages the engine and motor from the driveline when below 99 mph. This removes the engine's drag on the driveline while coasting, such as when going down hills. The hybrids also have regenerative braking and auto stop-start systems. All of these features result in an average combined fuel consumption rating of about 27 mpg.

Although these vehicles have low emissions and get good fuel mileage, they still perform quite well. In fact, Porsche claims that Panamera S Hybrid was the world's fastest production hybrid. It can accelerate from 0 to 60 mph in 5.7 seconds and has a top speed of 157 mph.

The hybrids also have unique instrumentation. There is a display, when it was introduced, that shows where the energy to move the vehicle is coming from. When the vehicle is powered by electricity alone, the display will show a green arrow pointing from the battery to the wheel. The ICE arrow is orange and a blue arrow shows the electricity either coming from or going to the battery. Once the ICE starts, a red arrow pointing to the wheel along with a green one pointing to the battery appears. This indicates that the engine is running and driving the generator to recharge the batteries. When there is only a green arrow pointing from the wheel to the battery, regenerative braking is recharging the battery. The instrument cluster also includes a display of the battery's SOC.

Audi Q5 Quattro Hybrid

The Q5 hybrid Quattro's electric motor replaces the torque converter in a highly modified, widely spaced eight-speed automatic transmission. A wet multi-plate clutch couples and decouples the electric motor and the engine. When the engine is not running, an electric pump maintains hydraulic pressure in the transmission to protect it. The Q5 has a turbocharged, 2.0L, four-cylinder engine. The engine has an output of 211 HP and 258 ft.-lb of torque available from 1,500 to 4,200 rpm. The ISAD 45-HP motor serves as an assist for the engine, a starter for stop-start function, and a generator for regenerative braking. In an all-electric mode, the Q5 hybrid can travel up to 1.8 miles at a maximum speed of 37 mph. Fuel consumption is rated at a combined 33 mpg.

The hybrid relies on a Li-Ion 1.3-kW battery pack. This air-cooled battery pack has 72 cells and can supply up to 266 volts. When ambient temperatures are low, air from the interior of the vehicle flows through the pack. As the battery's temperature rises, the pack is cooled by a branch of the vehicle's A/C system. The power electronics are in the engine compartment and are cooled by coolant circulated by a cooling system that is not part of the engine's cooling system.

OTHER ISAD EQUIPPED HYBRIDS

BMW 3 and 5 Series ActiveHybrids

BMW's 3 and 5 Series ActiveHybrids are full hybrids **(Figure 9-15).** A 54-HP (40-kW) electric motor is sandwiched between the engine and an eight-speed transmission. The engine is BMW's TwinPower Turbo, inline six-cylinder engine **(Figure 9-16).** The engine's efficiency (fuel economy and performance) is enhanced by the incorporation of the twin-scroll turbocharger with Valvetronic, double-VANOS, and high-precision fuel injection. Valvetronic controls valve lift or opening distance. VANOS is an acronym for variable Nockenwellensteuerung or variable valve timing.

Figure 9-15 A BMW 5-series hybrid.

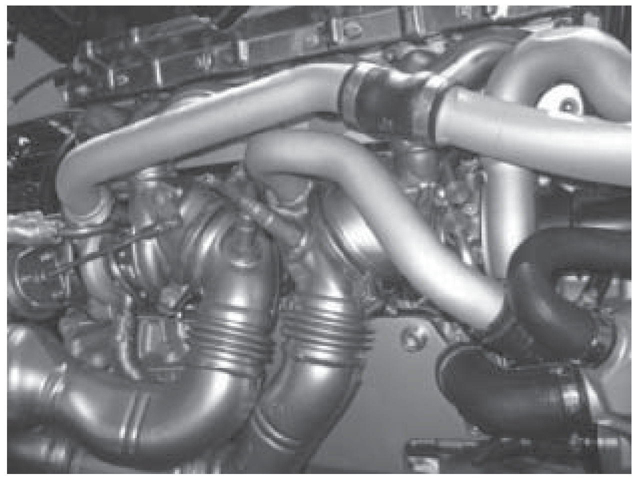


Figure 9-16 The twin turbo arrangement used on BMW's inline six-cylinder engines.

The engine can produce 300 HP. The electric motor can add another 55 HP and 155 ft.-lb of torque for a combined power output of 340 HP and 295 ft.-lb of torque. That power can move the car from 0 to 60 in 5.7 seconds.

A lithium-ion battery is used, and the car can move in the all-electric mode for up to a maximum speed of

engine during heavy acceleration and heavy loads. The hybrid has both brake regeneration and auto start-stop systems.

The ActiveHybrid's energy management system monitors information from the engine, chassis, and on-board driver assistance systems, including the

navigation system. The management system not only determines the most efficient power needs for current driving situations but can also prepare for conditions that are in the near future.

Hyundai Sonata Hybrid

The Sonata Hybrid **(Figure 9-17)** can go up to 75 mph propelled only by its electric motor. It has an EPA estimated fuel economy of 36 mpg in the city and 40 mpg on the highway. The combined power out of the engine and electric motor for this parallel hybrid is 206 HP and 195 ft.-lb of torque. To maximize fuel efficiency, the hybrid has been altered to reduce its air drag; the result is a drag coefficient of 0.25.

The electric motor is sandwiched between the engine and a six-speed automatic transmission. The motor, referred to as a **transmission-mounted electrical device (TMED)**, replaces the conventional torque converter. The TMED is comprised of two primary assemblies: a 40-HP electric drive motor and a solenoid-activated clutch pack. These parts fit in about the same space as a traditional torque converter. The clutch allows the power from the 166-HP 2.4L Atkinson-cycle four-cylinder gasoline engine, the electric motor, or both to pass through the transmission. The drive motor in the TMED also serves as a generator for regenerative braking.

The system also uses an 8.5-kW BAS motor driven by the engine's crankshaft. This unit does not assist the engine, it only provides for the stop-start operation of the engine. The engine is an Atkinson-cycle **(Figure 9-18)** 2.4L four-cylinder that provides up to 169 HP and 156 ft.-lb of torque.

The electric drive is powered by a 270V, 1.4-kW, 72-cell lithium polymer battery array. There is also a conventional 12V battery for the 12V systems and accessories.

In the instrument cluster there is a Hybrid Technology Display that summarizes the current operation of the hybrid system. The information displayed includes: the source of the energy being used, battery SOC, and average and instant mpg. If the car is equipped with the optional navigation system, the information will be displayed on that screen.

Figure 9-17 A Hyundai Sonata hybrid.

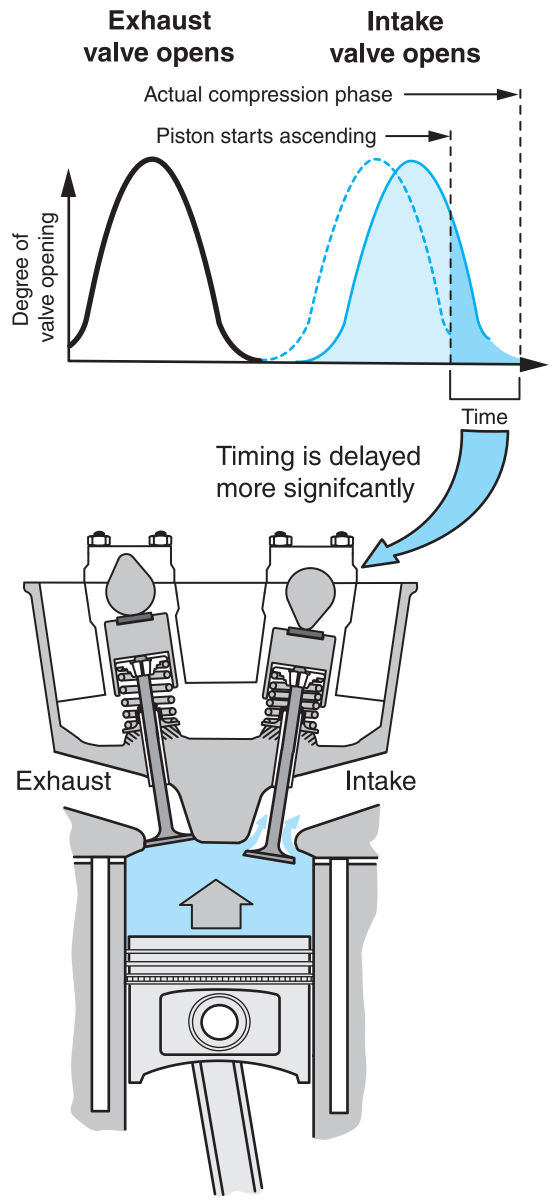


Figure 9-18 A quick explanation of the Atkinson cycle.

KIA Optima Hybrid. The Optima Hybrid **(Figure 9-19)** uses the 2.4L four-cylinder Atkinson-cycle engine and

ISAD-type motor is connected to the engine and the six-speed automatic transmission by a wet clutch. The motor can provide up to 40 HP and 151 ft.-lb of torque. Electrical power is supplied by an air-cooled 270V lithium-polymer battery. The car is capable of reaching about 62 mph in its full-electric mode.

Figure 9-19 A Kia Optima.

The EPA has rated the Kia's fuel economy at 35 mpg in the city and 40 mpg on the highway.

Infiniti M Hybrid

In an Infiniti M hybrid **(Figure 9-20),** the electric motor is sandwiched between the 3.5L V6 engine and a seven-speed automatic transmission. The engine can power the car with or without electrical assist. It can also serve as a generator during deceleration and braking. The 67-HP electric motor can power the car, assist the engine, start the engine, and serve as a generator. The car is EPA rated at 27 mpg in the city and 32 mpg on the highway.

The system relies on the Atkinson-cycle V6 rated at 302 HP and 258 ft.-lb of torque, a 50-kW electric motor, and two clutches. One of the clutches, a wet clutch, is positioned at the input of the transmission; it takes the place of a conventional torque converter. Set between the engine and the electric motor is a dry clutch. This clutch is capable of coupling and decoupling the engine and the motor. The system controls the clutch to allow the engine to turn off anytime the accelerator pedal is released, such as deceleration and coasting. The system can decouple the engine at any speed. The engine and electric motor combine to produce 360 HP.

The M hybrid's instrument display has an electric operation-only odometer, a display of the battery's SOC, and a real-time power diagram allowing the driver to see whether gas or electric power (or both) are being used. The driver can also choose to use a feature called "eco pedal." This feature pushes the accelerator pedal up if the system determines the driver is not driving efficiently.

Figure 9-20 An Infiniti M series.

MODELS USING A MOTOR IN THE TRANSMISSION

One design that has been used in an increasing number of applications is the incorporation of one or more electric motors within a transmission.

GM Two-Mode Hybrid System

GM, BMW, and DaimlerChrysler co-developed a two-mode full hybrid system that can be used with gasoline or diesel engines. The **two-mode hybrid system** relies on advanced hybrid, transmission, and electronic technologies to improve fuel economy and overall vehicle performance. It is claimed that the fuel consumption of a full-sized truck or SUV will be decreased by at least 25 percent when it is equipped with this parallel hybrid system.

GM offers this technology in its Chevrolet Silverado, Chevrolet Tahoe, GMC Yukon **(Figure 9-21),** and Cadillac Escalade. The hybrid system works with a 6.0L 332HP V8 gasoline engine, a 300-volt NiMH battery pack, and a two-mode transmission. GM calls the transmission an electrically variable transmission (EVT). The transmission has four fixed gear ratios but can alter the gear ratios between each of those ratios.

The system fits into a standard transmission housing and is basically three planetary gear sets coupled to

Figure 9-21 The GMC Yukon is available with a two-mode hybrid system.

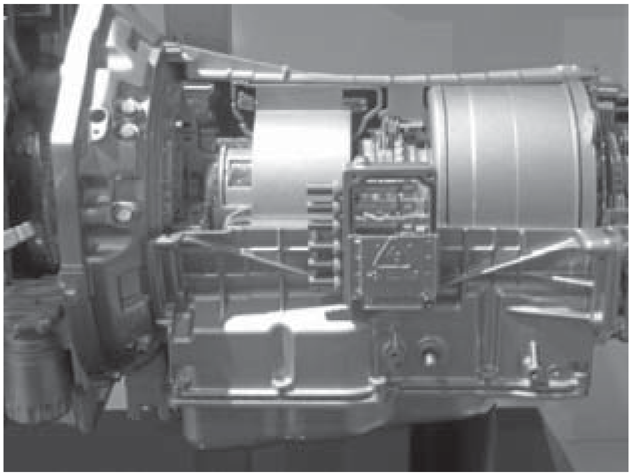


Figure 9-22 A cutaway of a GM two-mode transmission.

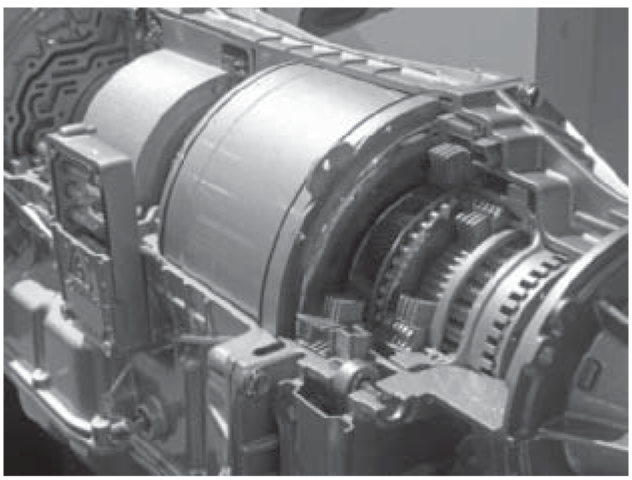


Figure 9-23 The motors and clutches inside a two-mode transmission.

two 60-kW motor/generators, which are electronically controlled. This combination results in a continuously variable transmission and motor/generators for hybrid operation **(Figure 9-22).** Four multi-disc clutches are used to transition the transmission from one gear ratio to another **(Figure 9-23).** When the vehicle is operated under a heavy load, the transmission functions like a conventional transmission with fixed gear ratios.

The system has two distinct modes of operation. It operates in the first mode during low-speed and low-load conditions, and the second mode is used while cruising at highway speeds.

Operation

Two compact AC synchronous motors are connected to the transmission's gear sets **(Figure 9-24).** The result is a continuously variable transmission that is based totally on planetary gears. The gears work to increase the torque output of the motors. This enables the system to rely on a relatively low voltage, which in turn means the inverter, converter, and controller can be made lighter and smaller. The NiMH battery pack has a nominal voltage of 300 volts and is contained in a housing equipped with a cooling circuit. As with other hybrids, keeping the battery pack within a specified temperature range is a top priority. The power electronics for the system are located under the hood and have their own temperature control unit.

The two-mode hybrid system can operate solely on electric or engine power or on a combination of the two. Electronic controls are used to control the output of the motors and the engine. Typically, when one of the motors is providing propulsion power, it is working as a generator driven by the engine or by the drive wheels for regenerative braking.

The first mode of operation is called the input split and the second is the compound split **(Figure 9-25).** During the input split mode, the vehicle can be propelled by battery power, engine power, or both. This is the normal mode of operation when the vehicle is slowly accelerating from a stop and when it is cruising at slow speeds. During this time, the vehicle will run solely on electric power or on a combination of the electric motors and gasoline power. Mode 2 comes into play when pulling heavy loads, when running at highway speeds, or during heavy acceleration.

When the control unit determines that battery power is sufficient for the current driving conditions, the engine shuts off. During this time, one motor is working to move the vehicle, while the other may be working as a generator to supply power for the traction motor or to recharge the battery. If the engine is commanded to start, the traction motor may shut down but the second motor can continue to operate as a generator if needed. When the truck comes to a stop, the gas engine shuts off. Electricity for the battery pack is supplied by capturing energy that is normally wasted when the vehicle is decelerating or the brakes are applied.

During normal driving under light loads, the vehicle is powered solely by the engine. Depending on the load and other conditions, the engine may turn off some of its cylinders. To help the engine maintain its

engine. When vehicle speed increases or when a heavy load is introduced to the vehicle, such as hard acceleration, climbing a hill, or towing, the system switches to the compound split mode.

The goal of the control unit is to maximize fuel economy while meeting the needs of the current

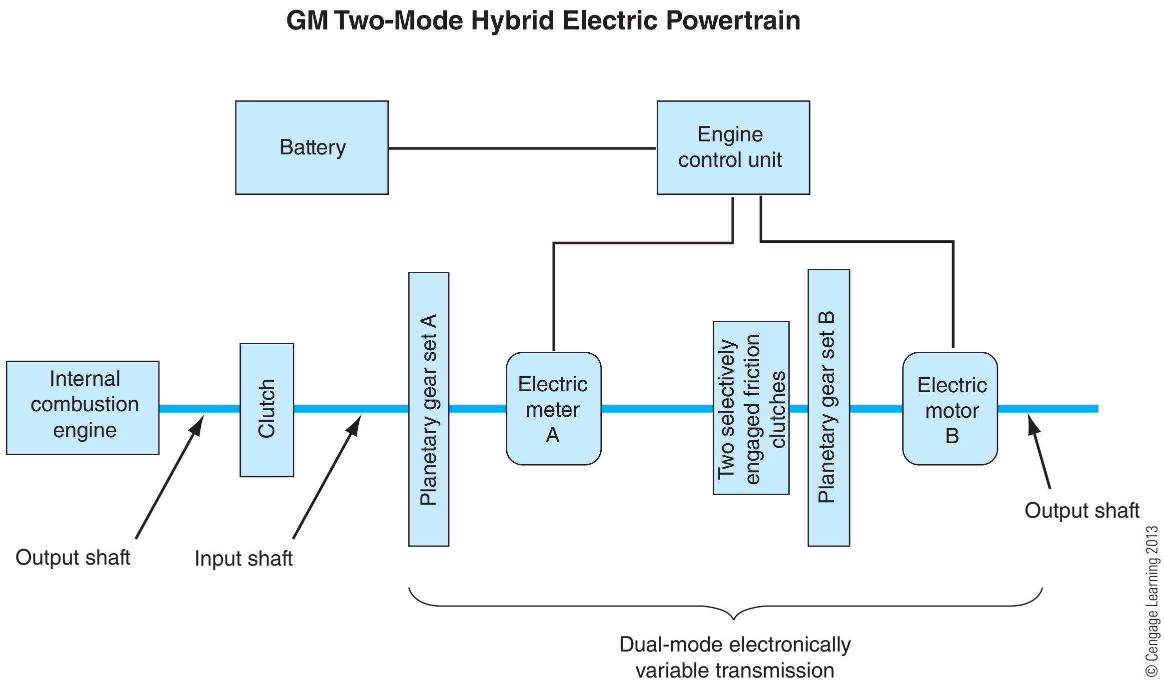
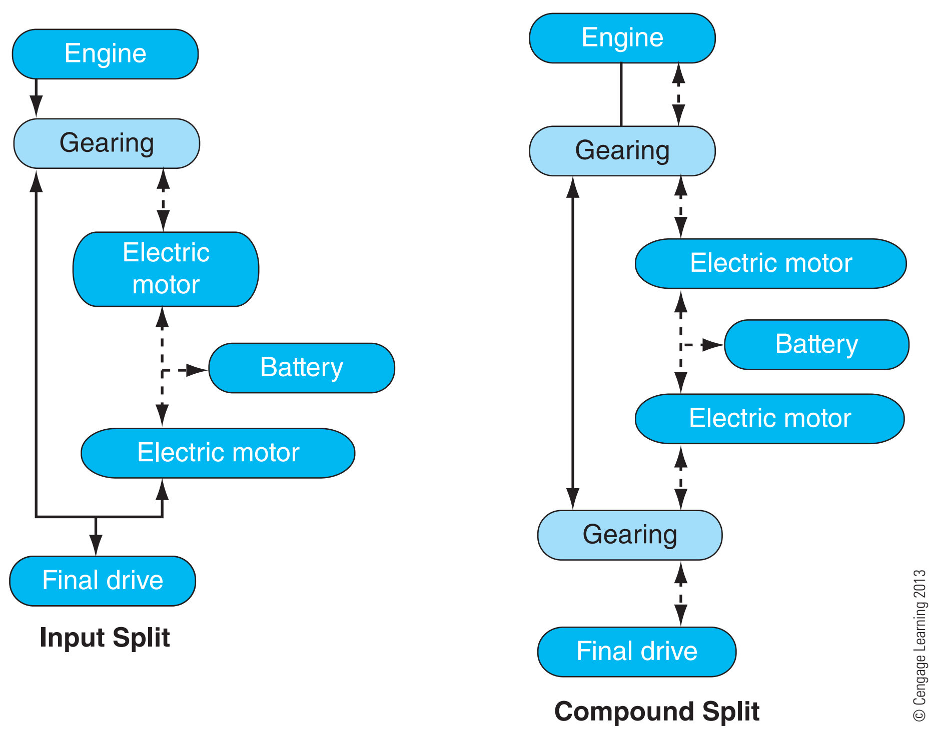


Figure 9-24 The two-mode hybrid system uses two electric motors connected to planetary gear sets to propel the vehicle or assist the engine during propulsion.



Figure

operating conditions. The control unit also works with engine controls to determine if the other fuel-saving features, such as cylinder deactivation and late intake valve closing (Atkinson cycle), should be initiated. It is important to realize that the deactivation of cylinders and the initiation of the Atkinson cycle reduces the power output of the engine. These fuel-saving features do not hurt the performance of the vehicle because the engine's output is supplemented by the electric motor.

This feature distinguishes a two-mode hybrid from other full hybrids. Typically, electric assist is available only when there is a high demand for power. In the two-mode system, on the other hand, the motors make it possible to reduce the work of the engine, even during light and moderate loads.

Hybrid Buses. The two-mode hybrid technology has been used for a few years in city buses. Although the hybrid components in these buses are different from those used in automobiles, the concept is the same. In 2003, GM equipped city buses in the Seattle area with a parallel two-mode hybrid system. The use of these buses has moved to many other major cities.

The GM/Allison hybrid system uses a 600-volt NiMH battery pack. There are two 100-kW electric motors and an electronically variable transmission. The combination of torque-increasing and speed-reducing gears allows the size of the engine to be decreased while providing the performance of a larger engine. This technology has also resulted in much less fuel consumption; in fact, a GM spokesperson claimed, "If we replaced the 13,000 buses (with the hybrid buses) in the nine largest U.S. cities, we would save 40 million gallons of fuel a year." The reduced engine size, along with a particulate filter, results in a 90 percent reduction in emissions.

This hybrid is called the "EP System" and combines a hybrid drive and an Allison transmission into one unit. This system provides 430- to 900-volt power to the motors and is able to capture regenerative energy at speeds up to 50 mph. The unit is cooled by a common oil-cooling system for the motors, drive unit, and control unit. When the vehicle accelerates from a stop, it uses the torque of electric motors, and then maintains the desired speed with its engine. During this time, the engine also drives the generator to charge the batteries.

BMW X6 ActiveHybrid

The BMW X6 ActiveHybrid **(Figure 9-26)** combines an ICE with two high-performance electric motors inside a transmission. This transmission was co-developed with General Motors and the old DaimlerChrysler and is commonly referred to as a two-mode

brid is a seven-speed automatic that actually operates as an electronic continuously variable transmission with four fixed ratios and three virtual ratios. It contains two synchronous AC electric motors, three planetary gear sets, and four sets of multi-disc clutches. The two electric motors serve as generators

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Figure 9-26 A BMW X6 SAV.

to charge the HV battery pack or power the hybrid with up to 91 HP. In all-electric driving, the hybrid can reach up to 37 mph and travel about 1.6 miles.

The transmission has two primary modes of operation: low and high speed. In each of these modes, one motor powers the hybrid while the other works as a generator. This is called the power-split drive mode, and it allows the powertrain to run at continuously variable speeds to achieve maximum efficiency regardless of load or speed. To operate the transmission, the hybrid uses an HV battery pack, a power electronics unit with an integrated inverter, and high-voltage cables.

The engine is a 4.4L, 480-HP V8 engine with TwinPower turbo technology, piezo direct fuel injection, and the Double-VANOS variable valve timing system. Since the motors produce an additional 86 to 91 HP and 192 to 206 ft.-lb of torque, the total available power output is 480 HP with 575 ft.-lb of torque.

A 312V NiMH battery pack is installed in the rear of the SUV and has a capacity of 2.4 kWh. The battery pack is liquid cooled and works with the A/C system or the power steering cooling system to control the battery's heat. If the battery's temperature rises too much, the system will automatically turn on the A/C system. A control unit is part of the battery pack and constantly monitors current battery and power levels.

This hybrid system reduces fuel consumption by up

ceptional performance. BMW claims the SUV can accelerate from 0 to 60 mph in about five seconds. According to the EPA, the hybrid can provide 17 mpg in the city and 19 mpg on the highway.

In the instrument panel there is a battery gauge and a four-segment bar graph that shows the amount of

power output by the motors. There is also an LCD screen in the center console that displays the flow of electrical energy, the SOC of the battery, the amount of electrical boost, and the amount of energy produced by the regenerative system.

BMW 7 Series ActiveHybrid

The hybrid technology used in a BMW 7 series **(Figure 9-27)** was co-developed with Daimler. The eight-speed transmission is bolted to BMW's 4.4L, 440-HP V8 engine with TwinPower Turbo technology, High Precision Direct Injection, and Double VANOS variable valve timing. The torque rating for this engine is 480 ft.-lb at 1,800 to 4,500 rpm. This is basically the same engine used in the BMW X6 ActiveHybrid.

Inside the transmission is a 20-HP (15-kW) electric motor that can supply up to 155 ft.-lb of torque. The combination of the engine and motor is capable of providing 455 HP and nearly 515 ft.-lb of torque. The electric motor in the transmission replaces the conventional starter and a belt-driven generator. When the motor is a generator, it recharges the 120-volt lithium-ion battery mounted behind the rear seat. The battery pack saves the electrical energy that is generated by the motor and supplies power to the network of the hybrid system.

The high capacity of the battery allows the system to maximize the efficiency of the regenerative brake system. The energy management control system immediately turns the motor into a generator as soon as the driver lifts off the accelerator pedal. There is an ActiveHybrid display in the instrument panel that shows the current flow of energy.

The hybrid also has the stop-start feature, as well as many other fuel-saving features such as active aerodynamics, low-rolling resistance tires, and many weight-saving techniques. All of these contribute to a decrease in fuel consumption and emissions. The EPA gives the car a combined rating of 20 mpg.

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Figure 9-27 A BMW 7 series hybrid.

The engine is rather unique. With the TwinPower turbo, each turbo feeds four cylinders. The location of the turbos is what makes the engine unique. Rather than mounting them in the typical way, on the outside of the engine, this engine has its turbos mounted in the V-space between the two rows of cylinders. The exhaust ports are in the V of the engine and the intake manifolds are mounted to the sides of the engine where the exhaust manifolds typically are. This design allows the action of the turbos to be very responsive to the accelerator pedal.

Fuel is delivered to the cylinders by direct injection technology known as High Precision Injection. This technology uses piezo injectors fitted into the cylinder head and placed next to the spark plugs. These injectors spray fuel into cylinders at a pressure of 2,900 psi.

The intelligent energy management system consists of the HV Li-Ion battery, a 12V AGM battery, and two on-board networks. There is a separate network for each of the power sources, but they are wired in parallel to each other. The 12V network contains all of the necessary components to operate and control the 12-volt systems in the car. The 120V network not only delivers to and receives high voltage from the motor, it also can be used to operate and control other high-voltage systems, such as the air conditioning compressor.

CONCEPT FULL HYBRIDS

Many other manufacturers plan to release full hybrids, and the following discussion merely introduces what they may present to the public. It is safe to say that many of the new hybrids that will be released in the near future will be modifications of the systems introduced by others. What follows are some of the vehicles considered or being tested by the manufacturers.

BMW i Concepts

BMW has developed a number of "i" concept cars. They use the prefix i for all concept vehicles that use electricity for mobility. Some of these concepts are series-type hybrids. The i3 and the i8 are discussed here because they demonstrate different ways to

still providing decent performance.

The i3 body sits on an aluminum structure called the "DriveCell." In the center of the structure is a liquid-cooled 22 kWh lithium-ion battery pack. The traction motor is mounted to the front of the rear axle. To serve as a range extender, there is a two-cylinder,

600-cc gasoline generator that can recharge the battery pack while driving. Since fuel is needed to run the generator, the car would undoubtedly be rated by the EPA as achieving about 50 mpg. When operating in a pure electric mode, it would be rated at more than 100 MPGe and have a 100-mile driving range. BMW claims this car can accelerate from 0 to 60 mph in less than 8 seconds.

The i3 has a unique accelerator pedal. The pedal functions more like a three-way switch than a variable one. When the pedal is pressed down to the floor, the car will accelerate. When pressure is removed from the pedal, regeneration takes place. Cruising speeds are determined by the position of the pedal between accelerate and decelerate. For stopping, the car has a conventional hydraulic brake system.

The i8 is an all-wheel-drive hybrid. The electric motor used at the rear of the i3 powers the front drive axles. At the rear axle is a transversely mounted 1.5L, three-cylinder engine that can produce 220 HP and 221 ft.-lb of torque. The combined power output of 349 HP should be able to propel the car from 0 to 60 mph in less than five seconds while providing 80 mpg.

Like the i3, the battery is mounted through the center of the car. The battery is less powerful than the one used in the i3 and has an output of 7.2 kWh. The car should have a driving range of 20 miles during all-electric operation. All four wheels can regenerate energy, plus the use of a high-capacity generator, driven by the engine, means the car will do a good job of recharging the battery. If the battery does need to be externally charged, it is estimated that it will take about two hours using 220V to fully charge the battery.

Ford C-Max

There are two hybrid versions of Ford's C-Max **(Figure 9-28);** the C-Max Energi, which is a plug-in hybrid, and a full hybrid called the C-Max Hybrid. Both are rated as Advanced Technology Partial Zero Emissions Vehicles (AT PZEV) by CARB. They are also equipped with a high-output electric motor powered by a lithium-ion battery and an Atkinson-cycle gasoline engine. Although based on the same vehicle, their appearance is slightly different than the standard C-Max. For example, the standard C-Max is a seven-passenger vehicle and has rear sliding doors, whereas the hybrid models only seat five and have conventional rear doors.

The C-Max Hybrid has an electric motor that can move the car at more than 47 mph on pure electric power before the gasoline engine is started. The C-Max Energi can be charged overnight on a home charger and is expected to have a range of more than 500 miles using the battery and engine.

Jaguar C-X75

Jaguar has designed at least two range-extending electric two-passenger supercars. These served as "proof of concept" models. Early prototypes had a pair of small gas turbine engines. These engines were mounted in the middle of the car and were used to charge the batteries. The turbine engines can rotate as fast as 80,000 rpm and generate 140 kilowatts of recharge. With these engines, the car had a driving range of 560 miles, 68 miles of which were provided by only battery power.

There is a 195-HP motor at each wheel, making the total possible amount of power available 780 HP and 1,180 ft.-lb of torque. This results in a car that has a top speed of 205 mph and can accelerate from 0 to 60 mph in 3.4 seconds.

The C-X75 **(Figure 9-29)** prototypes did not have the turbine engines; instead, a small-displacement, high-horsepower four-cylinder engine was used. Also, the car was equipped with only two electric motors, although it is speculated that the performance will be about the same as that of the early prototypes.

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Figure 9-28 A Ford C-Max crossover.

Jaguar Land Rover North America, LLC

Figure 9-29 A Jaguar C-X75.

VW Golf Hybrid

Volkswagen is working on a plug-in hybrid version of the Golf/Rabbit, named Twin Drive. This can be called an extended range EV. However, unlike others, the engine is clutched to the drive wheels and can power the car.

The gas engine is a 1.4L turbo direct-injection four-cylinder. The transmission is a single-speed designed for cruising and light loads. At lower speeds and heavier loads, the electric motor turns on to supply low-speed torque. Once the car reaches about 30 mph, the engine is started, and the clutch connects it to the driveline. From that point on the output from the motor is decreased until increased power is needed. A 12-kW lithium-ion battery pack is located in the rear of the car and is recharged by the motor turned generator and regenerative braking.

VW XL1 Prototype

VW developed a two-seat XL1 prototype that is capable of 235 mpg. This is an experimental car and will not see production. However, through this experiment Volkswagen can test many new technologies. The car was made as light as possible, about 1,700 pounds, and is very aerodynamic. The car relies on a lithium-ion battery pack, an electric motor, and a two-cylinder, 0.8L diesel engine. The entire powertrain is located in the rear of the car.

The diesel engine is rated at 47 HP and the electric motor is rated at 26 HP. All power flows through a seven-speed dual-clutch transmission. The engine is never used to charge the battery. Rather, the battery is charged through household current and regenerative braking. VW claims the XL1 can be driven for up to 22 miles on electricity and with its 2.6-gallon fuel tank, the driving range is about 340 miles.


Courtesy of Dr. Ing. h.c.F. Porsche AG

Figure 9-30 A Porsche® 918 Spyder® Hybrid.

Porsche 918

Although this car is in production, the Porsche 918 Spyder **(Figure 9-30)** is really a test car for various hybrid technologies. It also is a very exclusive car, costing $845,000, and production is limited to only 918 vehicles. Porsche claims the car can accelerate from 0 to 60 mph in 3.1 seconds. At the same time, the car can travel 16 miles on battery power alone and can achieve an overall fuel economy rating of 94 mpg.

The 918 has a 3.4L V8 engine that develops 500 HP at 9,000 rpm. It also has three electric motors, each rated at 178 HP. All of this provides about 718 HP. One motor is located at each front wheel, and the third is mounted within the seven-speed dual-clutch transmission, where it helps the engine power the rear wheels. Each of the motors works independently of each other and allows the vehicle to have a variable all-wheel drive system. The electrical energy is supplied by an air-cooled lithium-ion battery that has a capacity of 5.1 kW. Charging the battery pack takes two to seven hours, depending on the charging voltage. Naturally, the battery is charged through a regenerative system during coasting and braking.

Review Questions

1. Which of these hybrids is currently available with a manual transmission?

   A. Hyundai Sonata

   B. BWM X6 ActiveHybrid

   C. Infiniti M hybrid

   D. Honda CR-Z

2.

3. General Motors and DaimlerChrysler developed a two-mode hybrid system. What are the two modes and how is this system constructed?

4. In Honda's three-stage i-VTEC system, what are the three stages?

5. What two major things did Honda do to change the assist hybrid Civic into a full hybrid?

6. In a typical hybrid, which of these components converts the high voltage to a conventional 12 volts?

   A. Inverter
   B. DC/DC converter
   C. Battery control module
   D. Intelligent Power Unit

7. *True or False:* BMW's X6 hybrid uses the same engine and transmission as a BMW 7 series hybrid.

8. Name two advantages of using a multiple-speed transmission with an ISAD hybrid system.

9. *True or False:* The Hyundai Sonata Hybrid uses BAS and ISAD systems.

10. In a Honda hybrid, which of these components is responsible for switching the motor to a generator and vice versa?

    A. The MCM
    B. The IPU
    C. The PCM
    D. The BCM

CHAPTER 10 Basic Hybrid Maintenance and Service

Learning Objectives

After reading and studying this chapter, you should be able to:

- Describe the major considerations for servicing a hybrid, compared with performing the same service on a conventional vehicle.
- List and describe the common-sense precautions that should be adhered to while working around or on a hybrid vehicle.
- List the tools and equipment that are needed to safely service and repair hybrid vehicles.
- Describe the procedure for depowering the high-voltage system in Honda hybrids.
- Describe the procedure for depowering the high-voltage system in Toyota hybrids.
- Describe the procedure for depowering the high-voltage system in Ford hybrids.
- Describe the procedure for depowering the high-voltage system in GM hybrids.
- Explain how the manufacturers have designed their hybrid vehicles to ensure the safety of the passengers and technicians.
- Explain the vital role the 12-volt battery has in the operation of a hybrid vehicle.
- Describe how the 12-volt battery should be serviced.
- Describe how the high-voltage battery pack should be serviced.
- Describe what preventive maintenance procedures are unique to a hybrid vehicle.
- Explain the proper steps to take when diagnosing a problem in a typical hybrid vehicle.
- Describe the special diagnostic tools that must be used on a hybrid vehicle.
- Describe the special considerations and procedures that must be followed when servicing a hybrid vehicle's engine.
- Describe the special considerations and procedures that must be followed when servicing a hybrid vehicle's cooling system.
- Describe the special considerations and procedures that must be followed when servicing a hybrid vehicle's transmission.
- Describe the special considerations and procedures that must be followed when servicing a hybrid vehicle's brake system.

- Describe the special considerations and procedures that must be followed when servicing a hybrid vehicle's steering system.
- Describe the special considerations and procedures that must be followed when servicing a hybrid vehicle's air conditioning system.

Key Terms

auxiliary power outlet (APO)
category 3 (CAT III)
conductance test
energy storage box (ESB)
insulation resistance tester
lineman's gloves
polyvinyl ether (PVE) oil

INTRODUCTION

Hybrid vehicles **(Figure 10-1)** are maintained and serviced in the same manner as conventional vehicles, except for the hybrid components. The latter include the high-voltage battery pack and circuits, which must be respected when doing any service on the vehicles. This chapter covers the steps that should be followed to work safely around the high-voltage system and other service procedures unique to hybrid vehicles. Some of the latter are normal everyday services that must be completed in a different way.

For the most part, service to the hybrid system is not something that is done by technicians, unless they are certified to do so by the automobile manufacturer. Diagnosing the systems varies with the manufacturer, although certain procedures apply to all. Keep in mind that a hybrid has nearly all of the same basic systems as a conventional vehicle, and these are diagnosed and serviced in the same way. Through an understanding of how the hybrid vehicle operates, you can safely service them. This idea will be explained throughout this chapter.

Figure 10-1 A late-model hybrid vehicle.

Before performing any maintenance, diagnosis, or service on a hybrid vehicle, make sure you understand the system found on the vehicle and try to experience what it is like to drive a normal operating model. These vehicles offer a unique driving experience, and it is difficult to say what is working correctly if you do not have firsthand seat experience.

One of the things to pay attention to, both from the owners' or service manuals and driving experience, is the stop-start feature. You need to know when the engine will normally shut down and restart. Without this knowledge, or the knowledge of how to prevent this, the engine may start on its own when you are working under the hood. Needless to say, this can create a safety hazard. Imagine reaching into the engine compartment and the engine starts. There is a possibility that your hands or something else can be trapped in the rotating belts or hit by a cooling fan. Unless the system is totally shut down, the engine may start at any time when its control system senses the battery needs to be recharged.

In addition, there is a possibility that the system will decide to power the vehicle electrically. When it does this, there is no noise, just a sudden movement of the vehicle. This can be alarming and dangerous. To prevent both of these incidents, always remove the key from the ignition. If the vehicle has a "smart" key, move it at least 10 feet away from the vehicle. Make sure the "READY" lamp in the instrument cluster is

PRECAUTIONS

Hybrid vehicles have high-voltage systems **(Figure 10-2).** Careless handling of some components can lead to serious injury, including death.

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Figure 10-2 A typical high-voltage battery pack assembly.

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Figure 10-3 A high voltage warning label.

Always follow and adhere to the precautions given by the manufacturer. These precautions are clearly labeled in their service manuals. Also, emergency response guides are available from each manufacturer. These allow emergency workers to safely work around their vehicles in case of an accident. All emergency workers and technicians, especially body repair technicians, should be familiar with the contents in these guides. All service procedures should be followed exactly as defined by the manufacturer. Carelessness and/or not following the procedures can cause serious injury and can cause the battery to explode! Following is a list of common-sense items to consider when working on a hybrid vehicle:

- Before doing any service on a hybrid vehicle, refer to the service manual for that specific vehicle. All hybrids have similar operations, but they have different systems and components;

  manufacturer.
- All high-voltage (more than 42 volts) wires and harnesses are wrapped in orange-colored insulation. The 42-volt wires and cables are colored yellow. Respect the color and stay away from it unless the system is depowered.
- Warning and/or caution labels **(Figure 10-3)** are attached to all high-voltage parts. Be careful not to touch these cables and parts without the correct protective gear, such as safety gloves.
- Make sure the high-voltage system is shut down and isolated from the vehicle before working near or with any high-voltage component.
- Before doing any service to a hybrid vehicle, make sure the ignition is OFF.
- Move the key and/or key fob a good distance away from the vehicle before starting any service.
- If the vehicle needs to be towed into the shop for repairs, make sure it is not towed on its drive wheels. Doing this will drive the generator(s) to work, which can overcharge the batteries and cause them to explode. Always tow these vehicles with the drive wheels off the ground or move them on a flatbed.
- When working on or near the high-voltage system, even when it is depowered, always use insulated tools.
- Never leave tools or loose parts under the hood or close to the battery pack. These can easily cause a short.
- Never wear anything metallic, such as rings, necklaces, watches, and earrings, when working on a hybrid vehicle.
- In the case of a fire, use a Class ABC powder-type extinguisher or very large quantities of water.
- Before working on the vehicle or depowering it,

  are present, make sure you use caution when working on the hybrid vehicle (HV) system. P0AA6 indicates there is a problem that is isolating the HV battery from the system (this can be caused by decreased resistance in the HV insulation), and DTC P3009 suggests there is a short in the HV circuit.

Gloves

Always wear safety gloves during the process of depowering and powering the system back up again. These gloves must be class 0 rubber insulating gloves, rated at 1,000 volts (these are commonly called "**lineman's gloves**"). The condition of the gloves must be checked before each use. Make sure there are no tears or signs of wear. Electrons can enter through the smallest of holes in your gloves. To check the condition of your gloves, blow enough air into each one so they balloon out. Then fold the open end over to seal the air in. Continue to slowly fold that end of the glove toward the fingers **(Figure 10-4).** This will compress the air. If the glove continues to balloon as the air is compressed, it has no leaks. If any air leaks out, the glove should be discarded. All gloves, new and old, should be checked before they are used.

By regulation, the insulated gloves must be sent out for testing and recertified by an accredited laboratory every six months. If recertification is not possible, new gloves should be purchased. After recertification, the laboratory marks the date of certification on each rubber glove. Used gloves should be stored in their natural shape and protected from physical damage, in a cool, dark, and dry location.

Keep in mind that these insulating gloves are special gloves and not the thin surgical gloves you may be using for other repairs. You should never expose these gloves to petroleum products. Degreasers, detergents, and hand soaps may contain petroleum and should not come in contact with the gloves. Also, to protect the integrity of the insulating gloves, as well as you, while doing a service, wear leather gloves over the insulating gloves **(Figure 10-5).** However, never use the leather

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Figure 10-4 Checking an insulated glove for integrity.

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Figure 10-5 A pair of lineman's gloves covered with leather work gloves.

gloves without the insulating gloves when working on HV systems.

Buffer Zone

When working on a high-voltage system, it is best to keep anyone who is not part of the service away from you and the car. This can be accomplished by creating a buffer zone around the car. The outside edges of the zone should be at least three feet away from the car. Orange cones should be placed to define the outer boundaries of the zone. If the vehicle is sitting unattended, it should be marked off with "do not enter" tape, along with the cones **(Figure 10-6).**

Safety Hook. If a "hot" high-voltage cable is loose and you cannot safely turn off the power to it, use a fiberglass reach pole and hook **(Figure 10-7)** or a dry board to move or remove the wire. The reach pole should also be used to push or pull someone away from the wire.

DEPOWERING THE HIGH-VOLTAGE SYSTEM

The procedure for properly depowering and isolating the high-voltage system from the rest of a hybrid vehicle is very important and not very difficult. However, each manufacturer has its own procedure

nately, the various hybrid models offered by a particular manufacturer have much the same procedure. This does not mean you should not look for the correct procedure for a specific model you are working on. With the correct information and following the procedures, you may safely work on a hybrid vehicle.

Figure 10-6 Caution tape and orange cones marking off an unattended hybrid.

Figure 10-7 A fiberglass safety hook.

The following discussion covers the depowering procedures for the currently available assist and full hybrids. Other hybrids also have high-voltage systems. Those systems should also be depowered before performing any service. Regardless of the manufacturer of the hybrid vehicle, after depowering the system you should always wait at least 5 minutes to allow any and all high-voltage capacitors to discharge.

Honda Hybrids

Honda's procedure for depowering the high-voltage systems includes the following steps, which must be followed in the order in which they appear to avoid serious personal injury and damage to the vehicle's electrical system. Always wear undamaged electrically insulated gloves when inspecting and handling any high-voltage cable or component.

1. Turn the ignition switch OFF.
2. On many models, the rear seat back must be removed to gain access to the battery module.
3. Remove the switch lid from the IPU cover on the battery module.
4. Then remove the locking cover.

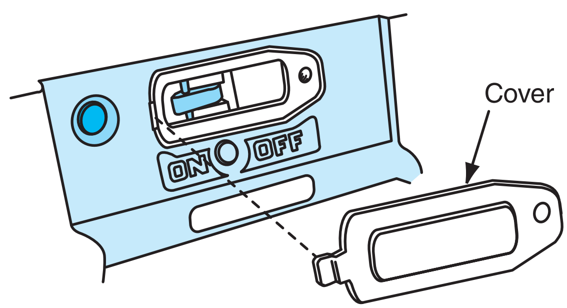

Figure 10-8 The battery module switch in a Honda hybrid.

5. Turn the battery module switch OFF **(Figure 10-8)**, and then reinstall the locking cover to secure the switch in the OFF position.
6. Wait for 5 or more minutes after turning the battery module switch OFF, to allow the ultra-capacitors to discharge.

7. Then disconnect the negative cable from the 12-volt battery.
8. Locate the terminals for the junction board.
9. Measure the voltage at those terminals. If the voltage is less than 30 volts, the system can be serviced. If the voltage is greater than 30 volts, there is a problem. This problem must be diagnosed before continuing with any service.
10. When the system is ready to be powered again, make sure all circuits have been securely reconnected, then reverse the depowering sequence.

WARNING *Always use the tools designed for rotor installation and removal. If you use your hands to install the rotor into the IMA, the magnetic field may suddenly pull the rotor toward the stator. If your hands are on the back of the rotor, they can be seriously injured by the force.*

Honda also recommends that certain precautions be taken when inspecting, diagnosing, and/or working on or around their IMA system:

- When the IMA system indicator is on, perform diagnostics on the IMA system before proceeding with any other service or check.
- After disconnecting any part of the high-voltage system, wrap all electrical contacts with insulated electricians' tape.
- Attach a sign to the steering wheel that says *''WORKING ON HIGH VOLTAGE PARTS. DO NOT TOUCH!''*
- When handling or servicing parts of the system that are not covered with insulating material, make sure you have insulated gloves on and that you only use insulated tools and equipment.
- The rotor assembly is comprised of very strong permanent magnets. Keep the rotor away from magnetically sensitive devices. Individuals with heart pacemakers or other magnetically sensitive medical devices should not handle the rotor.

Toyota Hybrids

With the exception of the first generation of Prius, all Toyota and Lexus hybrids have the same depowering sequence, although some use a much higher voltage than others

one additional precaution, that being the wait time for the capacitors to discharge. Toyota calls for a wait of at least 5 minutes. However, for the higher-voltage systems the waiting time should be 10 minutes or longer. For early hybrid models, Toyota does not specify that the 12-volt battery be disconnected first. Before working on the vehicle or depowering it, check for trouble codes. If there are codes available, make sure to record them before depowering the system. The basic procedure for depowering the high-voltage system includes:

1. Remove the key from the ignition switch. If the vehicle has a ''smart'' key, turn the smart key system OFF. This may be done by applying pressure to the brake pedal while depressing the START button for at least two seconds. If the READY lamp goes off, continue. If it does not, diagnose the problem before continuing.
2. Disconnect the negative (−) terminal cable from the auxiliary 12-volt battery. This should turn the high-voltage system off, but it does not complete the depowering process.
3. Remove the carpeting from the floor in the trunk or the rear of the vehicle.
4. Make sure you are wearing insulated gloves, and reach in at the location of the disconnect plug at the battery box **(Figure 10-9).**
5. Unlatch the lever on the plug and pull the lever down. Then remove the service plug from the battery module **(Figure 10-10).**
6. Put the service plug in your pocket or any secure place to prevent others from reinstalling it before the system is ready or while you are working on the vehicle.
7. Put electrical insulating tape over the service plug connector.
8. Wait at least 5 minutes before proceeding or doing any work on or around the high-voltage system.
9. Prior to handling any high-voltage cable or part, check the voltage at the terminals. There should be less than 12 volts.

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Figure 10-9 Removal of the service plug on a Toyota hybrid to disconnect the high-voltage circuits.

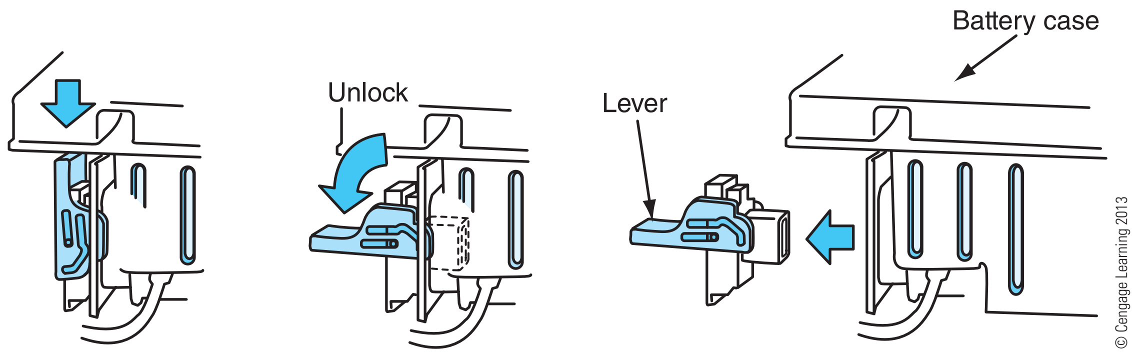

Figure 10-10 Positioning the lever on the disconnect plug so it can be pulled from the battery pack.

10. If a high-voltage cable must be disconnected for service, wrap its terminal with insulating tape to prevent a possible short.
11. When the service plug is reinstalled, make sure its handle is in the upright position; failure to do this may result in a loose plug that may set DCTs.

Ford Motor Company Hybrids

The different hybrids from Ford have different procedures for disconnecting the high-voltage systems from the vehicle. Before servicing an Escape or Mariner hybrid, follow this procedure:

1. Place the gear selector into the Park position and remove the ignition key. This will turn the hybrid system off, but will not isolate the high-voltage system.
2. Disconnect the negative cable at the 12-volt battery.
3. Lift up the carpeting behind the rear seat **(Figure 10-11).**

Figure 10-11 To gain access to the service plug in a Ford Escape, the rear carpet must be lifted up and moved out of the way.

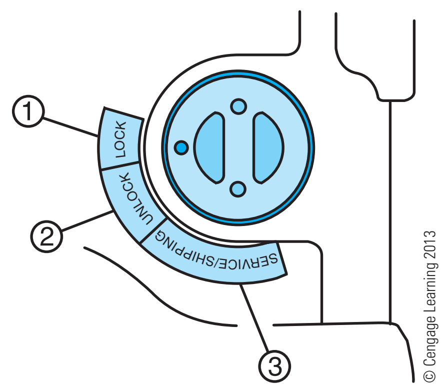

Figure 10-12 To isolate the high-voltage system, turn the service disconnect plug from the LOCK position (1) to the UNLOCK position (2). Then lift it out and reinstall it in the SERVICE/SHIPPING position (3).

4. Locate the service disconnect plug.
5. Wearing insulated gloves, turn the service disconnect plug from the LOCK position to the UNLOCK position.
6. Then lift it out and store it away from the vehicle. This disconnects the high-voltage battery pack from the vehicle.
7. After service, reinstall the plug with its arrow at the SERVICE/SHIPPING mark **(Figure 10-12).**

CAUTION *Although the removal of the plug disconnects the battery pack, it should be returned to its bore but in the SERVICE/SHIPPING position to prevent debris from entering into the battery pack while services are being performed.*

Ford Fusion. To disconnect the HV battery pack in a Fusion, Milan, and MKZ hybrid:

1. Locate the rear seat's backrest release levers.
2. Lower the back of the seat.

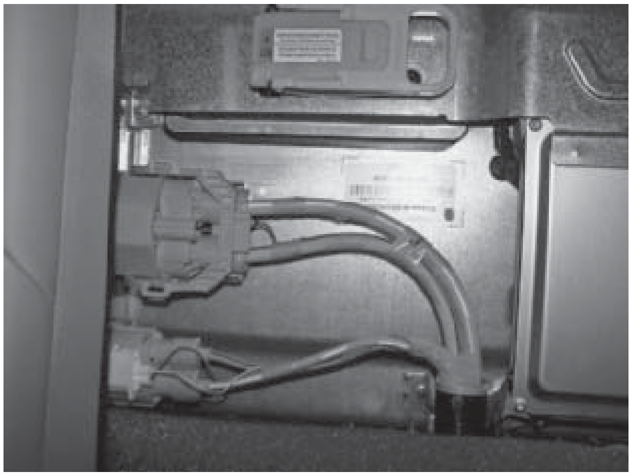

Figure 10-13 The service disconnect is located on the backrest of the rear seat in a Ford Fusion.

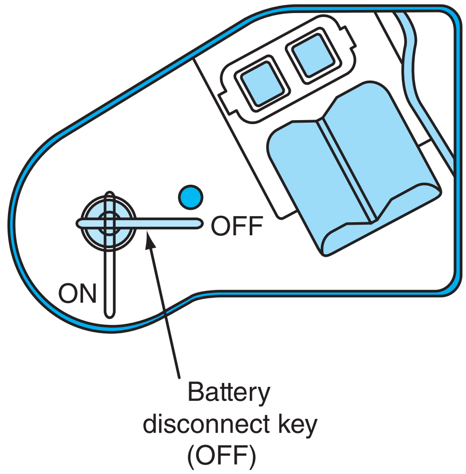

Figure 10-15 When the service disconnect switch for a GM hybrid switch is in the horizontal position, the switch is OFF.

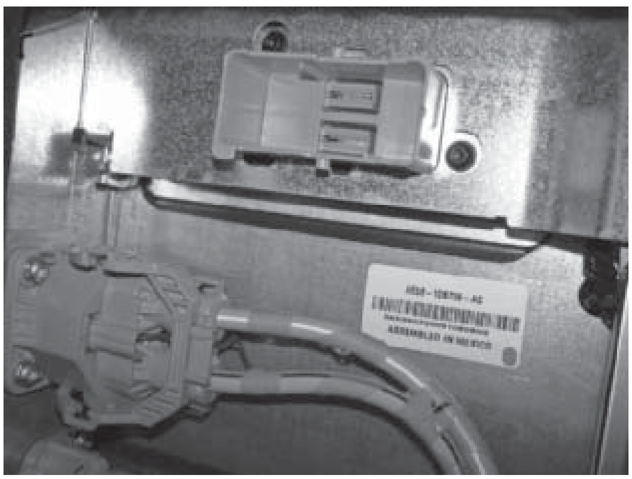

Figure 10-14 Once the service disconnect is removed, the battery circuit is open, but voltage can be checked across these two terminals.

3. Locate the orange HV service disconnect unit **(Figure 10-13).**
4. Rotate the handle until it is centered in the unit.
5. Pull the service disconnect unit out of the battery pack **(Figure 10-14).**
6. Place the disconnect away from the vehicle.

GM's Silverado/Sierra Hybrids

General
systems. The most common of these are found in the Silverado and Sierra pickups. These systems have a 42-volt starter/generator located between the engine and transmission. These vehicles also have a portable generator feature that can provide 110 volts of AC at power outlets. To safely work on these vehicles, both the 42-volt battery pack and the auxiliary power outlet system need to be depowered. All 42-volt and 110-volt circuits are labeled and colored orange.

These vehicles have a stop-start feature that is easily disabled by opening the hood. There is a hood ajar switch that prevents the engine from starting when the hood is open. However, if the engine is running and then the hood is opened, the engine will continue to run. To safely work under the hood of these vehicles, simply turn off the vehicle and open the hood.

To control the **auxiliary power outlet (APO)** circuit, there is an APO button on the dash and an APO indicator lamp. When the lamp is lit, the circuit is active. To turn off the system, depress the button, turn off the engine, and remove the key.

To disconnect the 42-volt system from the vehicle, there is a switch on the side of the battery pack, called the **energy storage box (ESB)**. The battery pack is located under the rear passenger seat. The service disconnect switch is located behind a removable cover on the battery pack. Once the cover is removed, the switch is turned to its horizontal or OFF position **(Figure 10-15).** This disconnects the 42-volt system from the rest of the vehicle.

General Motors also advises technicians to disconnect the 12-volt battery whenever working under the vehicle's hood and when working on or around any part related to the vehicle's hybrid system.

GM Two-Mode

To depower a vehicle equipped with a two-mode transmission, a disconnect lever assembly is removed from the battery pack. The high-voltage battery pack is located under the floor of the second row of seats.

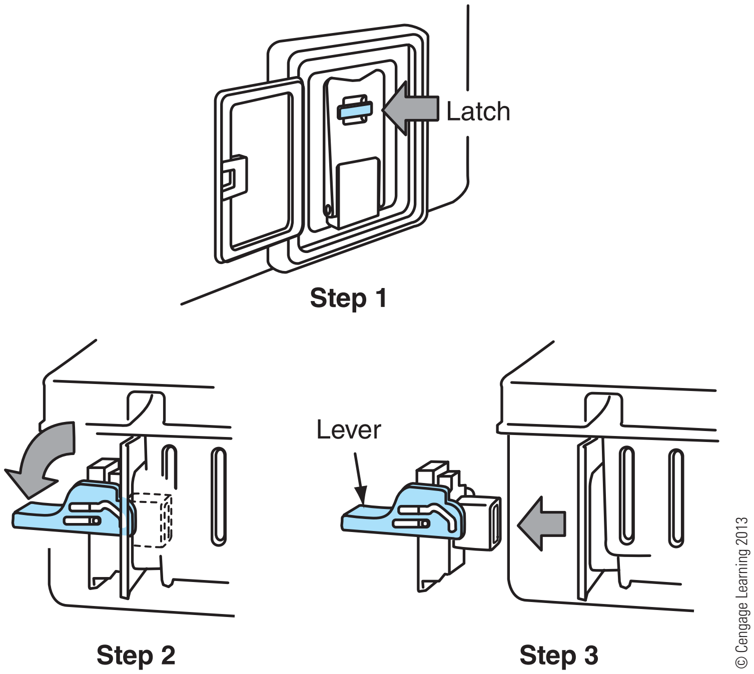

Figure 10-16 The power disconnect switch for a Hyundai. Step 1 involves lifting the latch so step 2 can be completed by pulling down the lever.

To remove the disconnect assembly, the lever is pulled down. Once it is in a totally horizontal position, the assembly can be removed.

Hyundai Sonata Hybrid

This hybrid system uses a 270V battery. Make sure the high-voltage circuit is isolated before working on any high-voltage system component. To do this:

1. Turn the ignition switch OFF and disconnect the auxiliary 12V battery negative (–) cable.
2. Remove the rear seat and partition tray trim.
3. Remove the high-voltage front cover.
4. Open the safety plug service cover.
5. Lift up on the lever's locking hook **(Figure 10-16).**
6. Pull out and down on the plug's lever and pull the plug out.
7. Wait for more than 5 minutes so that the capacitor in the high-voltage system can be naturally discharged.

SAFETY FEATURES

All hybrid vehicles have certain safety features that are designed to isolate the high-voltage system in the case of an accident or electrical fault. You should be aware of these features, as they may cause the hybrid system to be inoperable. Some of these safety features are unique to specific hybrid models, whereas others are universally applied.

On all hybrids, the high-voltage cables and connectors are colored orange, and warning labels are affixed to all high-voltage components. In addition, the battery packs are placed in protective zones **(Figure 10-17)** and are enclosed in containers. These containers are designed to withstand a degree of impact and to contain any chemicals that may leak from the batteries. The cables are also routed in "safe" areas, and if they are not routed through the vehicle's frame, they are protected with extra metal.

The damage that results from a collision can result in damage to the high-voltage cables and/or components, which could result in high-voltage shorts.

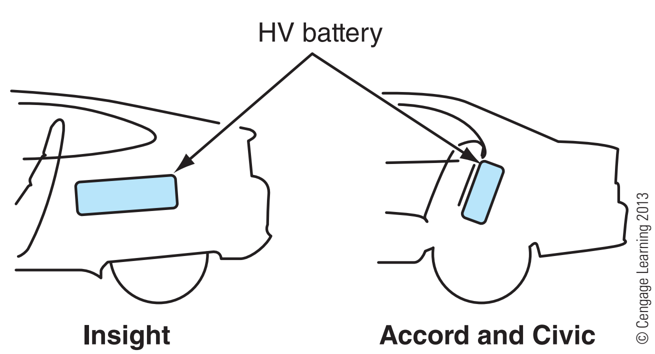

Figure 10-17 Battery packs are placed in areas where they are protected.

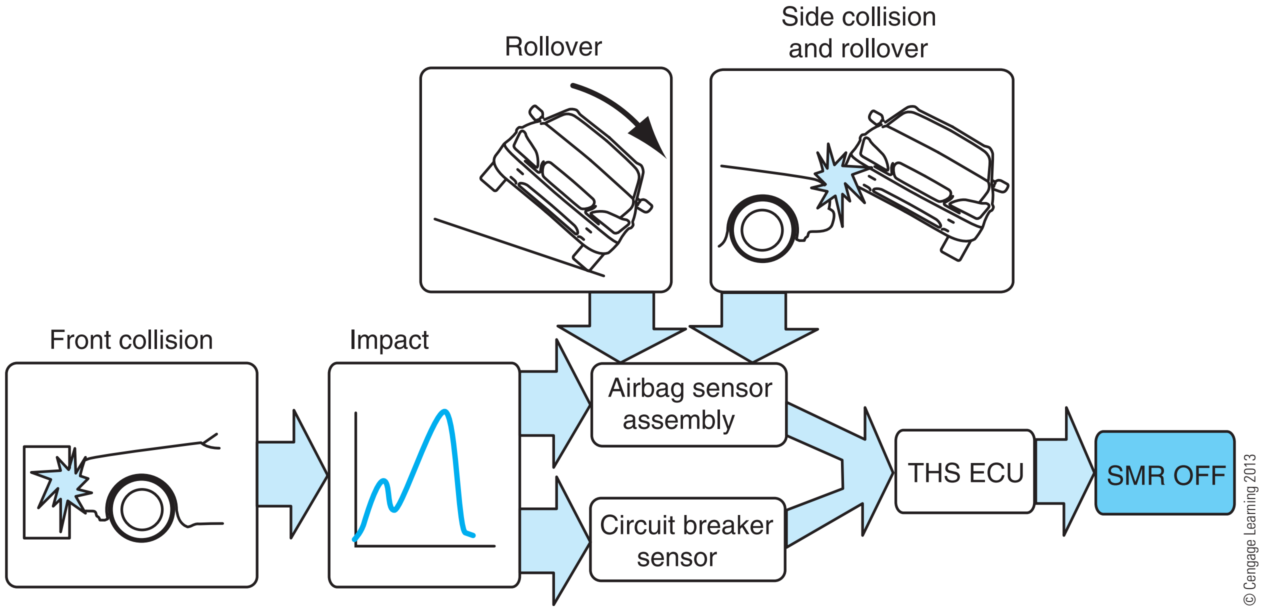

Figure 10-18 Through the use of sensors, high-voltage systems are shut down when a collision is detected.

These could be disastrous, for the vehicle, the passengers inside, and emergency responders. To immediately isolate or shut down the high-voltage system, hybrids are fitted with many sensors **(Figure 10-18).** These sensors respond to impact or the activation of the airbags. In most accidents, the high-voltage system is automatically and immediately disabled.

Every hybrid is designed to open the circuit from and to the battery pack whenever the airbag(s) are deployed. In many models, high voltage is shut down before the airbags are deployed. Impact sensors are placed strategically in the areas where the high-voltage system is located. On early GM hybrid pickups, the battery pack is located on the passenger side. A side impact sensor will trigger the battery cutoff switch to isolate the 42-volt battery pack and the auxiliary power outlet circuit if an impact to the passenger door is detected.

Ford hybrids have impact switches at the front and rear of the passenger side of the vehicle. If a force or jolt causes either of these switches to open, the high-voltage system and the circuit to the fuel pump are disconnected. On Toyota hybrids, the impact sensor is located inside the inverter. Again, when an impact is detected, the high-voltage system is shut down.

Other

from leaking into the passenger compartment. These sensors monitor the condition of the high-voltage wiring and cables. If there is any evidence of a short or high current through the circuit, the high-voltage system is immediately shut down. The high-voltage system will also be shut down if the circuit opens, which can be caused by such things as a broken wire or disconnected connector. Also, the system will shut down if battery temperatures rise beyond a specified temperature (normally 140°F).

On GM pickups with the auxiliary power outlets, the same techniques are used to protect the passengers from faults within that system. The APO circuit is fitted with a ground fault detection circuit. This is similar to those found in the kitchens and bathrooms of most houses. These circuits monitor the current flow through the wires of the circuit. If there is more than a few milliamps difference between the two wires (neutral and hot), the APO circuit will be shut down. The system will also shut down if there is an opening in the circuit.

BATTERIES

Most hybrids have two separate battery packs. One is the high-voltage pack and the other is a 12-volt battery **(Figure 10-19).** The high-voltage battery pack typically supplies the power to start the engine, assist the engine during times of heavy load, and in full hybrid mode it supplies the energy to move the vehicle without the engine's power. The battery pack is the

system. The 12-volt battery is associated with the rest of the vehicle, such as the lights, accessories, and power equipment. The 12-volt battery also supplies the power for the electronic controls that monitor and regulate the operation of the hybrid system. If this power source is not working correctly, the hybrid

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Figure 10-19 This warning label states that there are two separate batteries.

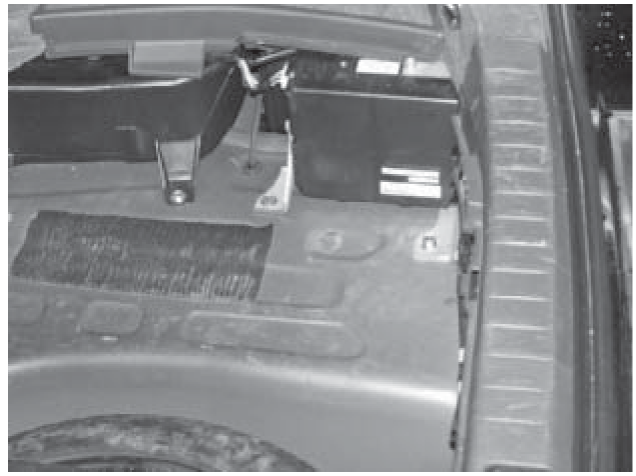

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Figure 10-20 Note that the auxiliary battery is tucked into the corner of this trunk.

system will not. Therefore, this low-voltage power source should never be ignored when working on a hybrid or a conventional vehicle.

WARNING *Batteries contain sulfuric acid. Wear eye protection when working near or with the battery. If the acid gets on your skin or in your eyes, flush immediately with water for a minimum of 15 minutes and get immediate medical attention.*

12-Volt Batteries

The auxiliary battery used in many hybrid vehicles is the same type found in conventional vehicles; however, some are AGM batteries. It is important that you properly identify the type of battery in the vehicle so that you correctly service the battery. For the most part, inspection of and service to the auxiliary battery in a hybrid is no different than if it were not in a hybrid. It is important to note that if the battery's voltage drops below a specific level, the emissions MIL and/or hybrid warning lights may illuminate. It is also important to know that if the vehicle has not been driven for more than a month, both the low-voltage and high-voltage batteries will be low on charge. Most manufacturers recommend that hybrids should be started and run for at least 10 minutes every month. This

enough to operate the vehicle but may not be enough to keep the low-voltage battery charged.

The 12-volt batteries are located in the trunk or under the hood **(Figure 10-20).** They should be inspected **(Figure 10-21)** on a regular basis. Make sure the cable connectors are tight. Also, make sure the

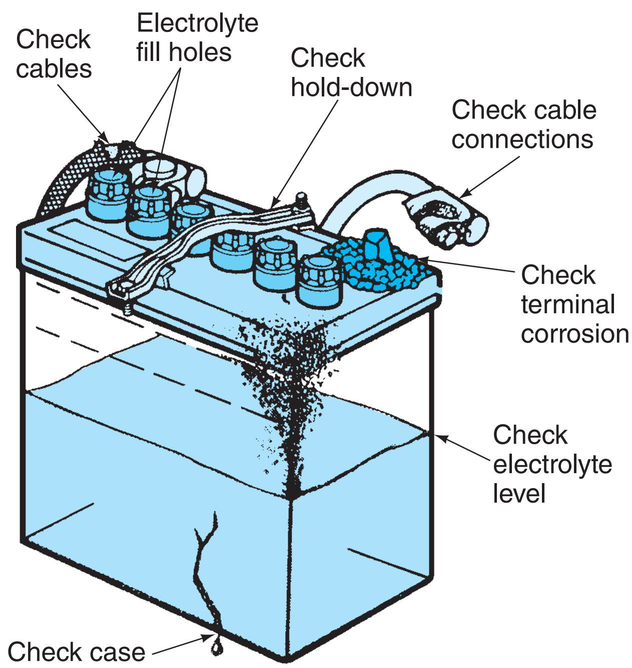

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Figure 10-21 Carefully inspect the auxiliary battery, especially if its voltage is low.

electrolyte level is satisfactory. The battery, its terminals, and cables should be clean. If there is dirt or corrosion on the battery or cable ends, clean them. If the battery cables are disconnected for cleaning, all control systems will lose their memory. This is not

taken to preserve the memory. Memory savers are available and should be used. Some manufacturers also give specific instructions for disconnecting the battery while maintaining memory. When disconnecting battery cables, always remove the ground cable from the negative terminal first and reinstall it last.

WARNING *Do not conduct this test on a lead-acid battery that has recently been recharged. The gases released by the battery during charging may ignite during this test. Also, if the vehicle has been recently driven, wait at least 40 minutes to allow the gases to dissipate and for all control modules to power down.*

Battery voltage is quickly checked with a voltmeter. Typically, a good 12-volt battery will have 12.6 to 14.2 volts, although anything above 12 volts would indicate the battery is near fully charged. An auxiliary battery can be low on charge for a number of reasons. It could be a bad battery, poor connections, or the charging system is not functioning properly. However, a common problem is parasitic drain.

Vehicles should have no more than a 50-mA current draw with the ignition off. To measure the drain on the battery and to identify the source of the excessive current draw, use an inline digital ammeter rated at 10 amps with the capability of measuring in milliamps. Make sure the battery is clean, and check for voltage leakage through the battery case. Then connect a jumper wire fitted with a 10-amp circuit breaker or fuse between the negative battery cable and the negative battery post. This will maintain the memories in the vehicle. Then disconnect the negative cable at the battery. Be careful not to disconnect the jumper wire while doing this. Connect the inline ammeter between the end of the negative cable and the battery's negative post. Once the meter is in place, remove the jumper wire. Observe the reading on the meter.

If the reading is excessive, pull one fuse at a time from the fuse box. Check the current after each one is removed. When the current drops significantly after a fuse is removed, the cause of the excessive drain is most likely in the circuit being protected by that fuse. If all of the fuses have been removed and there is still excessive draw, check the wiring diagram to identify the circuits that are not protected by the fuses that were removed. Then disconnect these circuits, one at a time, until the problem circuit is identified. Once the problem is identified and repaired, replace all fuses and reconnect everything. Do not remove the ammeter until the fused jumper wire is placed between the battery

reconnect the battery's negative cable, making sure that the jumper wire stays in place. Once the cable terminal is tightened, the jumper wire can be removed.

Battery Capacitance Test. The auxiliary battery can be load tested using a conventional battery tester. However, many manufacturers recommend that a battery capacitance or **conductance test** be performed. Conductance describes a battery's ability to conduct current. It is a measurement of the plate surface available in a battery for chemical reaction. Measuring conductance provides a reliable indication of a battery's condition and is correlated to battery capacity. Conductance can be used to detect cell defects, shorts, normal aging, and open circuits that can cause the battery to fail.

A fully charged new battery will have a high conductance reading, anywhere from 110 percent to 140 percent of its CCA rating. As a battery ages, the plate surface can sulfate or shed active material, which will lower its capacity and conductance. When a battery has lost a significant percentage of its cranking ability, the conductance reading will fall well below its rating, and the test decision will be to replace the battery. Because conductance measurements can track the life of the battery, they are also effective for predicting end of life before the battery fails.

To measure conductance, the tester **(Figure 10-22)** creates a small signal that is sent through the battery, and then measures a portion of the AC current response. The tester displays the service condition of the battery. The tester will indicate that the battery is good, needs to be recharged and tested again, has failed, or will fail shortly.

Removal and Installation. The procedure for removing the auxiliary battery from a hybrid vehicle is the same as for a conventional vehicle. However, in some hybrids with the auxiliary battery in the trunk, a Prius for example, it may be impossible to get to the battery if it is dead. The lack of battery power will prevent the rear hatch from opening. To gain access to

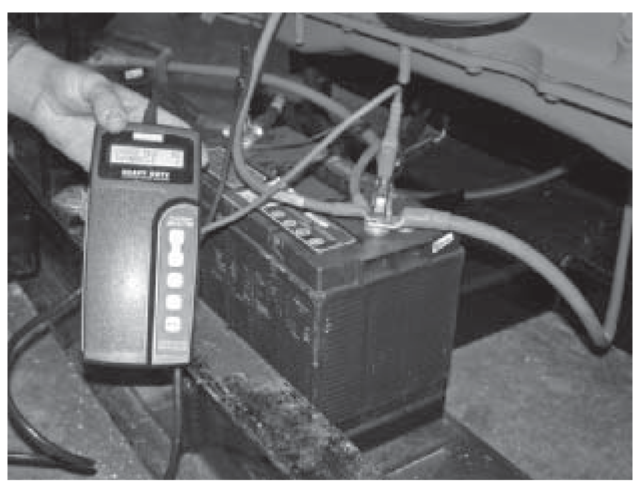

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Figure 10-22 A battery conductance tester.

the battery, the vehicle will need to be jump-started. Toyota has a special jump-starting terminal under the front hood. Once the car is started, the trunk can be opened normally. Always adhere to all safety precautions when removing and installing a battery.

WARNING *When lifting a battery, excessive pressure on the end walls can cause acid to leak through the vent caps. The acid can cause burns and/or skin irritation. Always lift a battery with a battery carrier or with your hands on opposite corners of the battery.*

Because of the advanced electronics in hybrids, steps must be taken after installation to allow the computers to relearn. The regenerative braking system needs to relearn the initial position of the brake pedal. After the battery is reconnected, slowly depress and release the brake pedal one time. The engine also needs to relearn its idle and fuel trim strategy. If this is not done immediately after reconnecting the battery, the engine will idle and run poorly until it sets up its strategy. A typical procedure begins with turning off all accessories and starting the engine. The engine is idled until it reaches normal operating temperature, then it should be allowed to run at idle for one minute. After that time, the air conditioning is turned on and the engine again is allowed to idle for at least one minute. Now the vehicle should be driven for about 10 miles. All manufacturers have their own sequence for doing this, so be sure to follow their procedure.

On some vehicles, such as the Honda Civic Hybrid, the battery level gauge will not display the battery's state of charge when the engine is first started after the auxiliary battery has been replaced or disconnected. To reactivate the indicator, start the engine and run it at 3,000 to 4,000 rpm with all accessories off. Keep the engine at that speed until the battery level gauge displays at least three bars or segments.

Recharging. The correct method for recharging the auxiliary battery varies with the type of battery. Most manufacturers recommend a slow charge of less than 3.5 amperes. However, others recommend the use of an intelligent charger. In most cases, the vehicle's engine is the best and safest charger. If the engine runs and the charging system works normally, drive the vehicle to charge all of the batteries. When recharging, always consider the following precautions:

- Never recharge the battery when the hybrid system is on.
- Turn off all accessories before charging the battery and correct any parasitic drain problems.
- Make sure the charger's power switch is off when you are connecting or disconnecting the charger cables to the battery.
- Always charge the battery in an unconfined and well-ventilated area.
- Keep all flames, sparks, and excessive heat away from the battery at all times, especially when it is being charged.

High-Voltage Batteries

Any discussion about high-voltage battery and energy systems must include warnings regarding the need to isolate the high voltage from the rest of the vehicle and reminders to adhere to all precautions stated by the manufacturer **(Figure 10-23).** This is important for all services, not just electrical. Air conditioning, engine, transmission, and bodywork can require services completed around and/or with high-voltage systems. If there is any doubt as to whether something has high voltage or not, or if the circuit is sufficiently isolated, test it before touching anything.

To test high-voltage systems you need a **Category 3 (CAT III)** digital volt ohmmeter **(Figure 10-24)** and,

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Figure 10-23 The warning label on an HV battery pack.

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Figure 10-24 Only meters with this symbol should be used on the high-voltage systems in a hybrid vehicle.

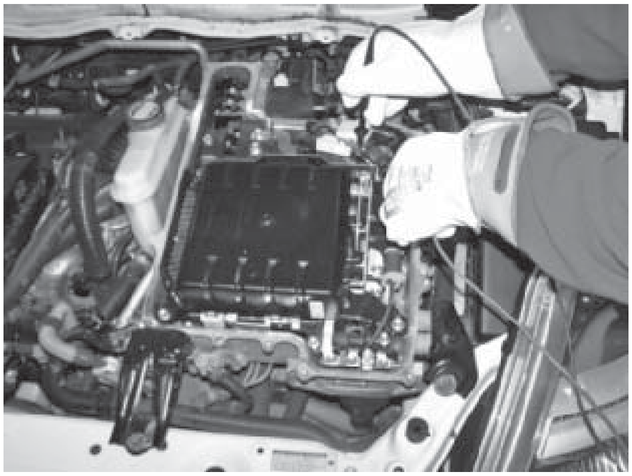

Figure 10-25 Testing voltage at the inverter.

of course, a good pair of insulating gloves. Although the high-voltage system can be isolated from the rest of the vehicle, high voltage is still at and around the battery pack. When checking for the presence of high voltage, make sure to check the inverter assembly **(Figure 10-25).** This is typically where the large or ultra-capacitors are, and until they are discharged, they are lethal.

The high-voltage battery packs in nearly all HEVs are made up of several NiMH cells. There are certain characteristics about these cells that must be understood and remembered, especially for diagnostic purposes and safety:

- NiMH batteries do not store well for long lengths of time, so if the vehicle has not been driven for a while, the battery may lose quite a bit of its normal capacity.
- These batteries have a limited number of charging cycles (the number of times a battery can be charged and discharged).
- All hybrids charge the battery as you drive.
- The capacity of NiMH batteries decreases with an increase in heat.
- If the battery is exposed to intense heat, it is possible that hydrogen will be released from the battery, and hydrogen can be explosive when introduced to flame or sparks.
- The battery cells contain a base electrolyte comprised mostly of potassium hydroxide.
- Exposure to the electrolyte can cause skin/eye irritation and/or burns.
- The battery packs are very heavy.
- Used batteries should be disposed of according to local and federal laws.

Whenever a battery pack, cooling system components **(Figure 10-26),** or other hybrid parts must be removed, serviced, and/or replaced, also follow the specific procedures given by the manufacturer. If these are not followed exactly, injury to you, the vehicle, and others can result.

Recharging. Recharging the high-voltage battery pack is best done by the vehicle itself; however, there are times when it may be necessary to recharge the battery in the shop. Doing so is not a typical procedure. Chances are your shop will not have the correct charger. For example, Toyota hybrid batteries require a special charger that is not sold to its dealerships **(Figure 10-27).** If there is a need for one, the dealership must contact the regional office and have one delivered, and only someone from that office is

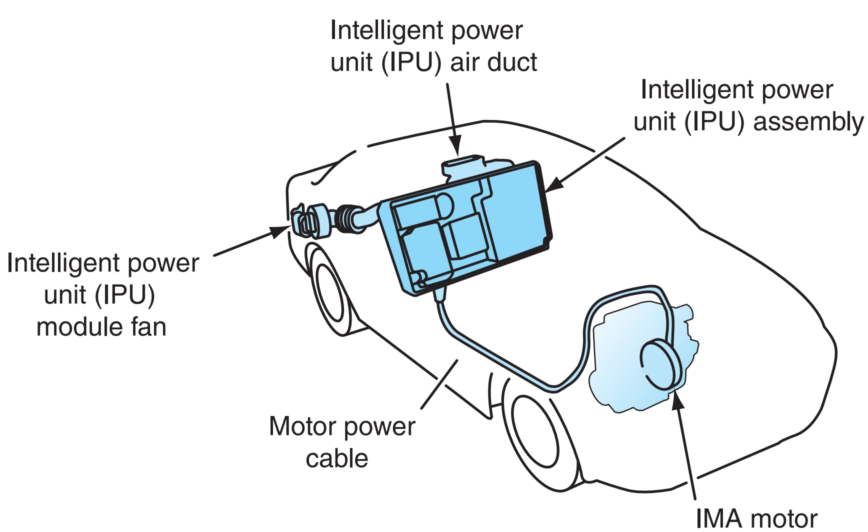

Figure 10-26 The battery pack and associated components in a Honda Civic.

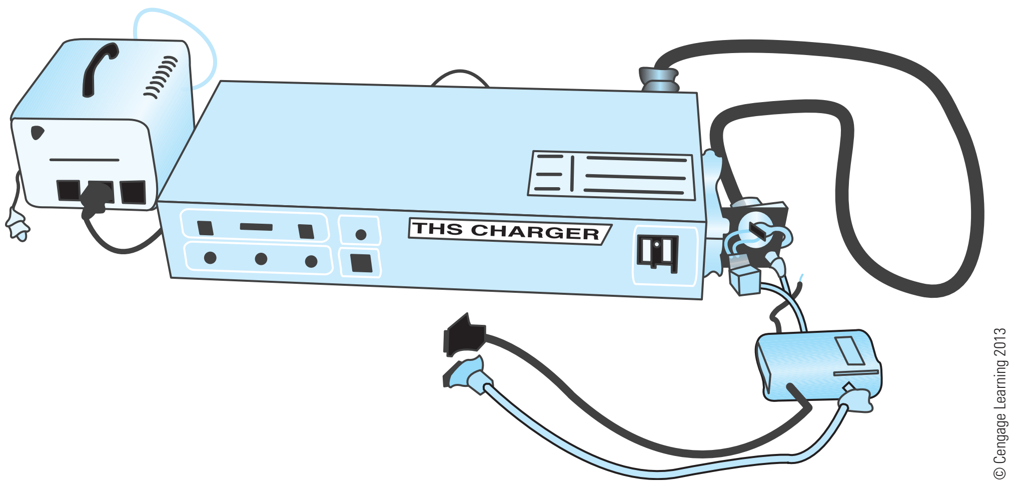

Figure 10-27 The high-voltage battery charger for Toyota hybrids. There are two output cables, one for the battery pack and the other to operate the 12V system for the battery-cooling fans and computer.

allowed to operate it. This charger has the normal connections plus a cable to power the battery's cooling system. The charger is designed to bring the battery pack to a 40 to 50 percent state of charge within three hours. This is enough to start the vehicle and allow the engine to bring the battery back to full charge.

Jump-Starting

If the vehicle will not start, several things can be the cause. Like conventional vehicles, the vehicle must have fuel; there must be ignition, intake air, compression, and exhaust. Before proceeding with a no-start diagnosis, make sure the immobilizing system is working properly. Most hybrid vehicles cannot be push- or pull-started. If the auxiliary or high-voltage battery is discharged, the engine will not start, nor will the vehicle be able to operate on electric power only. Manufacturers have built in ways to jump-start these vehicles, if and when the batteries go dead. The basic connection from a booster battery to the dead battery is the same, but the connecting points may be different, and there are certain precautions to consider when jump-starting. There are also separate procedures for jump-starting with the low- and high-voltage systems. Some of the precautions are:

- Be sure the connections are done correctly and tightly.
-

  vehicles are off.
- When making the connections, do not lean over the battery or accidentally let the jumper cables or clamps touch anything except the correct battery terminals.
- Use only a 12-volt supply as the booster battery.
- The gases around the battery can explode if exposed to flames, sparks, or lit cigarettes.

To jump-start a typical hybrid vehicle with the battery of another vehicle, follow this procedure:

1. Park the booster vehicle close to the hood of the disabled vehicle, making sure the two vehicles do not touch.
2. Set the parking brake on both vehicles.
3. Turn off the hybrid system and remove the ignition key.
4. Open the hood or trunk to gain access to the auxiliary battery. On some hybrid vehicles with the battery in the trunk, there is a special jump-starting terminal under the hood.
5. Connect the clamp of the positive (red) jumper cable to the positive terminal on the battery or the jump-starting terminal.
6. Connect the clamp at the other end of the positive (red) jumper cable to the positive (+) terminal on the booster battery.
7. Connect the clamp of the negative (black) jumper cable to the negative (−) terminal on the booster battery.
8. Connect the clamp at the other end of the negative (black) jumper cable to an exposed metal part of the dead vehicle's engine **(Figure 10-28),** away from the battery and the fuel injection

   or rocker arm covers, or the intake manifold as the grounding point for making this negative connection.
9. Make sure the jumper cables are clear of fan blades, belts, moving parts of both engines, or any fuel delivery system parts.

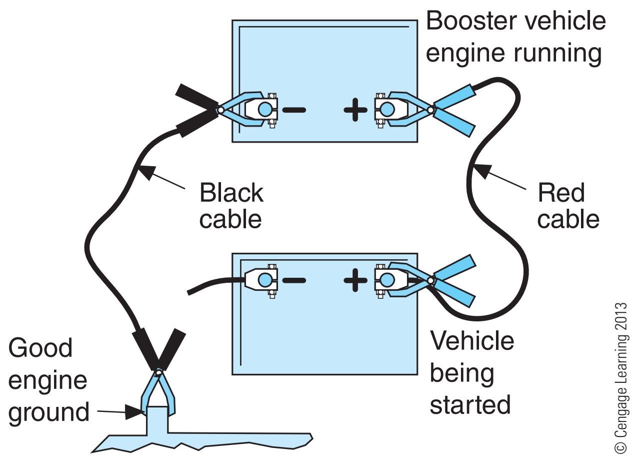

Figure 10-28 The correct cable hookup for jump-starting.

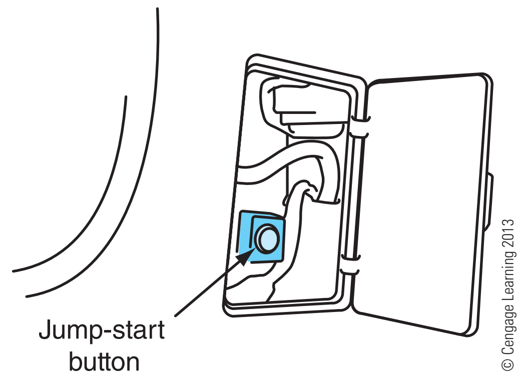

Figure 10-29 To jump-start a Ford Escape or Mariner Hybrid high-voltage battery, turn the ignition OFF, open the access panel on the driver's side foot well, and press the jump-start button.

10. Run the engine of the booster vehicle at a medium speed for about 5 minutes.
11. Now, attempt to start the hybrid vehicle.
12. If the hybrid vehicle did not start, check the connections of the jumper cables and if a problem was found, correct it and try again. If the engine still does not start, the low- or high-voltage battery should be replaced.
13. Once the disabled vehicle has started, allow both engines to run for about 5 minutes.
14. Then disconnect the negative cable from the hybrid vehicle, and then from the booster battery.
15. Next, disconnect the positive cable from the hybrid vehicle, and from the booster battery.

CAUTION *Never connect the end of the second cable to the negative terminal of the battery that is being jumped.*

High-Voltage Batteries. Some hybrid vehicles have separate procedures for jump-starting, one for the low-voltage battery and the other for the high-voltage battery. If the vehicle cranks but the engine does not start, the high-voltage battery may need to be jump-started. Also, the "Service Soon" lamp may be illuminated to indicate a problem.

To

Escape or Mariner Hybrid, make sure the ignition is OFF before proceeding. Then, open the access panel on the driver's side foot well and press the jump-start button **(Figure 10-29).** Wait at least 8 minutes before continuing. This is important! If you continue sooner, the energy from the auxiliary battery will not be able to supply enough power to start the engine by the battery pack. When you depress the button, the system sends energy from the auxiliary battery to the battery pack. If the auxiliary battery has ample energy, it will be enough to start the engine. However, if the auxiliary battery is weak, it should be jump-started rather than the high-voltage battery pack. After pressing the button, you should wait 8 minutes before attempting to start the engine; otherwise, the high-voltage battery may not receive sufficient charge to start the engine.

After the wait time, the warning lamp may blink for up to 2 minutes. After it stops, attempt to start the engine. If the engine still does not start, try again in a couple of minutes. If the engine still does not start, the low-voltage battery must be recharged or the vehicle jump-started through the 12-volt battery.

WARNING *This is just a summary of the procedure and should not be followed to correct the problem. ALWAYS follow the instructions given by the manufacturer.*

MAINTENANCE

Maintenance of a hybrid vehicle is much the same as a conventional vehicle. The manufacturers list the recommended service intervals in their service and owner's manuals. Nearly all of the items are typical of a conventional vehicle. Care needs to taken to avoid

procedures.

The computer control systems are extremely complex, especially in assist and full hybrids, and are very sensitive to voltage changes. This is why the manufacturers recommend a thorough inspection of the auxiliary battery and connections every six months.

The engines used in hybrids are modified versions of engines found in other models offered by the manufacturer. Other than fluid checks and changes, there is little maintenance required on these engines. However, there is less freedom in deciding the types of fluids that can be used and the parts that can replace the original equipment. Hybrids are not very forgiving. Always use the exact replacement parts and the fluids specified by the manufacturer.

Typically, the weight of the engine oil used in a hybrid is very light **(Figure 10-30).** If the weight is increased, it is possible that the computer system will see this as a problem. This is simply caused by the extra current needed to turn over the engine. If the computer senses very high current draw while attempting to crank the engine, it will open the circuit in response.

Special coolants are required in most hybrids because the coolant not only cools the engine, but also cools the inverter assembly. Cooling the inverter is important, and checking its coolant condition and level is an additional check during preventive maintenance. The cooling systems used in some hybrids feature electric pumps and storage tanks. The tanks store heated coolant and can cause injury if you are not aware of how to carefully check them. The battery cooling system may need to be serviced at regular intervals. There is a filter in the ductwork from the outside of the vehicle to the battery box. This filter needs to be periodically changed. If the filter becomes plugged, the temperature of the battery will rise to dangerous levels. In fact, if the computer senses high temperatures it may shut down the system.

A normal part of preventive maintenance is the checking of power steering and brake fluids. The power steering systems used by the manufacturers vary; some have a belt-driven pump, some have an electrically driven pump, and others have a pure electric and mechanical steering gear. Each variety requires different care; therefore always check the service manual for the specific model before doing anything to these systems. Also, keep in mind that some hybrids use the power steering pump as the power booster for the brake system.

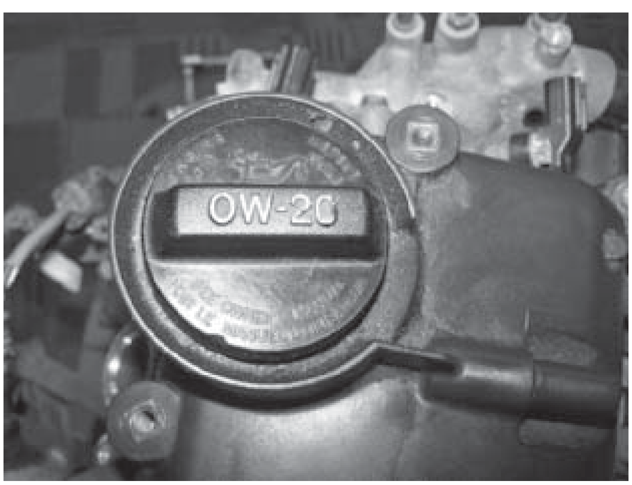

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Figure 10-30 Many hybrids require very light engine oil.

Hybrids are all about fuel economy and reduced emissions. Everything that would affect these should be checked on a regular basis. Items such as tires, brakes, and wheel alignment can have a negative effect, and owners of hybrids will notice the difference. These owners are constantly aware of their fuel mileage, due to the displays on the instrument panel.

Note: It should be remembered that the hybrid system is viewed as another emission control device by OBD II, and all information from the computers will relate to emissions first.

DIAGNOSTICS

A hybrid vehicle is an automobile and as such is subject to many of the same problems as a conventional vehicle. Most systems in a hybrid vehicle are diagnosed in the same manner as well. However, a hybrid vehicle has unique systems that require special procedures and test equipment. It is imperative that you have good information before attempting to diagnose these vehicles. Also, make sure you follow all test procedures precisely as they are given.

Hybrids present unique considerations when they have a driveability problem. The problem can be caused by the hybrid system, engine, or transmission. Determining which system is at fault can be difficult. On some hybrids, it is possible to shut down the hybrid system and drive the vehicle solely by engine power. On others, such as Toyota and Ford hybrids, this is not possible. If electric power can be shut off and the vehicle still drives poorly, the problem is the engine or transmission. If it is not possible to shut down either power source, your diagnosis must be based on the symptom and information retrieved with a scan tool.

Gathering Information

Diagnosis of a hybrid vehicle should follow a logical approach. The first step is gathering as much information as possible from the customer about the concern. This is followed by a thorough inspection of

the vehicle. A road test is then taken to verify the problem, as well as to define the problem. After having a good understanding of what is and is not working properly, all service bulletins that relate to the problem should be read and the appropriate procedures followed. If the cause is still unknown, specific tests should be conducted to pinpoint it. Once the cause is identified, repairs should be made and then the repair should be verified.

In order to properly diagnose a problem, you must totally understand the customer's concern or complaint. It is essential that you gather as much information from the customer as possible **(Figure 10-31).** Get a good description of the concern from the customer. Find out when the problem was first noticed and if the problem is evident now. Find out as much as you can about the conditions that exist when the problem occurs. The conditions to consider are weather conditions, vehicle load, city or highway driving, acceleration, coasting, and braking.

Figure 10-31 Diagnostics should begin with getting as much information as you can from the customer.

It is very important that you experience how a normal hybrid reacts to certain situations. There are many characteristics of a normal operating system that may seem strange and can be labeled as abnormal when it is actually a characteristic of the system. Start and drive a similar model hybrid before making any conclusions about the vehicle you are diagnosing. This is also important to the customer, as most have never had a hybrid vehicle, and their concerns may not be the result of a problem, but may be just part of the system!

Conducting a thorough inspection of the entire vehicle is extremely important. Inspect the battery and all related wiring and connectors. Make sure you are wearing lineman's gloves while inspecting the system, and make sure the high-voltage system is isolated. Check the wheels and tires of the vehicle. Make sure they are the correct size for the vehicle; a change in tire diameter can affect hybrid operation. Also, identify any and all non-factory-installed electrical accessories. Make sure these have been properly installed. If these were incorrectly connected to the system or connected into a control module's harness, the system will not operate properly.

All warning lamps in the instrument panel should be checked **(Figure 10-32).** If any of these remain on after the engine is started, the cause should be identified and corrected before continuing with diagnosis. Last, a scan tool should be used to retrieve any fault codes held in the computer's memory. In many cases, a manufacturer-specific scan tool is required to test hybrids. Aftermarket scan tools may be able to retrieve codes and display some data, but they may have limited capabilities. Also, follow the prescribed sequence for retrieving and responding to all diagnostic trouble codes (DTCs). Details about using a scan tool on the common hybrids are covered later in this chapter.

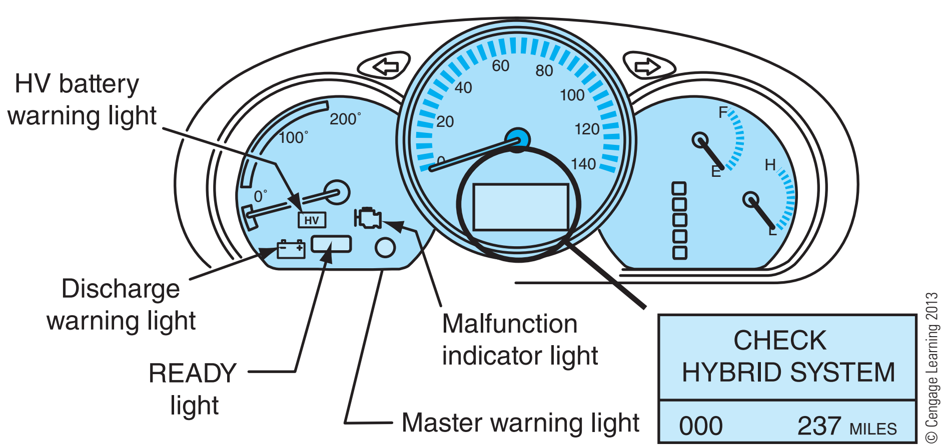

Figure 10-32 An example of some of the warning lights on a hybrid vehicle.

Test Equipment

An important diagnostic tool is a DVOM. However, this is not the same DVOM you use on a conventional vehicle. The meter used on hybrids (and EVs and FCEVs) should be classified as a Category III meter. There are four categories for low-voltage electrical meters, each built for specific purposes and to meet certain standards. Low voltage, in this case, means voltages less than 1,000 volts. The categories define how safe a meter is when measuring certain circuits. The standards for the various categories are defined by the American National Standards Institute (ANSI), the International Electrotechnical Commission (IEC), and the Canadian Standards Association (CSA). A CAT III meter is required for testing hybrid vehicles because of the high voltages, three-phase current, and the potential for high transient voltages. Transient voltages are voltage surges or spikes that occur in AC circuits. To be safe, you should have a CAT III 1,000V meter. Within a particular category, meters have different voltage ratings. These reflect a meter's ability to withstand higher transient voltages. Therefore, a CAT III 1,000V meter offers much more protection than a CAT III meter rated at 600 volts.

Another tool that will save much time and effort during diagnosis is an **insulation resistance tester**. These meters can check for voltage leakage from the insulation of the high-voltage cables **(Figure 10-33).** Obviously no leakage is desired, and any leakage can cause a safety hazard as well as damage to the vehicle. Minor leakage can also cause hybrid system-related driveability problems. This meter is not one commonly used by automotive technicians, but should be for anyone who might service a damaged hybrid vehicle, such as doing body repair. This should also be a CAT III meter, for the same reasons as the DVOM. In fact, these meters often have the capability of checking resistance and voltage of circuits, like a DVOM.

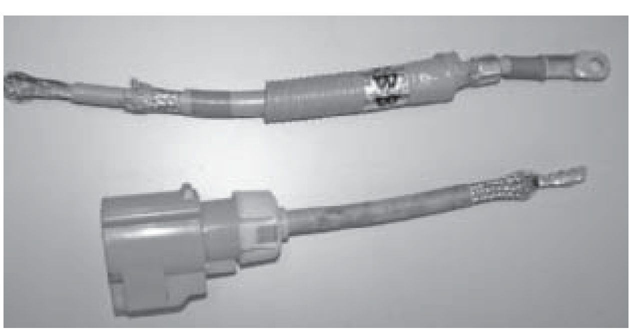

Figure 10-33 A look at the insulation used in high-voltage cables.

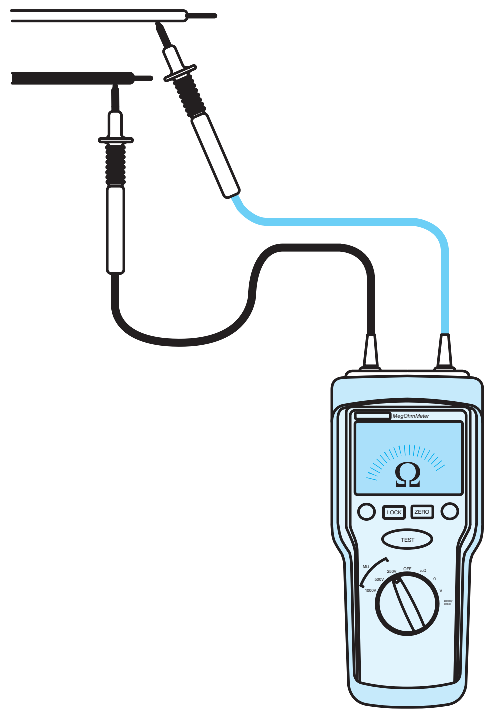

Figure 10-34 Connecting a MegOhmMeter to check the resistance of the wire insulation in a circuit.

WARNING *Always follow the test procedures defined by the equipment manufacturer when using this type of equipment.*

To measure insulation resistance, system voltage is selected at the meter, and the probes placed at their test position **(Figure 10-34).** The meter will display the voltage it detects. Normally, resistance readings are taken with the circuit de-energized, and this is true for resistance checks with this meter unless you are checking the effectiveness of the cable or wire insulation. In this case, the meter is measuring the insulation's effectiveness and not its resistance.

The probes for the meters should have safety ridges or finger positioners. These help prevent physical contact between your fingertips and the meter's test leads.

SPECIFIC DIAGNOSTICS FOR MANUFACTURERS

If you approach diagnostics with the idea that a hybrid system is just another emission control device, you will not allow the complexities of the system to get in the way. The normal steps for diagnosing any problem should be followed.

Ford Diagnostics

Ford hybrids require specific troubleshooting procedures that must be followed. Like other hybrid models, these hybrids are diagnosed primarily with a scan tool. The DTCs will lead to a general area where additional tests should be made. The basic diagnostic procedure begins with gathering information from the customer to define the problem. The vehicle should then be taken on a test drive to verify the customer's concerns. The concerns should then be matched to any related technical service bulletins, and the action prescribed by these should be followed.

Diagnostics continue with a thorough visual inspection of the mechanical and electrical systems. This inspection should include the transmission, battery pack and its components, the jump-start switch, and junction and fuse boxes. Make sure you are wearing lineman's gloves, and follow all manufacturer-specific precautions. If you discover a likely cause for the customer's concerns, correct the problem before continuing.

Check the auxiliary battery; it should have at least 12 volts. If it does not, identify and correct that problem before continuing. If the battery is okay, make sure the ignition is off and connect the scan tool to the DLC. Record all DTCs **(Figure 10-35)** and match them to the pinpoint tests given in the service manual. All engine-related DTCs should be corrected first. Follow the steps given for each test exactly as they are listed. Failure to do so may lead to a misdiagnosis or damage to the electrical circuit. If no DTCs related to the customer's concerns are

B1016	Jump-Start Control Module Fault
B1143	Excessive Battery Contractor Close Requests
B1239	Airflow Blend Door Driver Circuit Failure
B1342	ECU Is Faulted
B2950	Air Conditioning System Fault
C1862	Contractor Circuit Failure
P0535	A/C Evaporator Temperature Sensor Circuit
P0A0A	High-Voltage System Interlock Circuit
P0A1F	Battery Energy Control Module
P0A27	Hybrid Battery Power Off Circuit
P0A7D	Hybrid Battery Pack State of Change Low
P0A7E	Hybrid Battery Pack Overtemperature
P0A80	Replace Hybrid Battery Pack (End of Useful Life)
P0A81	Hybrid Battery Pack Cooling Fan 1 Control Circuit
P0A8B	14-Volt Power Module System Voltage
P0A8D	14-Volt Power Module System Voltage Low
P0A8E	14-Volt Power Module System Voltage High
P0A95	High-Voltage Fuse
P0A96	Hybrid Battery Pack Cooling Fan 2 Control Circuit
P0A9B	Hybrid Battery Temperature Sensor Circuit
P0AA6	Hybrid Battery Voltage System Isolation Fault
P0AA7	Hybrid Battery Voltage Isolation Sensor Circuit
P0AAC	Hybrid Battery Pack Air Temperature Sensor A Circuit
P0AB1	Hybrid Battery Pack Air Temperature Sensor B Circuit
P0ABF	Hybrid Battery Pack Current Sensor Circuit Open
P0AC0	Hybrid Battery Pack Current Sensor Circuit Range/Performance
P0AE1	Hybrid Battery Precharge Contractor Circuit
P2533	Ignition Switch Run/Start Position Circuit
P2612	A/C Refrigerant Distribution Valve Control Circuit Low
P2613	A/C Refrigerant Distribution Valve Control Circuit High
U0001	High Speed CAN Communication Bus
U0073	Control Module Communication Bus Off
U0100	Lost Communication with PCM
U0101	Lost Communication with eCVT Transmission Control Module (TCM)
U0300	Internal Control Module Software Incompatibility
U0401	Invalid Data Received from PCM
U0402	Invalid Data Received from TCM

Figure 10-35 A list of hybrid-related DTCs for a Ford Escape and Mercury Mariner Hybrid.

retrieved, diagnose the problem with the symptom charts given in the service manual **(Figure 10-36).**

CAUTION *Always follow the precautions given by the manufacturer when conducting a compression test or other engine-related tests. Also, wear the proper protective gear when working near the high-voltage system.*

With hybrids, it is often difficult to control the operation of the hybrid system so certain tests can be conducted. Ford has built into its control system two scan tool–controllable modes for diagnostics. The engine cranking mode allows the engine to crank without the engine starting. During this mode, the TCM orders the starter/generator to rotate the engine at 900 to 1,200 rpm.

Ford also offers a running diagnostic mode. In this mode, the engine will run until it is ordered to stop by the scan tool or the ignition is turned off. In normal operation, the engine will not idle for very long without being shut down by the system. Therefore, when diagnostics require that the engine be idling, the engine running mode allows for this.

Toyota Hybrids

Diagnosis of Toyota hybrids depends on common sense, and of course, what the control modules tell you. After the customer interview, visual inspection, and review of information, Toyota instructs you to connect the scan tool to DLC3, which is the diagnostic connector that ties into the multiplex system. You should record all codes as they appear. If the codes are hybrid

Condition	Possible Sources
No communication with the traction battery control module (TBCM)	Fuse(s) Circuitry
The charging system warning indicator is on with the engine running and the charging system voltage does not increase—battery icon ON, low-voltage charging system at the DC/DC converter	Electronically controlled continuously variable transmission (eCVT) DC/DC converter interlock circuit(s) High-voltage cable(s) Traction battery control module (TBCM) Powertrain control module (PCM)
The charging system warning indicator is on with the engine running and the charging system voltage does not increase—battery icon ON	DC/DC converter interlock circuit(s) High-voltage cable(s) Low-voltage cable(s) 12-volt battery DC/DC converter
The charging system warning indicator is on with the engine running and the charging system voltage does not increase—battery icon ON	Instrument cluster Climate control system Traction battery control module (TBCM) Powertrain control module (PCM)
The charging system warning indicator is off with the ignition switch in the RUN position and the engine is off	Instrument cluster
The high-voltage traction battery (HVTB) is noisy	HVTB internal cooling fans (part of the HVTB) HVTB Air leakage from the climate control system
Radio interference	Audio unit Generator (part of eCVT) DC/DC converter
The low-voltage battery is discharged or battery voltage is low	12-volt battery 12-volt cables DC/DC converter

Figure 10-36 A typical symptom chart that should be used when diagnosing a Ford Escape and Mercury Mariner Hybrid.

system related, they should be divided by their power source. All engine- and emission-related DTCs should be handled first, and then move on to the other systems.

Toyota's instructions continue with a test drive. Starting or driving a hybrid is much different than driving a conventional vehicle. Remember, when the car is ready to be driven, the engine may not be running; all that happens is the READY lamp will be lit. If the READY lamp does not come on, the vehicle cannot be driven. Typical causes for this are:

- The service plug is removed.
- The inverter unit cover is not closed securely.
- There is excessive current in the inverter circuit.
- There is a problem with the hybrid system.
- One or more electric motors/generators are drawing excessive current.
- One or more of the impact sensors have been tripped.

During the test drive, note the operation of the vehicle at different speeds and conditions, and pay attention to the speed of the vehicle, electric motors, and engine. The recommended test speeds are acceleration to 20 mph, and then steady speeds of 35 and 45 mph. During each of the transitions between speeds, the system should be monitored to identify what is providing the propulsion power and what the SOC of the battery is. Fortunately, Toyota has a test drive sheet available that will help you identify what needs to be observed and recorded. The basic premise of the test drive is to determine what system may be causing the problem.

Some of the DTCs retrieved with the scan tool will also display three-digit information codes that will help your diagnosis **(Figure 10-37).** They provide additional information and freeze-frame data. As an example, the DTC-P0A4B indicates there is a problem with the generator position (resolver) sensor circuit. To help identify the problem, three information codes are also displayed on the scan tool: code 253 (Interphase short in resolver circuit), 513 (Resolver output is out of range), and 255 (Open or short in resolver circuit). These codes further define the problem, as well as give guidance as to what should be checked. All DTCs and information codes should be interpreted according to the charts given in the service manual. Each code has specific procedures for further testing; these should be followed.

Th

enable you to excite or disable certain outputs so their operation can be monitored. These "inspection modes" can crank the engine to conduct a compression test, turn the traction control on and off, and turn the inverter on and off. The value of these modes is the ability to isolate systems, which will definitely help in diagnosis.

Honda Hybrids

Honda hybrids are more like conventional vehicles in that they have a normal transmission. Driveability problems are caused by either the hybrid system or the engine. If there is a problem with the hybrid system, the IMA warning lamp will be lit **(Figure 10-38).** When the lamp is lit, that system should be checked first. Remember to take all necessary precautions when working around the high-voltage system.

If the IMA warning lamp stays on when the engine is running, turn the ignition off. Then connect the scan tool to the DLC. Once it is securely connected, turn the ignition on. Select the IMA system on the scan tool and record all DTCs. Also, check the freeze frame data to get a complete picture of what was happening when the computer noted the fault.

Using the DTC chart in the service manual, match the code with the appropriate troubleshooting procedure. Make sure to follow all sequences exactly as they are presented. If the code was set by an intermittent fault, you may not be able to identify it. Therefore, the codes should be cleared and the vehicle driven to see if the codes are reset. Codes can be cleared through the commands of the scan tool or by removing the No. 9 Backup fuse from the under-hood fuse/relay box for 60 seconds. Using the latter technique will cause the IMA battery level indicator to show zero bars. To bring a voltage reading back to the meter, start the engine and run it at about 4,000 rpm until at least three or four bars are displayed on the gauge.

Prior to the road test, perform a wiggle test on all connectors to see if this resets the codes. Make sure you are wearing lineman's gloves when moving wires and connectors around.

Once diagnostics are complete, clear any existing codes from the memory. Then turn off the ignition and disconnect the scan tool. Again, the IMA battery gauge will need to be reset, so start the engine and run it until at least three bars appear on the gauge. Once this is complete, the PCM must relearn the idle strategy if the battery was disconnected or the codes were cleared by any means other than the scan tool.

The procedure for conducting "PCM idle learn" begins with turning off all accessories. Then start the engine and run it at about 3,000 rpm until the electric cooling fan comes on. Then the engine should idle for at least 5 minutes before it is turned off.

The scan tool is also used to reset or calibrate the electric motor's rotor. This must be done whenever the following components have been removed and/or replaced:

- Motor Control Module (MCM)
- Motor rotor position sensor
- Stator or rotor of the IMA motor

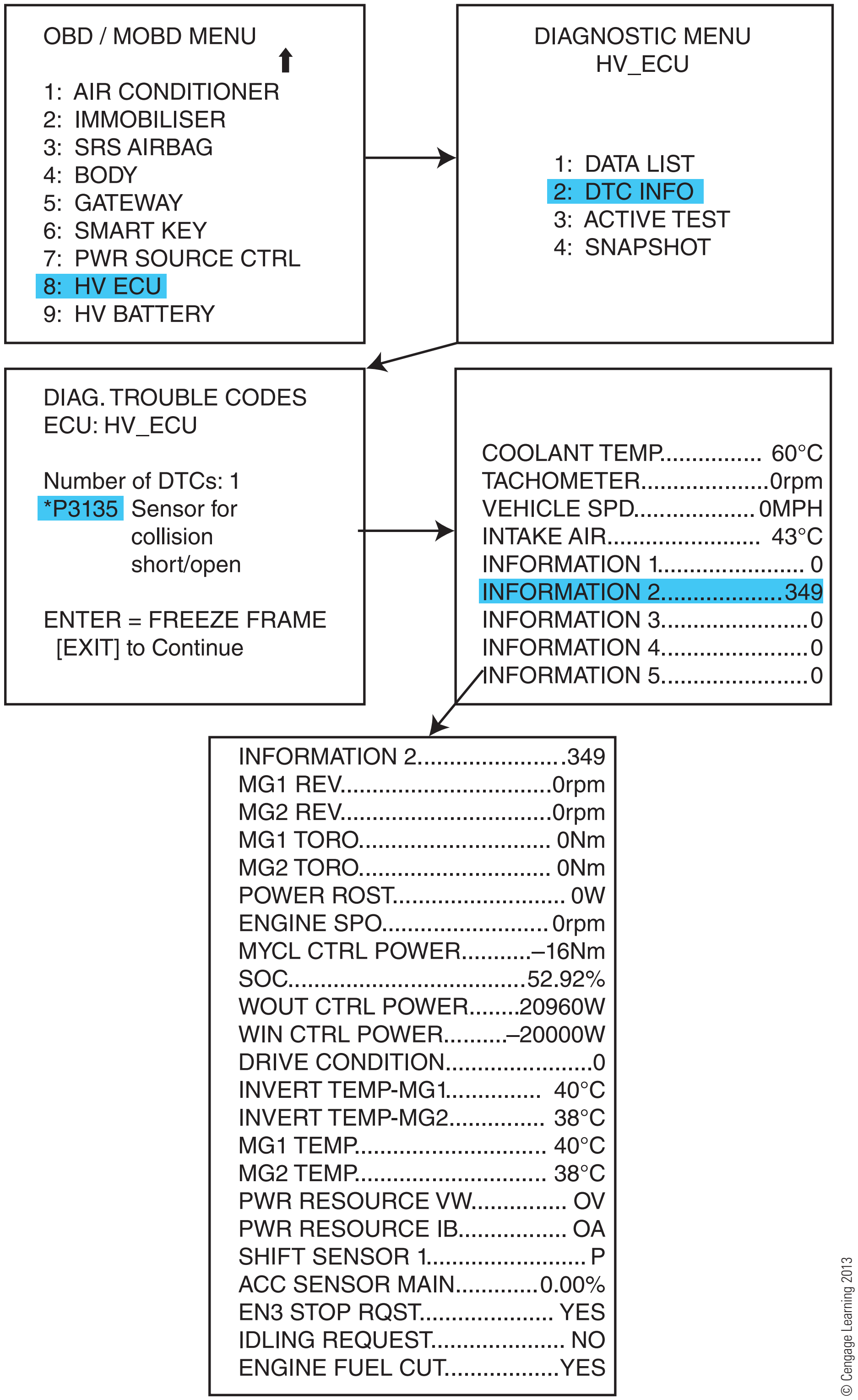

Figure 10-37 When retrieving DTCs on a Toyota, additional information codes may appear that will aid in diagnostics.

- Engine
- Transmission

To calibrate the rotor position sensor, connect the scan tool with the ignition off. Then turn the ignition on. Select the IMA System on the scan tool. Then scroll the adjustment menu and select Motor Rotor Position Calibration. The sensor should now be reset. Turn the ignition off and disconnect the scan tool.

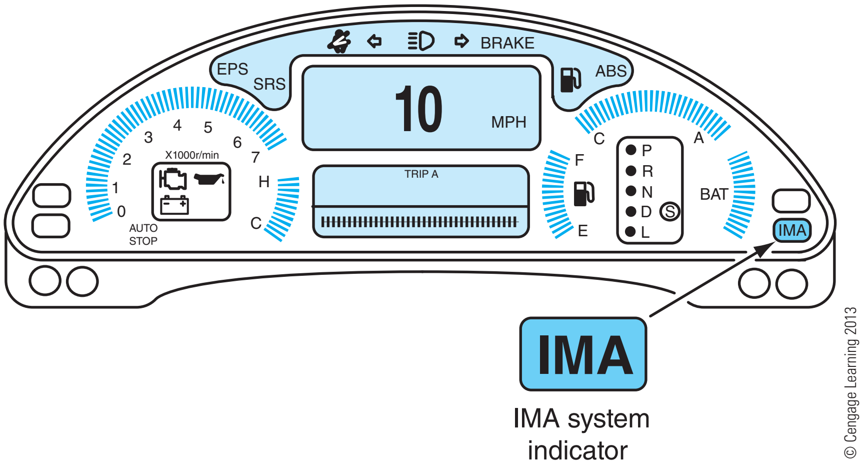

Figure 10-38 When the IMA warning lamp remains lit after the engine is started, the control system has detected a problem.

ENGINES

Most engines used in hybrid vehicles are based on engines used in other models of vehicles, but they are usually modified to increase fuel mileage and reduce emissions. Testing these engines is much the same as doing so in conventional vehicles. However, because any time the engine rotates it may be rotating the generator, there is a potential safety hazard. Keep this in mind when conducting a compression test on the engine. In most hybrids, the engine is cranked by a high-voltage motor. Because this motor is required to run the test, the high-voltage system cannot be isolated. Therefore, extreme care must be taken.

The procedure for conducting a compression test on Honda hybrids is much the same as that for a conventional vehicle. Before beginning the test, use the scan tool to shut off the fuel injection and ignition systems. To run a compression test on a Honda hybrid:

1. Warm up the engine to normal operating temperature.
2. Turn the ignition switch OFF.
3. Connect the scan tool to the DLC.
4. Following the menu of the scan tool, turn off all fuel injectors.
5. Disconnect and remove all of the ignition coils.
6. Remove all of the spark plugs.
7.

   a spark plug bore **(Figure 10-39).**
8. Open the throttle to its wide-open position and hold it there.
9. Crank the engine with the starter motor.
10. Record the compression readings on the gauge.
11. Repeat the process at each cylinder.

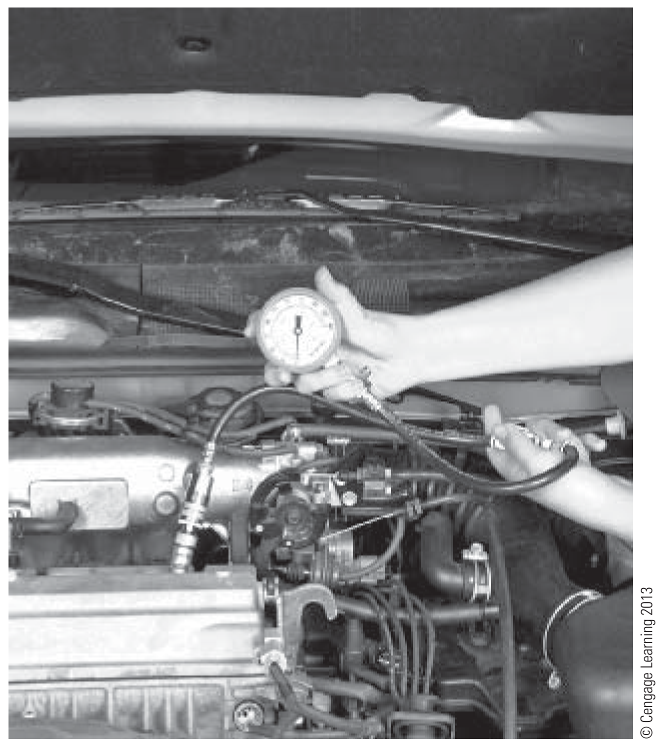

Figure 10-39 A compression tester connected to a cylinder.

The results of the compression test can be interpreted in the same manner as for a conventional engine. The pressure should be greater than 135 psi (930 kPa), and there should less than 28 psi (200 kPa) difference

parts reinstalled, the PCM must be reset. If this step is not done, the injectors will not work.

Ford, Toyota, and many other hybrids use Atkinson cycle engines. If you recall, these engines delay the closing of the intake valve. As a result, the overall compression ratio and displacement of the engine are

slightly reduced. Therefore, when conducting a compression test on these engines, expect a slightly lower reading than what you would expect from a conventional engine. Intake manifold vacuum will also be lower. Normally a healthy engine produces at least 17 in. Hg (57 kPa) during cranking. The expected reading from an Atkinson cycle engine is at least 15 in. Hg (51 kPa).

To conduct a compression test on a Ford Escape, you must use a scan tool, and the one from Ford is preferred. The scan tool allows you to enter into the engine cranking diagnostic mode. This mode allows the engine to crank with the fuel injection system disabled. It also makes sure the starter motor/generator is not activated (except for activating the starter motor to crank the engine), which is not only good for safety purposes, it is also good because the load of the generator cannot affect the test results because it is not energized. Always follow the sequence as it is stated in the service manual. Failure to do so will result in bad readings.

Note: If the battery pack has an SOC of less than 35 percent, the engine will not crank for the test.

1. Apply the parking brake and start the engine. Allow it to run until it reaches normal operating temperature.
2. Turn the ignition off.
3. Connect the scan tool.
4. Remove all spark plugs.
5. Install the hose for the compression tester in cylinder number 1.
6. Set the scan tool to the cranking diagnostic check.
7. Place the gear selector in the Park position.
8. Depress and hold the brake pedal.
9. Move the ignition to the ON position, but do not start the engine.
10. Within five seconds, press the throttle pedal to the floor and hold it there for 10 seconds.
11. Release the pedal, shift the transmission into Neutral, and fully depress the throttle pedal again.
12. Hold the throttle pedal down for 10 seconds.
13.
the Park position. If this sequence is done properly, the hazard indicator on the dash will flash once per second.
14. Turn the ignition to the START position, crank the engine through a minimum of five compression strokes, and record the highest reading.
15. Put the ignition switch back into the ON position.
16. Release the accelerator and brake pedals.
17. Repeat the sequence on each cylinder and record the results. Make sure the engine is cranked through five compression strokes.
18. Position the key to the OFF position to deactivate the cranking diagnostic mode.
19. Clear all DTCs.
20. Compare your results with the specifications.

Cooling Systems

Normal maintenance and service to engine cooling systems in hybrid vehicles can become a hazardous, frustrating event. For example, late-model Toyotas have a system that heats a cold engine with retained hot coolant to provide reduced emissions levels. This is a great idea, but it can cause problems for technicians servicing the cooling system.

CAUTION *The coolant in the coolant heat storage tank may be HOT when the engine and radiator are cold. Also, NEVER remove the radiator cap when the engine or radiator is hot.*

Hot coolant is stored in a container **(Figure 10-40),** and it will circulate through the engine immediately after startup. The fluid also may circulate through the engine many hours after it was shut off. This fluid is under pressure and can cause serious burns to anyone who opens the system for inspection and/or repairs. To safely service the cooling system, the pump for the storage tank must be disconnected. The cooling system also is tied into the inverter assembly. This also presents a potential problem, as it is easy to trap air in

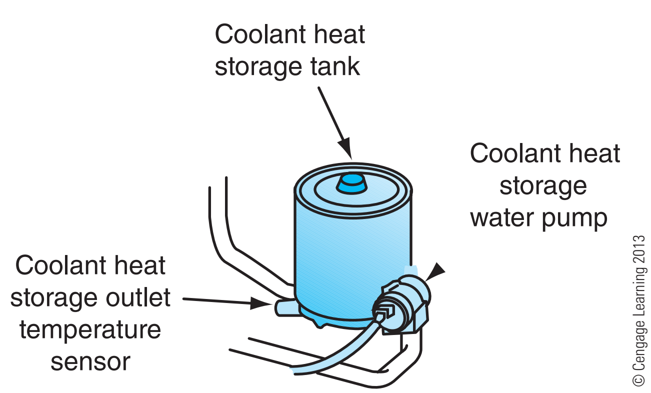

Figure 10-40 The hot coolant storage tank for Toyota hybrids.

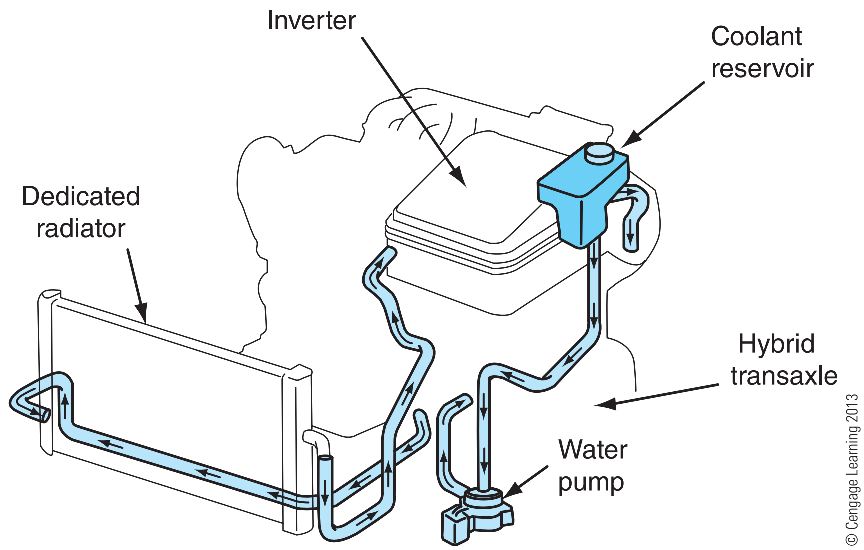

Figure 10-41 Air is easily trapped after servicing the cooling system because of the route the coolant takes; therefore, bleeding the system may be necessary.

the cooling system due to the path of coolant flow **(Figure 10-41).** To purge the system of air, there is a bleeder screw, and a scan tool is used to run the electrical pump. The recommended procedure for draining and refilling the cooling system on a Toyota hybrid includes the following steps:

1. Remove the radiator's top cover and cap.
2. Disconnect the connector for the coolant heat storage tank's water pump to prevent circulation of the coolant. (To gain access to the connector, either remove the left headlamp assembly or pull down on the front portion of the left front fender liner).
3. Connect a drain hose to the drain port on the bottom of the coolant heat storage tank, and then loosen the yellow drain plug on the tank.
4. Connect a drain hose to the drain port on the lower left corner of the radiator, and then loosen the yellow drain plug on the radiator.
5. Connect a drain hose to the drain port on the rear of the engine and loosen the drain plug.
6. After the coolant is drained, tighten the three drain plugs.
7. Reconnect the connector to the coolant heat storage tank's water pump.
8. Connect a hose to the radiator's bleeder valve

   coolant reservoir tank.
9. Loosen the radiator's bleeder plug.
10. Fill the radiator with the specified coolant.
11. Tighten the radiator's bleeder plug and install the radiator cap.
12. Connect the scan tool to DLC3.
13. Using the scan tool, run the water pump for the storage tank for 30 seconds.
14. Then, loosen the radiator's bleeder plug.
15. Remove the radiator cap and top off the coolant in the radiator.
16. Repeat the refilling and bleeding sequence as often as necessary. Normally, when no additional coolant is needed after the sequence, the system is bled.
17. Start the engine and allow it to run for 1 to 2 minutes.
18. Turn off the engine and top off the fluid, if necessary.

Toyota hybrids have a separate cooling loop for their inverter and other electronic equipment under the hood. The coolant level for the inverter should not be ignored **(Figure 10-42).** The inverter produces a great

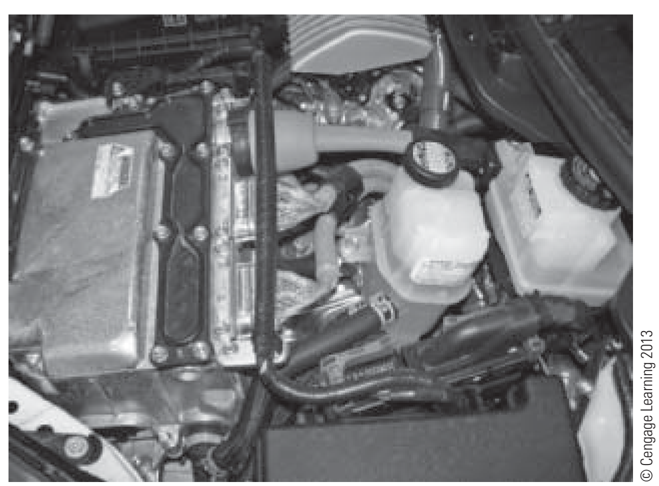

Figure 10-42 A coolant reservoir for an inverter.

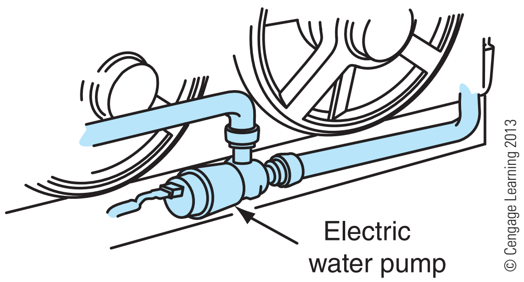

Figure 10-43 The electric water pump for the M/E cooling system on a Ford Escape Hybrid.

amount of heat, and if the heat is not controlled, many electronic components will be destroyed.

Ford hybrids have two separate cooling systems: one is for engine cooling and the other is for hybrid system components, called the Motor Electronics (M/E) cooling system. The engine cooling system is conventional. The M/E cooling system uses an electric water pump **(Figure 10-43)** to move coolant through the inverter, transmission, and a separate radiator mounted next to the conventional radiator **(Figure 10-44).** The M/E coolant reservoir is located behind the engine coolant reservoir. Although the two systems operate similarly, the M/E cooling system typically operates at lower pressures and temperatures. The fluid levels in both cooling systems must be maintained.

It is easy to trap air in the M/E cooling system when filling and/or flushing the system. The system is fitted with a bleeder screw at the top of the inverter **(Figure 10-45).** When servicing the system, make sure the high-voltage system is isolated by having the service connector in the SERVICE/SHIPPING position. Also, wear lineman's gloves because the bleeder screw is very close to the high-voltage cables.

To drain, refill, and bleed the system, put the vehicle on a hoist. Remove the splash shield from the left front of the vehicle. Then loosen the hose clamps and

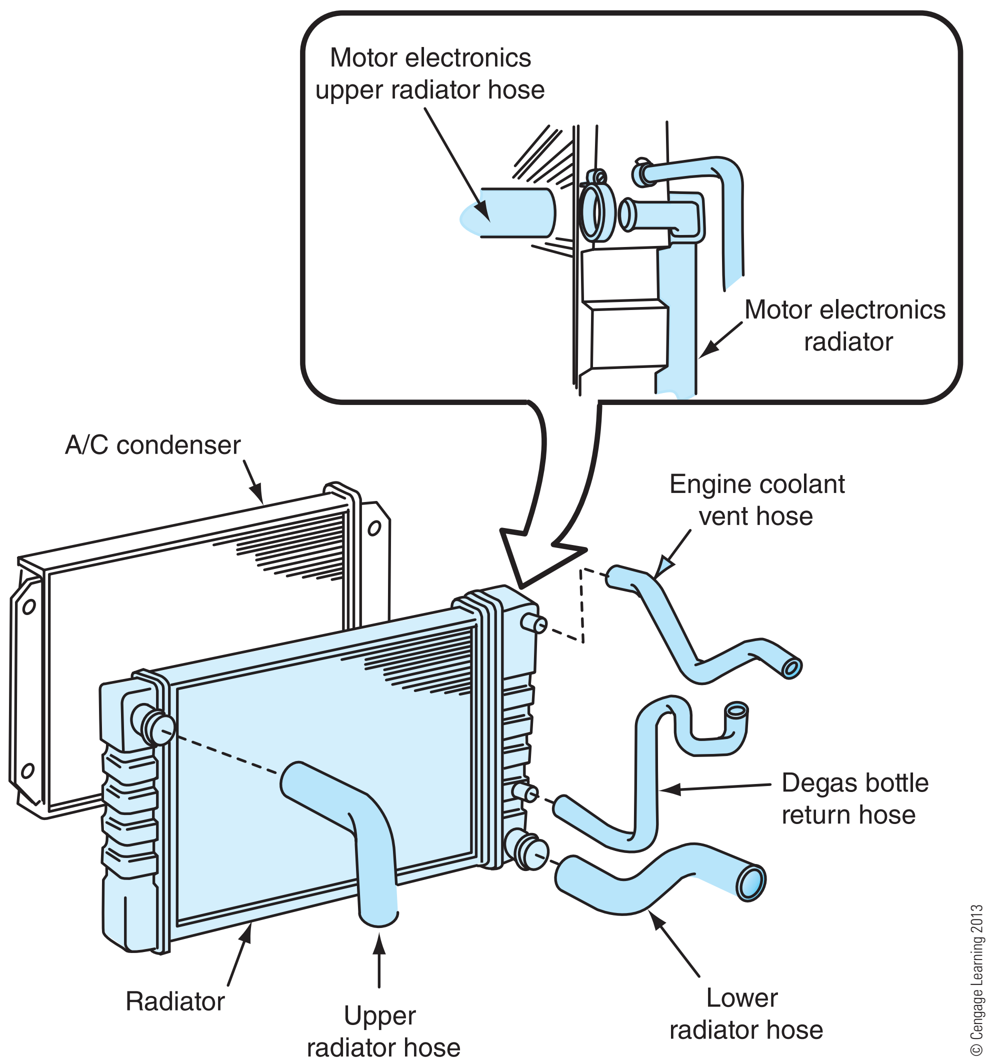

Figure 10-44 The radiator assembly for a Ford Escape Hybrid.

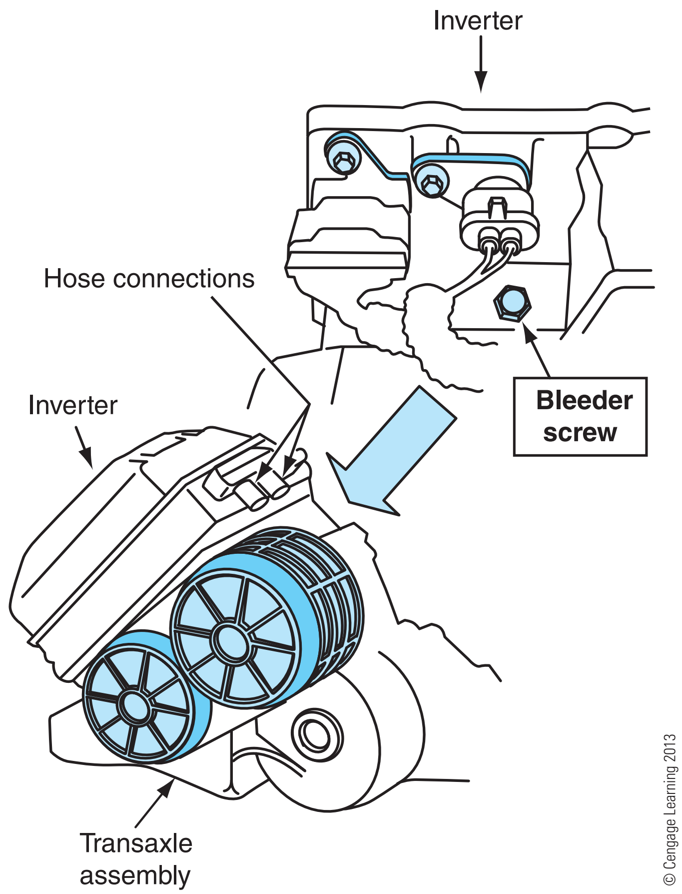

Figure 10-45 Location of the cooling system bleeder screw on a Ford Escape Hybrid.

remove the coolant hoses at the transaxle and allow the coolant to drain into a catch can. Once the fluid is drained, reinstall the hoses and tighten the clamps. Reinstall the splash shield and lower the vehicle. Loosen the bleeder screw and pour the specified type of coolant into the coolant (degas) reservoir. Fill the reservoir until coolant starts to leak from the bleeder screw, then tighten the bleeder screw. Turn the ignition on to allow the M/E water pump to run. Add coolant to the reservoir as the level drops. Once the level stays at the FULL mark, loosen the bleeder screw slightly to allow any air to escape. Tighten the bleeder screw and bring the coolant level back to the correct level.

Battery Cooling System Filter. The battery may have its own cooling or air conditioning system. The control module monitors the temperature of the cells and activates

when the temperature rises. The battery pack's cooling system draws in outside air from a vent built into the rear side window. Within the ductwork there is an air filter that requires periodic replacement (every six months in normal conditions). If the filter is dirty or restricts airflow, the battery can overheat, which may cause the hybrid system to shut down. To inspect and/or change the filter, remove the access panel in the rear trim panel on the driver's side of the vehicle. The cover for the filter is retained by small tabs. To remove the cover, push on the tabs while pulling on the cover **(Figure 10-46).** Remove the filter. When installing the filter, make sure it is positioned correctly. Then reinstall the filter's cover and the access panel.

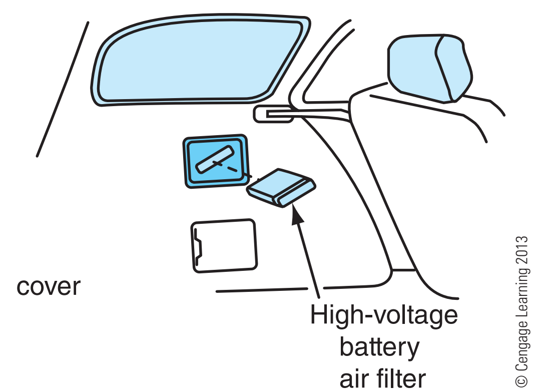

Figure 10-46 Changing the high-voltage battery air filter element on a Ford Escape Hybrid.

TRANSMISSION

Transmission service in a hybrid vehicle is no different from that in a conventional vehicle for about half of the hybrids on the road. Hondas use conventional-type transmissions, and many GM hybrids do also. The only real difference is that the flywheels on these hybrids bolt to the electric motor's rotor. This means the high-voltage systems must be isolated prior to performing any transmission service. In addition, because the rotor is a strong permanent magnet, all precautions regarding the rotor must be adhered to **(Figure 10-47).**

The hybrids made by Toyota and Ford, as well as the two-mode transmissions used in some GM and Chrysler hybrids, are unique units. The only services that can be done to these transmissions are fluid checks, fluid changes, and replacing the entire unit. The required precise position of the motors in a two-mode transmission makes them very unlikely candidates to be rebuilt in a regular service department.

CAUTION *Remember to isolate the high-voltage system prior to checking these components. Also, make sure you are wearing good lineman's gloves.*

The transaxles used in Toyota and Ford hybrids are also not rebuildable and are replaced as units if they fail.

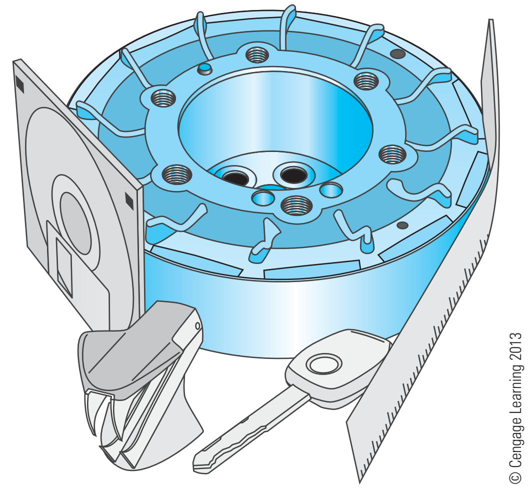

Figure 10-47 The permanent magnet rotor in the IMA is very strong. All iron, magnetic, and electronic materials must be kept away from the rotor. People with pacemakers should not handle an IMA rotor.

These transaxles contain a single or compound planetary gear set and two motor/generators **(Figure 10-48).** Some designs have an additional set of reduction gears in the housing. The transaxles not only provide different forward drive ratios and a reverse, they also blend the torque output from the engine and the traction motor. The transaxles are CVTs, but are unlike CVTs used in conventional vehicles.

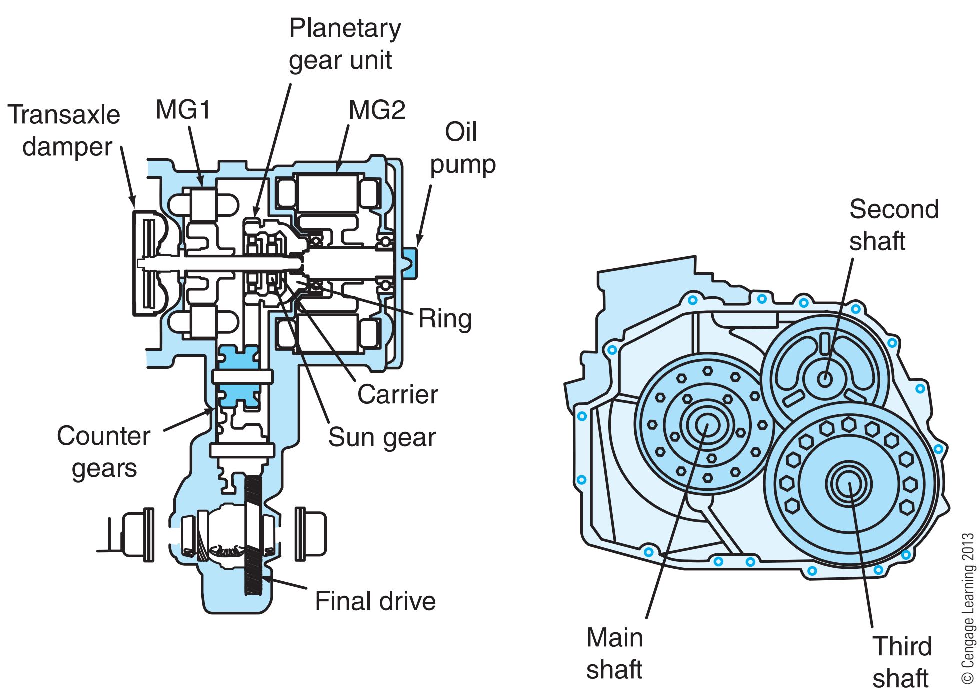

Figure 10-48 A compound gear set–equipped Toyota transaxle.

These CVTs can be diagnosed with a scan tool, which can retrieve codes pertaining to the transaxle. Keep in mind, problems with the motors and engine can also cause the transaxle not to operate properly. Normal diagnostic procedures should begin with a customer interview, verifying the customer's concerns, researching all service information, and conducting a thorough inspection of the vehicle, especially the components of the hybrid system.

Part of the inspection should include checking the condition of the auxiliary battery and observing all warning light activity. If the cause of the concern is not found during these checks, the scan tool should be connected to retrieve all DTCs. All codes that are directly related to emissions should be diagnosed first. Match all codes with the appropriate chart, and follow the specific procedures for identifying the exact cause of the problem. If no DTCs are retrieved, diagnostics should continue according to the symptoms of the problem. The rear transaxle assemblies in 4WD Toyota hybrids are also diagnosed with the scan tool.

The fluid level in all transmissions and transaxles must be periodically checked. Some have dipsticks and others have level plugs. Many designs also require periodic fluid and filter changes. To check the fluid on an automatic transmission equipped with a dipstick, place the vehicle on a level surface. Wipe all dirt off the filler or dipstick tube and the dipstick handle, before removing the dipstick. Most often, the fluid level can only be accurately checked when the transmission is at operating temperature. Most manufacturers recommend running the engine while checking the fluid level. Always refer to the service manual to identify the correct procedure. Also, make sure that the parking brake is engaged, and take all necessary safety precautions while working under the hood.

Remove the dipstick and wipe it clean with a lint-free cloth or paper towel. Reinsert the dipstick, remove it again, and note the reading. Markings on a dipstick indicate ADD levels, and on some models, FULL levels for cool, warm, or hot fluid. If the fluid level is low and/or off the crosshatch section of the dipstick, the problem could be external fluid leaks. Check the transmission case, oil pan, and cooler lines for evidence of leaks.

Low fluid levels can cause a variety of problems. Air
can mix with the fluid. This will result in aerated fluid, which causes slow pressure buildup, and low pressures, which will cause slippage between shifts or delayed shifts.

Excessively high fluid levels can also cause aeration. As the planetary gears rotate in high fluid levels, air can be forced into the fluid. Aerated fluid can foam, overheat, and oxidize. All of these problems can interfere with normal valve, clutch, and servo operation. Foaming may be evident by fluid leakage from the transmission's vent.

The condition of the fluid should be carefully examined while checking the fluid level. The normal color of automatic transmission fluid (ATF) is pink or red. If the fluid has a dark brownish or blackish color and/or a burned odor, the fluid has been overheated. A milky color indicates that engine coolant has been leaking into the transmission's cooler in the radiator. If there is any question about the condition of the fluid, drain out a sample for closer inspection.

After checking the ATF level and color, wipe the dipstick on absorbent white paper and look at the stain left by the fluid. Dark particles are normally band and/or clutch material, whereas silvery metal particles are caused by the wearing of the transmission's metal parts. If the dipstick cannot be wiped clean, it is probably covered with varnish, caused by fluid oxidation. Varnish will cause the spool valves to stick, causing improper shifting speeds. Varnish or other heavy deposits indicate the need to change the transmission's fluid and filter. Contaminated fluid can sometimes be felt better than it can be seen. Place a few drops of fluid between two fingers and rub them together. If the fluid feels dirty or gritty, it is contaminated with burned frictional material.

The fluid level of most CVTs (including those used in Toyota and Ford hybrids), manual transmissions, and the rear transaxle in four-wheel drive Toyota hybrids is checked by removing the filler plug on the side of the transaxle. Each manufacturer specifies a distance below the filler plug bore that the fluid level should be **(Figure 10-49).** If the level is

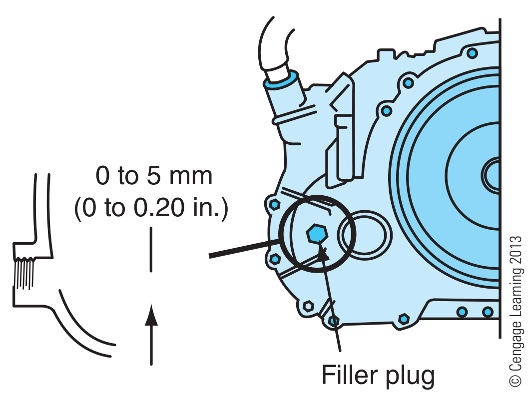

Figure 10-49 Each manufacturer specifies a distance below the filler plug bore where the fluid level should be.

low, fluid should be added. However, before adding any fluid, make sure it is the type specified for that transmission. If internal damage is suspected, the fluid from these transmissions should be drained through an absorbent white paper into a catch can. The paper should then be carefully inspected for residue.

CAUTION *If the fluid level is so low that it does not appear on the dipstick or is at the very bottom of the dipstick, the vehicle should not be driven until the level is brought up to normal. Driving with a very low level can cause internal transmission damage.*

BRAKES

The brake systems used in hybrids are quite conventional. The most noticeable difference is the regulation of the hydraulic system to allow for regenerative braking. All this means is that the action of the normal brake system is delayed to allow the generators to work. Basically, the control module determines how much regenerative braking there should be and how much hydraulic pressure is needed to stop the vehicle. For the most part, there are no physical changes to the hydraulic brake system, except for an electronic control that interrupts the flow of pressurized fluid from the brake master cylinder to the wheel units **(Figure 10-50).**

The brake system in Ford hybrids has a feature that can become a safety hazard to the unknowing. The system basically checks for leaks by applying the brakes without being commanded to do so by the driver. (This could take place during a normal brake job if the system is not disabled first.) The hydraulic control unit (HCU) controls the brake force distribution and the antilock brake system. The HCU has an accumulator and an electric pump **(Figure 10-51).** The pump charges the accumulator when the brakes are applied, and whenever the vehicle's doors are opened, the ignition switch is turned on and the brake pedal is depressed. The latter conditions put the system into a self-test. During this time, brake fluid is drawn from the master cylinder and sent to the wheel units. The pressure in the system is monitored. If there is a leak, the HCU will sense the drop in pressure and turn on the appropriate warning light. If there is no leak after 4 minutes, the fluid is returned to the master cylinder. To prevent an unwanted application of the brakes while working on the brakes, the auxiliary battery should be disconnected

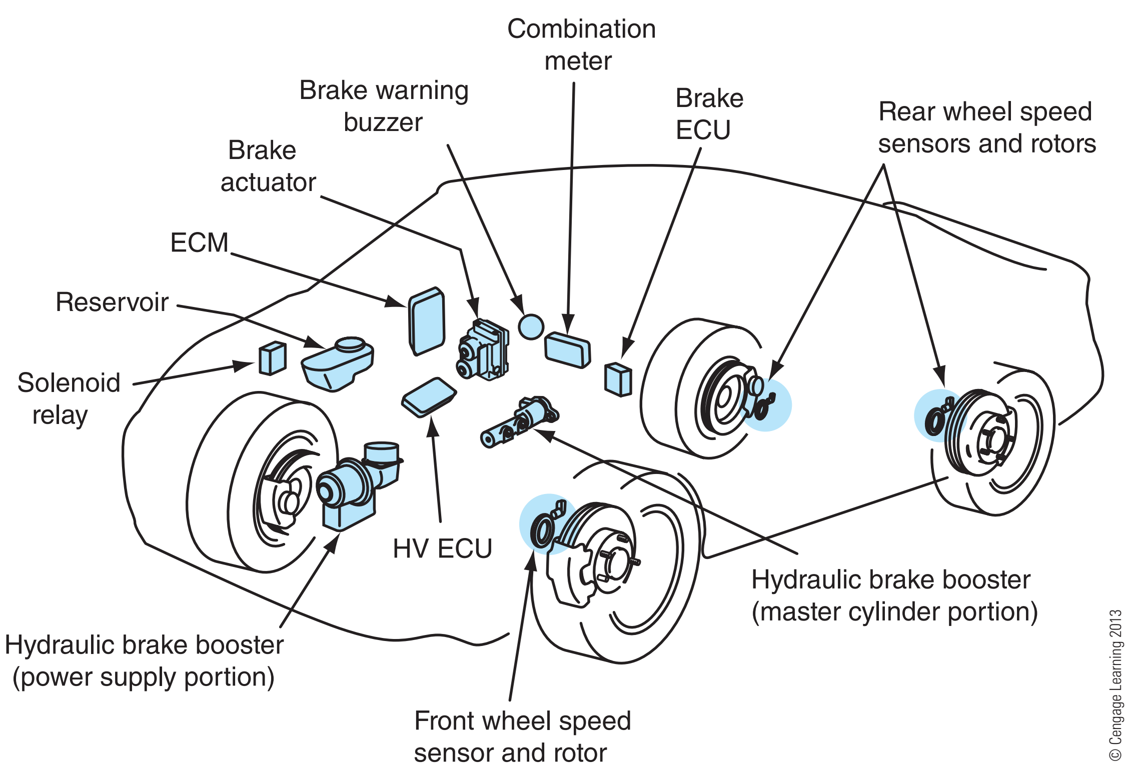

Figure 10-50 The major components in the brake system for an early Prius.

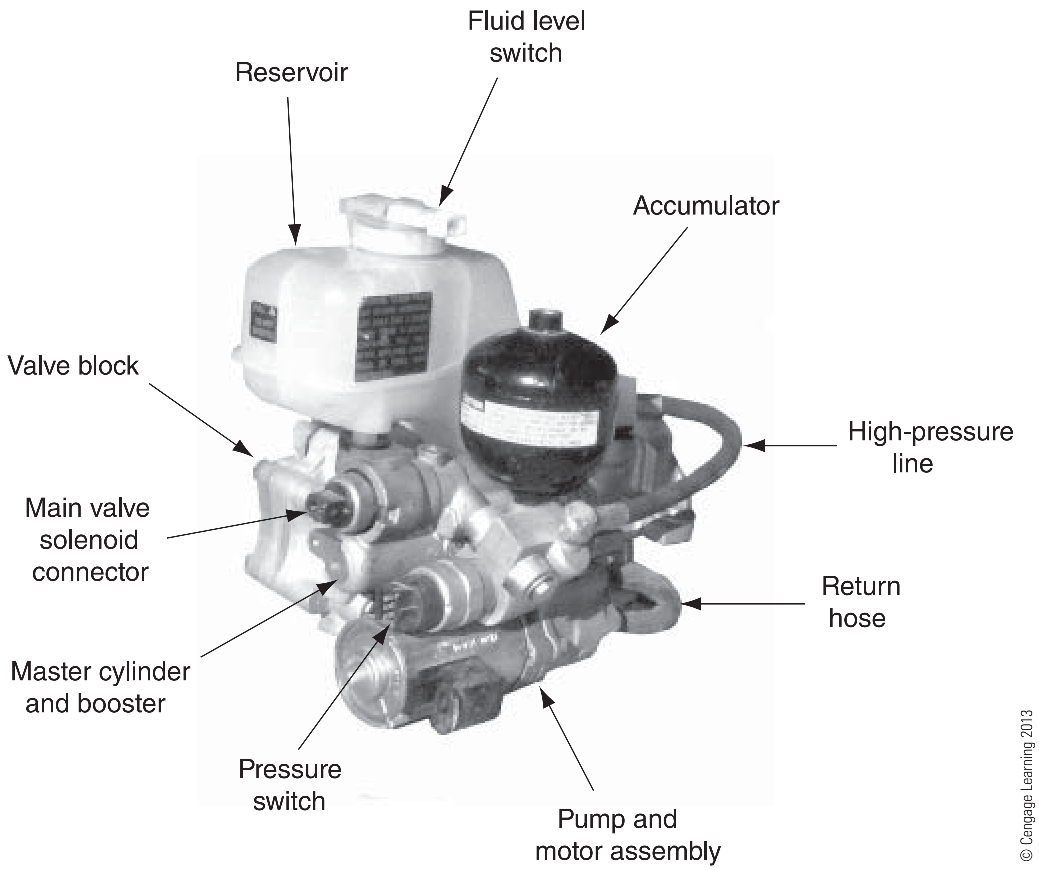

Figure 10-51 A typical electronically controlled hydraulic control unit.

and two fuses (numbers 24 and 31) removed from the fuse box under the hood.

Electronically Controlled Brake System

Toyota's electronically controlled brake (ECB) system was introduced on late-model hybrids along with the introduction of more powerful motors/generators. Because these can provide more propulsion power, they are also very efficient at capturing energy during regenerative braking. The ECB system **(Figure 10-52)** controls power brake assist, ABS, traction control, and on some models, vehicle stability control. The ECB calculates the required braking force based on the amount of effort and force applied to the brake pedal. The ECB then appropriately

draulic brakes.

The system does not use a conventional brake power booster. Also, during normal braking, the fluid pressure developed in the brake master cylinder **(Figure 10-53)** does not go directly to the wheel units. The pressure is applied to the brake actuator, which controls and sends the pressure to the wheels. The brake actuator houses an accumulator, electric pump, solenoids, and several valves. The pump supplies pressurized fluid to the accumulator, which supplies pressure to the hydraulic brake system. Brake assist is provided by the pressure in the accumulator, which varies according to current conditions, the required braking force, and driver demands.

On late-model hybrids, Toyota has added a power source backup unit **(Figure 10-54)** to allow the ECB system to operate when the auxiliary battery fails. This backup power source is only designed to allow the vehicle to stop, and cannot provide continuous power. The backup unit is made up of individual capacitors. The capacitors discharge when the ignition switch is turned OFF. If you need to replace this unit, use a voltmeter to see if it is discharged before

The system is diagnosed with a scan tool. It is important to understand that this electronic system controls the action of the hydraulic brake system. Therefore, when the vehicle has a brake problem, diagnosis should lead to defining the problem as being electrical or hydraulic.

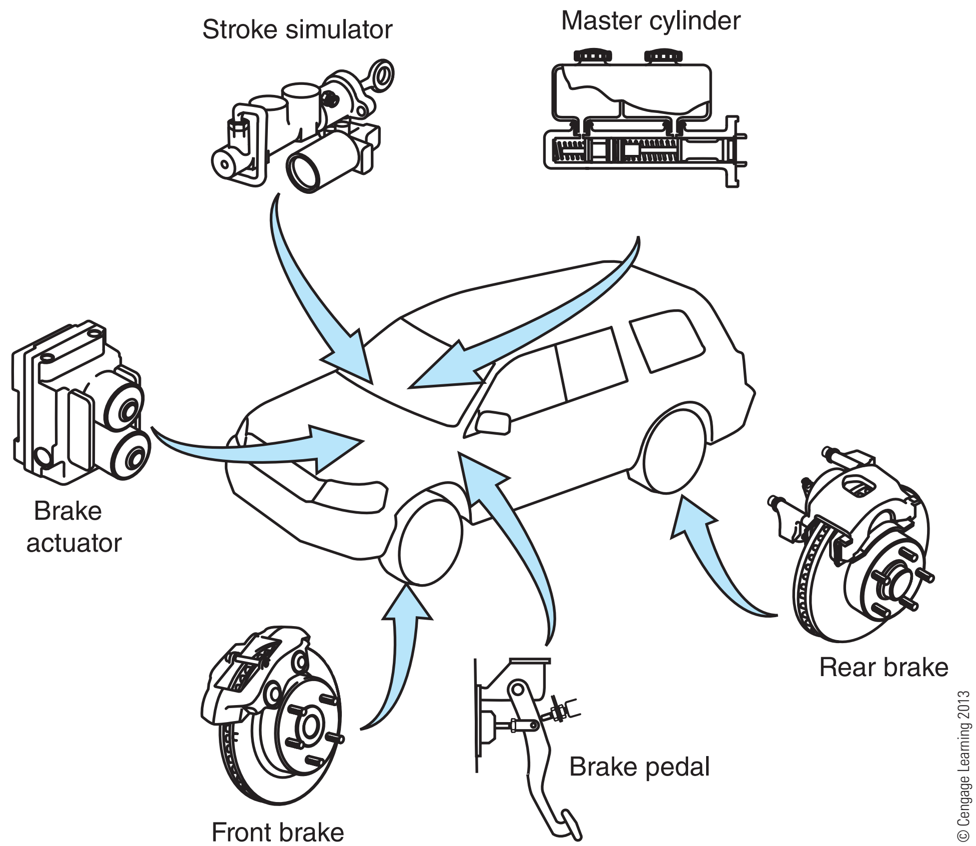

Figure 10-52 The main hydraulic components in Toyota's ECB system.

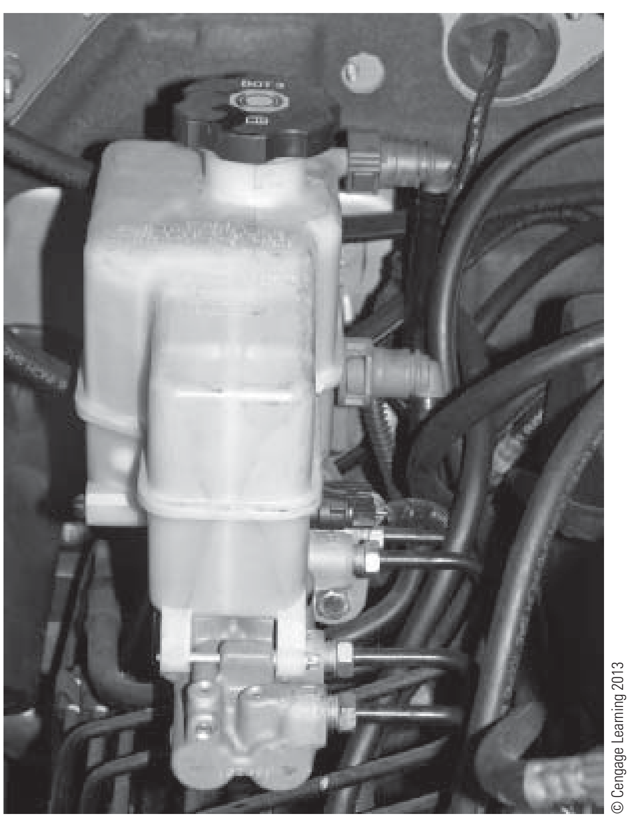

Figure 10-53 The master cylinder in a typical hybrid.

Toyota Pad Replacement

To enter the Pad Service mode of the ECB, do the following:

1. Place the vehicle in Park.
2. Turn the ignition to RUN.
3. Apply and hold the brake pedal down.
4. Turn the ignition OFF and then ON three times within three seconds.
5. Then release the brake pedal.
6. The brake warning lamp will flash as the stored hydraulic pressure is being released and will remain on until the pressure is completely released.

To exit Pad Service mode:

1. Apply the brake pedal.
2. Turn the ignition OFF and then ON. This will
3. Once pressure has returned, the brake lamp will go out.

Bleeding. The system must be disabled whenever the hydraulic brake system needs to be bled and when

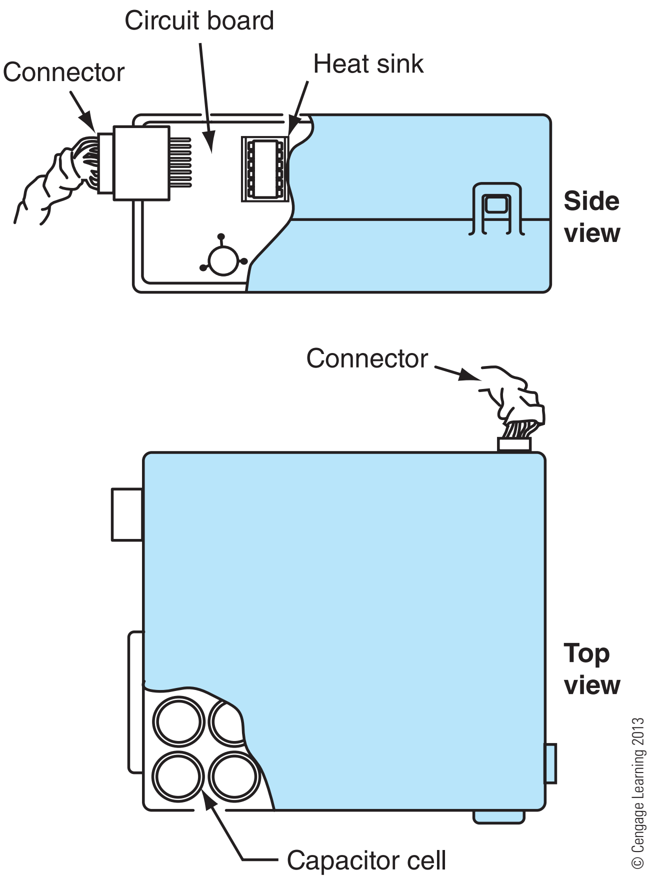

Figure 10-54 The power source backup unit for the ECB system.

other brake work is being done. The system is disabled by removing the system's two relays from the junction/fuse box or by using the scan tool to shut the system down. Check the service manual for the correct procedure.

STEERING

Most hybrid vehicles have electric power steering (EPS). These systems do not have a power steering pump and require no fluid services. A 12-volt motor **(Figure 10-55)** is fit into the steering column and provides steering assist according to commands given by the EPS control unit. Because these systems are electronically controlled, diagnosis is performed in the typical way. There is a warning lamp on the dash that comes on when a problem is detected. A DTC will also be set. In most cases, when the warning lamp is lit, there will be no power assist available.

The systems are constantly (from key on to key off) monitored by the control unit. If a problem is detected, the EPS lamp may stay lit after the ignition is turned on, or it may come on while it is being driven. To identify the reason for the illumination of the lamp, interview the customer to find out when and where it first came on. Try to duplicate the situation during a road test and then retrieve any and all DTCs **(Figure 10-56).** If the problem cannot be duplicated, do a careful inspection of all associated wiring and connectors.

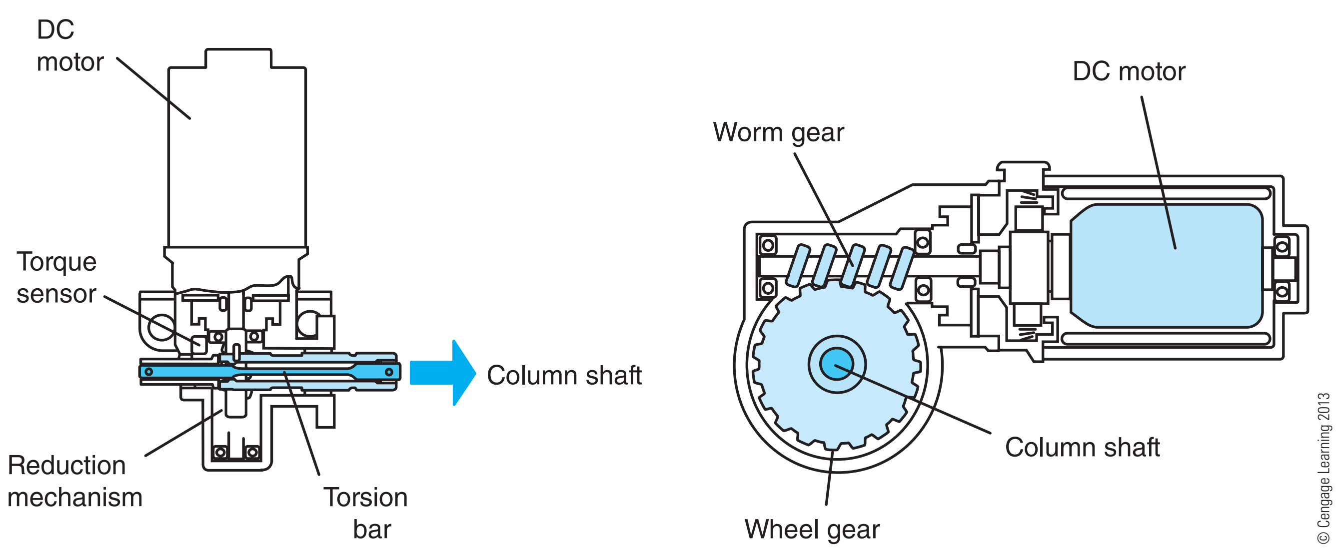

Figure 10-55 The DC motor used in an EPS system.

TRQ1.................................... 2.53V
TRQ2....................................2.51V
TRQ3....................................2.34V
SPD...................................... 0MPH
MOTOR ACTUAL.......................0A
COMMAND VALUE....................0A
THERMISTOR TEMP.............21°C
PIG SUPPLY..........................12.1V
IG SUPPLY............................ 11.9V
TRQ1 ZERO VAL..................2.51V
TRQ2 ZERO VAL..................2.49V
TRQ3 ZERO VAL..................2.37V
MTR TERMINAL (+)................5.8V
MTR TERMINAL (–)................5.8V
MTR OVERHEAT...................Unrec
MTR LOW POWER...............Unrec
CONTROL MODE................$010E
IG ON/OFF TIMES......... 255 times
#CODES.......................................0
ASSIT MAP.................................02
ECU I.D. 01
TEST MODE STAT.......... NORMAL
READY STATUS...................... OFF

Figure 10-56 This screen print from a scan tool represents a normal condition for the EPS system.

AIR CONDITIONING

Hybrids are equipped with air conditioning systems with either a belt-driven or an electrically powered A/C compressor **(Figure 10-57)** or, on some Honda hybrids, there is a dual compressor that is driven by a belt or an electric motor depending on the operating mode. The electrical units are powered by high-voltage and all precautions should be taken to work safely with these units. Always wear lineman's gloves when inspecting or servicing high-voltage air conditioning systems.

The refrigerant oil used in all electrically operated compressors must meet the specifications given by the manufacturer. In nearly all cases, it is nonconductive, synthetic oil that not only serves as a lubricant, but it must also be able insulate the various electrical parts of the compressor from each other. The most common is **polyvinyl ether (PVE) oil**. Always refer to the service manual to identify the proper oil for the compressor. The use of the regular refrigerant oil (PAG) will cause an insulation fault in the compressor, in which case the compressor must be replaced and the rest of the A/C system must be flushed and recharged **(Figure 10-58).** Also, special procedures must be followed when recycling refrigerant to make sure all residual PAG oil in the service hoses and gauges is purged to prevent the oil from entering the electric compressor.

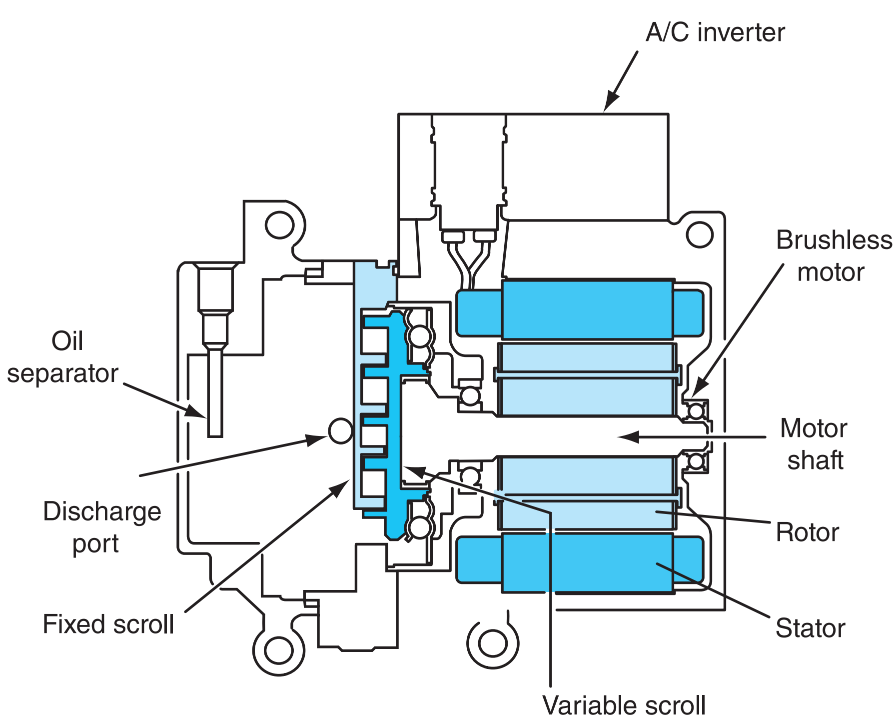

Figure 10-57 An air conditioning compressor driven by a high-voltage motor.

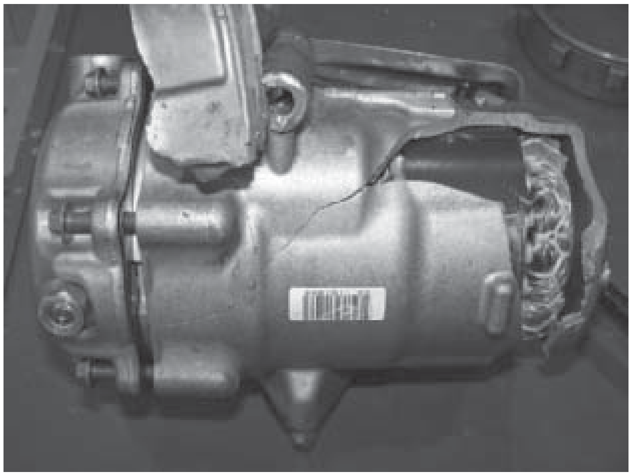

Figure 10-58 This is what can happen to a compressor if the wrong refrigerant oil is used.

All air conditioning diagnosis and service on a hybrid vehicle are the same as that for a conventional vehicle. The exceptions are the special needs of the electric compressor, if the vehicle has one. Like all high-voltage systems, the cables to the compressor will be orange, and there will be caution labels affixed to the compressor. (Respect the voltage!)

The operation of the air conditioning system may affect the stop-start feature. If the A/C is turned on, the engine may not shut down when the vehicle comes to a stop. This occurs mostly on hybrids with a belt-driven compressor, but it can occur on others if battery voltage is low and the engine is needed to drive the generator and recharge the battery pack. When the compressor is driven by the engine, there will be no cooling if the engine is shut down.

Review Questions

1. What is the correct procedure for testing the integrity of lineman's gloves, and why is this an important thing to do?

2. List five common-sense rules that should be followed when working on a hybrid vehicle.

3. Describe the procedure for checking for parasitic battery drains.

4. What is the best way to recharge a high-voltage battery pack?

5. After isolating the high-voltage system, what is the minimum time you should wait before beginning to work on or around the hybrid system?

   A. 1 hour　　C. 15 minutes
   B. 30 minutes　　D. 5 minutes

6. *True or False:* All hybrids use the engine's cooling system to cool the inverter assembly.

7. List and simply describe three important tools that should be used when troubleshooting a hybrid system.

8. When using a scan tool on Toyota hybrids, which of the following will be displayed after the DTCs to help guide the diagnostic procedure?

   A. Pinpoint diagnostic charts　　C. Information codes
   B. Related technical bulletins　　D. Intermittent codes

9. Which of the following is NOT powered by the auxiliary battery in Ford and Toyota hybrids?

   A. Hybrid control module　　C. Exterior lights
   B. Engine starter　　D. Power steering motor

10. Why should only CAT III meters be used to test the circuits and components in a hybrid system?

CHAPTER 11 Fuel Cell and Other Alternative Power Vehicles

Learning Objectives

After reading and studying this chapter, you should be able to:

- Describe the basic configurations for the power train in a fuel cell vehicle.
- Describe the major components of a fuel cell vehicle.
- Explain how a fuel cell works.
- Describe the different types of fuel cells currently being considered for use in vehicles.
- Explain why fuel cell vehicles are not yet practical for the average consumer.
- Describe what hydrogen is and where it can be found.
- Explain the various processes used to produce hydrogen.
- Describe the different ways hydrogen can be stored.
- Explain the various technologies that can be incorporated into an internal combustion engine vehicle to make it more efficient.
- List and describe the power plants for a zero-emission vehicle.
- Describe the technologies that may make diesel automobiles more common on U.S. roads.
- Describe how steam can be used as an auxiliary power source in an automobile.

Key Terms

air engine
alkaline fuel cell (AFC)
direct-methanol fuel cell (DMFC)
electrolysis
fuel cell stack
hydrogen
molten carbonate fuel cell (MCFC)
phosphoric acid fuel cell
photo biological methods
photo electrolysis
proton exchange membrane (PEM) fuel cell
selective catalytic reduction (SCR)
solid oxide fuel cell (SOFC)
steam reforming
Turbocharged Direct Injection (TDI)

INTRODUCTION

The main topics of this chapter are fuel cells, fuel cell vehicles, and hydrogen fuel. Also discussed are some of the alternate propulsion systems that may be used in the future. This chapter looks at the future; how much in the future is a good question. Most of what is covered exists in concept vehicles and systems that have been produced. Some have already been leased to businesses and individuals (such as the Honda Clarity) to serve only as proof-of-concept vehicles.

How soon you will see a fuel cell vehicle is anyone's guess, and there are many guesses. These vehicles are the topic of much news and, for many, a topic of interest.

Fuel cell electric vehicles are the result of the many years of research and development on electric and hybrid vehicles. Electric vehicles (EVs), hybrid electric vehicles (HEVs), and fuel cell electric vehicles (FCEVs) are all electric drive vehicles. They share many of the same technologies but differ greatly in the source of energy used to power the electric motors that are used to move the vehicle.

An EV relies on the energy stored in batteries as the sole energy source. The energy that is stored comes from readily available electrical power from external power lines. To refill or replenish the energy, or fuel, the batteries are charged by the normal source of electricity: an electrical outlet. It takes many hours to refill the batteries. An EV also stores electricity that is captured during braking. EVs offer the most economical and cleanest alternative to an internal combustion engine vehicle (ICEV). However, they have a very limited driving range and require very long refilling (recharging) times. Both of these are contrary to the driving habits and desires of most consumers and are the primary reasons EVs are not commonly seen on the roads today.

Solar-powered EVs are also being tested. Currently, these have not proven to be very practical due to the required size and location of the solar panels. However, further development can lead to more efficient traction motors and additional applications of solar energy.

An HEV has two different sources for energy: the battery and the engine. The batteries are charged by using some of the energy from the engine to turn a generator. The energy in the batteries can be used to propel the vehicle. An HEV battery also stores electricity that is captured during braking. Although no external means is necessary to refill or charge the batteries, the vehicle must be refilled with fuel for the engine. HEVs achieve excellent fuel mileage and lower emissions when compared to an ICEV. When compared to an EV, they offer a much longer driving range but emit some pollutants and still rely on a fossil fuel for energy.

FCEVs have electric motors, but the energy source for those motors is not necessarily batteries. Some FCEVs use an ultra-capacitor in place of the battery pack. Regardless of where the energy is stored, all FCEVs rely on the DC voltage generated by an onboard fuel cell assembly. The energy from the fuel cell can directly power the DC motors or be sent to the storage device **(Figure 11-1).** Some FCEVs also have regenerative braking. An external energy source is not required to refill the electrical storage unit; however, the fuel used in the fuel cell must be refilled. Pure water and heat are the only emissions from a fuel cell. This technology is not new, nor is it unproven; NASA (National Aeronautics and Space Administration) has been using this technology in its spacecraft for years. Fuel cells provide the energy for the various electronic

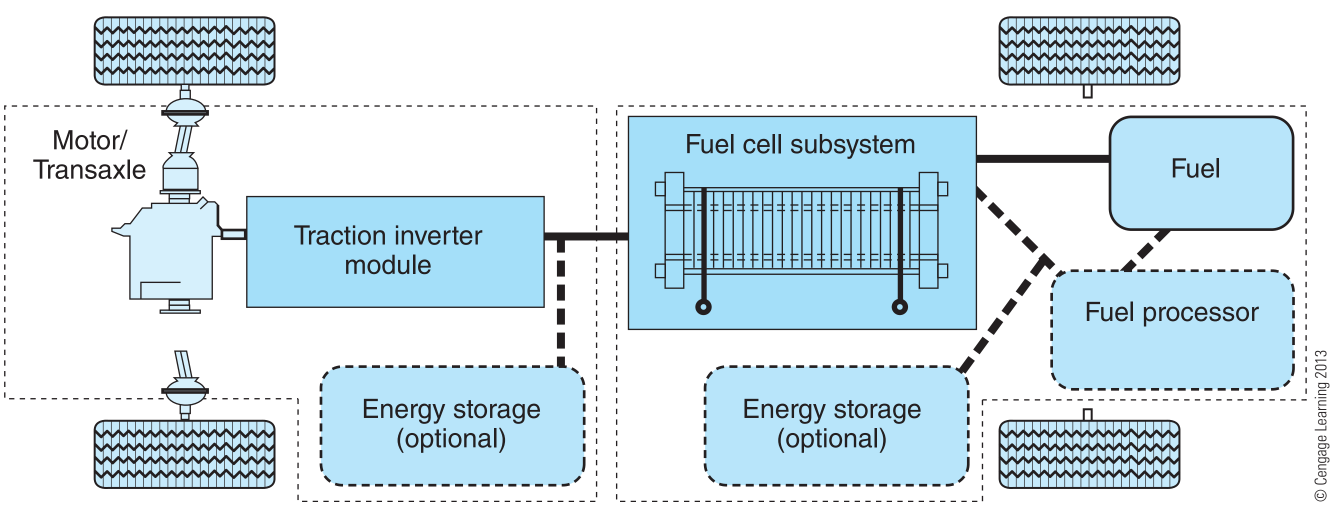

Figure 11-1 The basic layout for a fuel cell vehicle.

devices on board the spacecraft and the by-product—water—is what the astronauts drink.

FUEL CELL VEHICLES

Fuel cell vehicles use hydrogen as their fuel or energy source **(Figure 11-2).** The supply of hydrogen can be stored in tanks in the vehicle or can be provided by a reformer that extracts hydrogen from another fuel, such as gasoline, methanol, or natural gas. A major obstacle in the practicality of a fuel cell vehicle is the absence of an infrastructure for supplying pure hydrogen. A reformer answers that concern, as the required fuels are readily available. However, the cost of the reformer adds to the already high cost of a fuel cell.

Many manufacturers have joined together in this effort, whereas others are working alone. Ford and Daimler are minority owners of Ballard Power Systems Inc., which is a leading developer and manufacturer of fuel cell stacks. Ballard also has supplied fuel cells to Mitsubishi, Nissan, Volkswagen, and Honda. A fuel cell vehicle is much like a battery-operated electric vehicle. It operates like one and has many of the same characteristics as one: electricity powers an electric motor to drive the vehicle, the vehicle operates very quietly, and the output of CO_2 and other harmful emissions is zero, unless it relies on a fuel reformer. The main powertrain components in a typical fuel cell vehicle are:

- Fuel cell stack—An electrical generation device made up of several individual fuel cells.
- High-pressure hydrogen supply system or reformer with a fuel tank.
- Air supply system—A pump to supply the fuel cells with air.
- Humidification system—Recycles water vapor generated in the fuel cell (FC) stack to humidify the hydrogen and air, so the fuel cell's membrane does not dry out.
- Fuel cell cooling system.
- Storage battery or ultra-capacitor.
- Traction motor and transmission.
- Control module and related inputs and outputs—includes a DC/DC converter.

The energy generated by a fuel cell can directly power the traction motor of the vehicle or it can be stored in a battery or ultra-capacitor. If there is no storage (battery or capacitor) in the system, regenerative braking cannot exist. However, when a vehicle is equipped with a battery or capacitor, regenerative braking is used, and the energy stored in either one can provide power boosts for the vehicle.

FUEL CELLS

A fuel cell produces electricity through an electrochemical reaction that combines hydrogen and oxygen to form water. The basic principle is the opposite of electrolysis. **Electrolysis** is the process of separating a water molecule into oxygen and hydrogen atoms by passing a current through an electrolyte placed between two electrodes **(Figure 11-3).** In an internal combustion engine, fuel is combined with oxygen, and

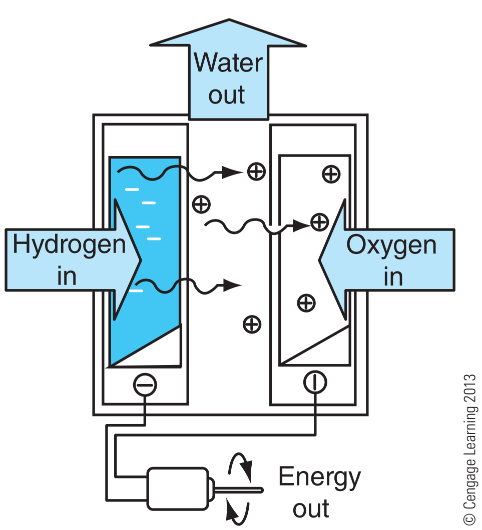

Figure 11-2 The basics of fuel cell operation.

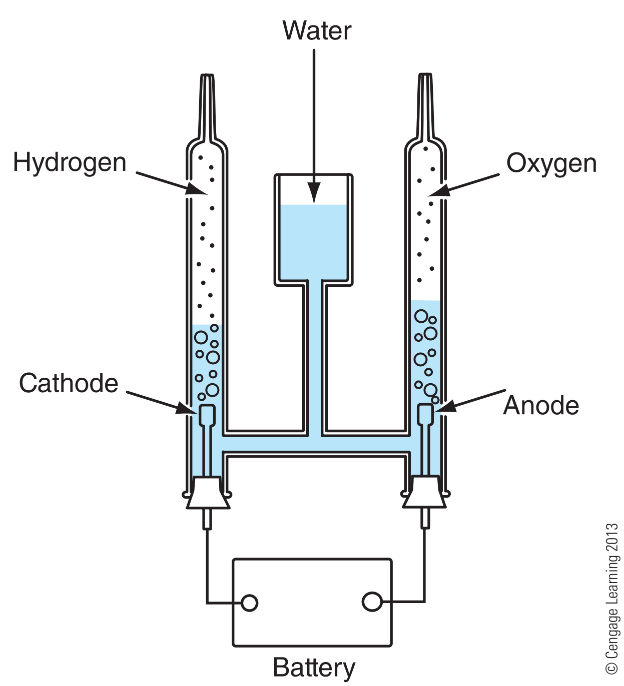

Figure 11-3 The process of electrolysis converts water into hydrogen and oxygen using electricity as the source of energy to cause the reaction.

this causes combustion. In combustion, the chemical energy in the fuel is changed to heat energy. In a fuel cell there is no combustion; the reaction is purely chemical. Catalysts are used to combine the fuel (hydrogen) with oxygen. The reaction releases electrons or electrical energy. Fuel cells have no moving parts and can continue to work until the fuel supply is depleted. In other words, the driving range of a fuel cell vehicle is largely dependent on the amount of fuel it can carry.

Fuel cell technology is not new. In 1839, a British scientist, William Robert Grove, proved it was possible to reverse electrolysis and produce electricity. However, the first successful fuel cell was not developed until 1959. Since then, using fuel cells as power generators has increased rather rapidly. However, fuel cells are expensive to make. Therefore, they have been mostly used where practicality and necessity outweigh cost, such as space programs. The idea of using fuel cells in vehicles did not make sense until new, low-cost materials could be used to make a fuel cell.

A single fuel cell produces very low voltage, normally less than 1 volt. To provide the amount of power needed to propel a vehicle, several hundred fuel cells are connected in series. This assembly is the **fuel cell stack** **(Figure 11-4),** called this because the cells are layered or stacked next to each other. Each fuel cell

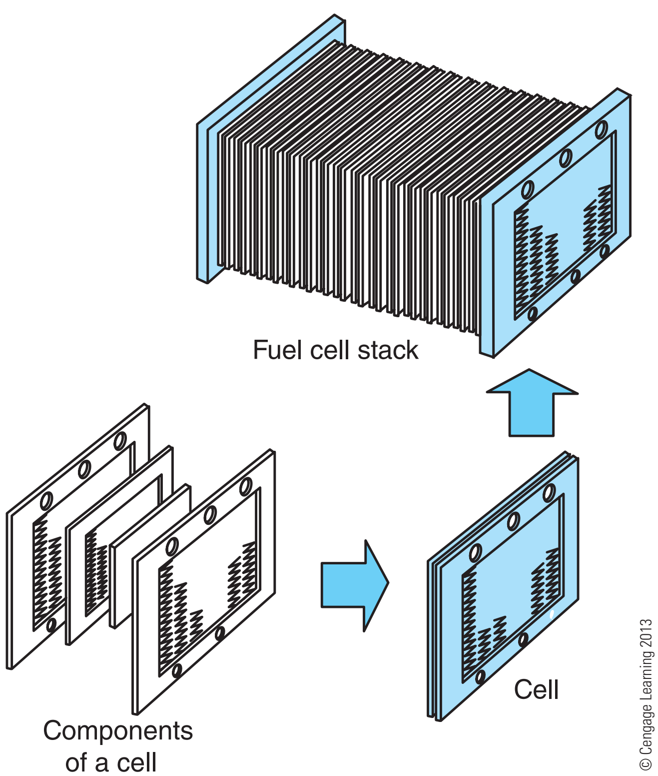

Figure 11-4 A fuel cell stack.

produces electricity, and the combined output of the cells is used to power the vehicle.

A fuel cell has two electrodes coated with a catalyst. The electrodes are separated from each other by an electrolyte and separators **(Figure 11-5).** One of the electrodes has a positive polarity, the anode, and the other is negative and is the cathode. The electrolyte is most often a polymer membrane, called the proton or ion exchange membrane. Polymers can be very resistant to chemicals and can serve as electrical insulators or separators. The polymer membrane in a fuel cell does both. The catalyst, normally platinum, on the electrodes causes the chemical reaction in the fuel cell, but it does not materially take part in the reaction. Therefore, the catalysts are not consumed during the operation of a fuel cell. A fuel cell consumes only hydrogen and oxygen. The oxygen is delivered to the cell by an air compressor that draws air in from outside the fuel cell. Hydrogen is fed into the fuel cell from a pressurized tank or from a reformer. In a direct hydrogen fuel cell vehicle, there are zero emissions. However, if the hydrogen is extracted from a fuel by a reformer, there will be some vehicle emissions.

When hydrogen is delivered to the anode, the catalyst causes the hydrogen atoms to separate into electrons and protons. Electrons always move to something more positive, but they cannot pass through the membrane. Therefore, their only path to the positive side of the fuel cell is through an external circuit. The movement of the electrons through that circuit results in direct current flow. It is this current flow that powers the vehicle's electric propulsion motors.

Oxygen enters the other side of the fuel cell and reacts to the catalyst on the cathode. This reaction splits the oxygen molecules into oxygen ions. The protons (hydrogen ions) that were released from the hydrogen at the anode move toward the oxygen ions. The membrane that separates the two electrodes will only allow protons to pass through, and they do. At the cathode, two hydrogen ions bond with each oxygen ion to form water.

To function, the ion exchange membrane must be kept moist. Therefore, some of the water produced by the fuel cell is used to humidify the incoming hydrogen and oxygen. The remaining water is emitted as exhaust from the fuel cell. Some heat is also emitted by the fuel cell. The heat is either released to the

can also be used to heat the passenger compartment.

Types of Fuel Cells

The fuel cell just described, the *proton exchange membrane (PEM)*, is currently the most commonly used

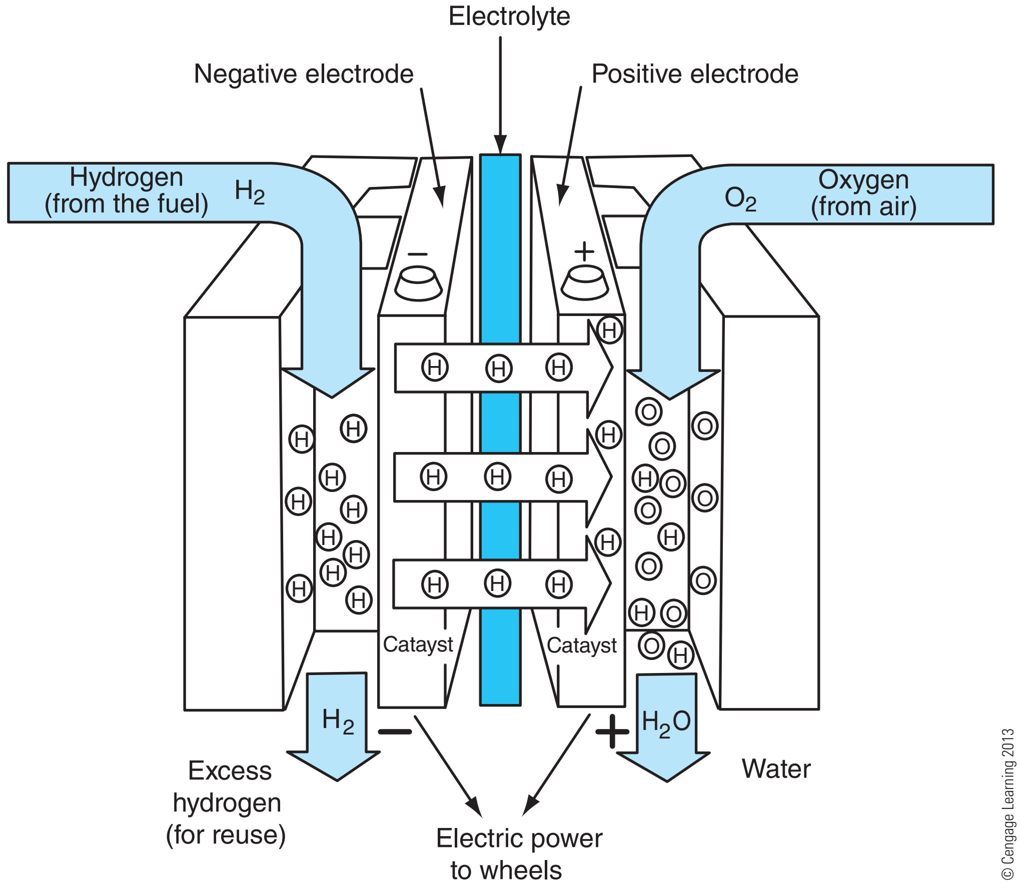

Figure 11-5 All fuel cells contain two electrodes—one positively and one negatively charged—and an electrolyte sandwiched between them.

type of fuel cell in concept vehicles. There are many other designs; some are impractical for use in an automobile, whereas others show promise. The following descriptions only include those that exist or are being developed at the time of this writing. At this point, it is hard to tell what design will actually be used on the roads of tomorrow, but it seems certain that a fuel cell will eventually power some of the vehicles of tomorrow. Most fuel cell designs vary by size, weight, fuel, cost, and operating temperature. However, all have two electrodes and an electrolyte between them. In addition, all types of fuel cells are more efficient than an internal combustion engine.

Proton Exchange Membrane. The **proton exchange membrane (PEM) fuel cell** **(Figure 11-6),** or derivatives
because it allows for adjustable outputs, which are necessary for driving. The speed of the vehicle can be controlled by controlling the output of the fuel cell. Although it is quite compact, it is capable of providing high outputs. When compared to other fuel cell designs, it is most efficient at relatively low temperatures of 86 to 212°F (30 to 100°C). However, it is expensive to manufacture. The cost is relatively high because the catalysts are platinum based. One of the biggest disadvantages of the PEM cell is the need to keep the membrane moist. In cold temperatures, the water can freeze, making the fuel cell very difficult to get started. Also, carbon monoxide (CO) can weaken the platinum catalysts. Because outside air is delivered to one side of the cell, the presence of CO in that air will reduce the output of the cell. Much research and development is taking place to alleviate these obstacles.

Solid Oxide. The **solid oxide fuel cell (SOFC)** may be the first design to be used in a mass-produced automobile. However, it will not be used to power a traction motor. Instead it may be used to replace the

tion engines. Current alternators are not very efficient, and their output is dependent on rotational speed. They also rely on engine power to operate, which means they contribute to an engine's fuel consumption. Removing the alternator and using an SOFC will increase the efficiency of the engine. The SOFC can also

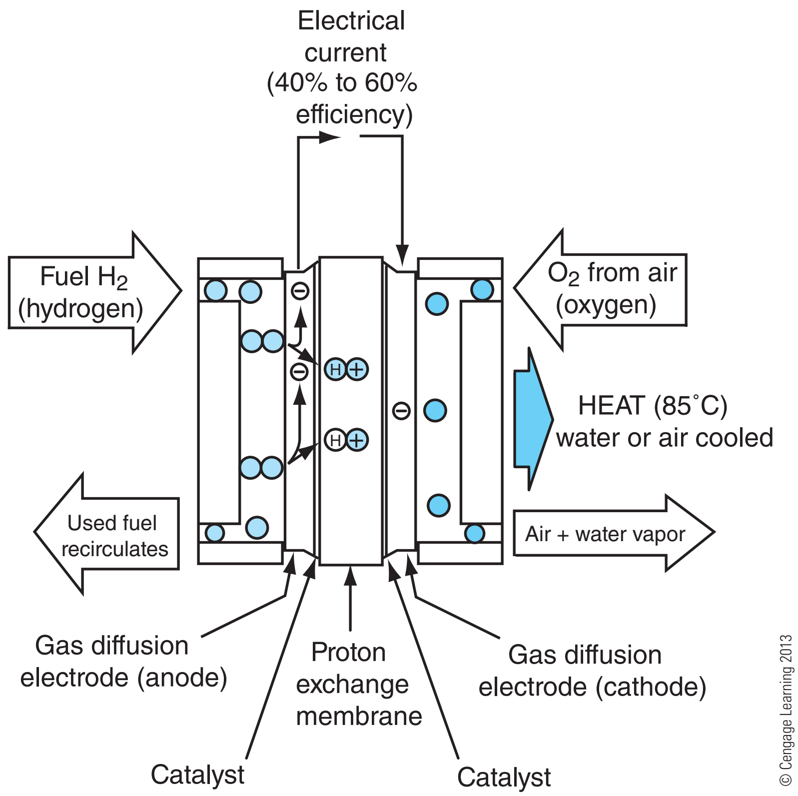

Figure 11-6 A PEM fuel cell.

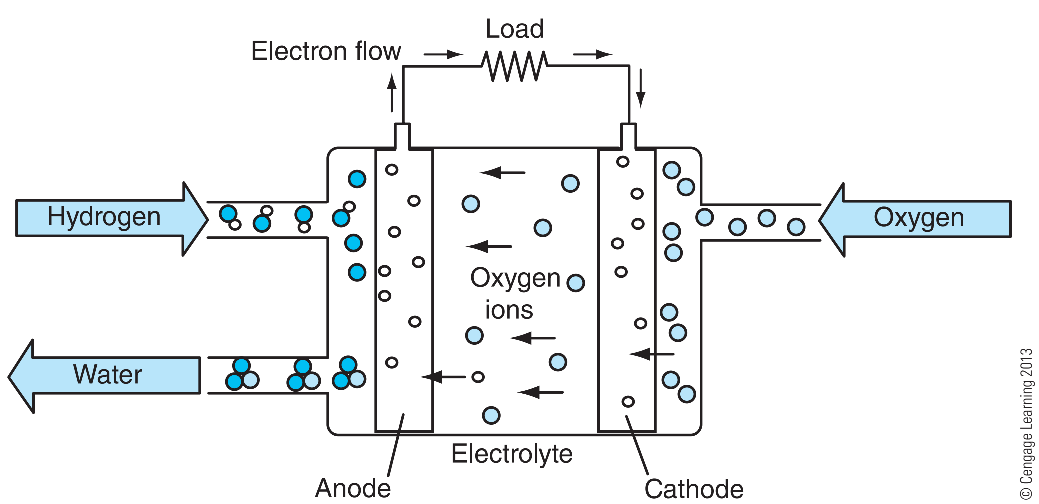

Figure 11-7 A solid oxide fuel cell (SOFC).

provide much higher power levels, which means more accessories can be electrically driven. This again will increase

will also allow accessories to operate when the engine is not running and without draining the battery. In addition, the heat generated by the cell can be used to heat the passenger compartment.

These cells have a ceramic anode, a ceramic cathode, and a solid electrolyte **(Figure 11-7).** To be efficient, these cells must operate at very high temperatures, from 1,290 to 1,830°F (700 to 1,000°C).

terials that can be used in the cells to ceramics, they also eliminate the need for expensive catalysts. Lower production cost is one of the reasons SOFCs are considered to be a likely choice to replace the alternator. These fuel cells can operate with a simple, single-stage, built-in reformer because of the high operating

temperatures. Also, the high temperatures eliminate the chances of CO poisoning the electrodes. Efficiency estimates for this type of fuel cell vary from 40 to 45 percent, as compared to 20 to 30 percent for an internal combustion engine.

The high operating temperature is also a reason these fuel cells may not be used to power a vehicle. When this high heat is generated, it must be released. Releasing a large quantity of high heat can cause many problems in other automotive systems. When such a fuel cell is used only to replace the alternator, the quantity of heat produced is far less, and it can be easily moved away from the vehicle.

Molten Carbonate. This design of fuel cell is unlikely to ever be used in an automobile; it is best suited to be a power generator to supply factories and perhaps cities. It has the ability to generate electricity from coal-based fuels or natural gas. The **molten carbonate fuel cell (MCFC)** uses a liquefied carbonate salt as its electrolyte. This fuel cell operates best at between 1,110°F (600°C) and 1,200°F (650°C). However, its output is strongly dependent on operating temperatures, as a drop of just 100°F (50°C) will reduce its output by as much as 15 percent. It also needs to recirculate carbon dioxide (CO_2), which is one of its by-products. The other end product is water. Recirculating the CO_2 and making sure all of the hydrogen fed into the cell is used are the two major issues with this design. Research is ongoing to develop a membrane that will recirculate the unused hydrogen back into the fuel intake.

The anode is typically made from a highly sintered nickel powder alloyed with chromium, and the cathode is a porous nickel oxide alloyed with lithium.

Direct Methanol. The **direct-methanol fuel cell (DMFC)** is a type of PEM fuel cell. Liquid methanol, rather than hydrogen, is the fuel oxidized at the anode, and the oxygen from the outside is reduced at the cathode. Methanol is considered an ideal hydrogen carrier because it takes little energy to cause it to release its hydrogen. A mixture of methanol and water is delivered directly into this modified PEM cell and releases the hydrogen needed by the fuel cell. This cell uses a thin membrane lightly covered on both sides with a layer of a platinum-based catalyst. A reformer is not ne
than the PEM. This is because less platinum is needed. Liquid methanol is also easier to store than hydrogen and has a much higher energy density than compressed hydrogen.

These cells are also simple and compact units that can provide a good amount of energy for a long period of time. They operate at about the same temperature as PEMs, but these cells are not as efficient as PEMs, and their response time is slower than that of a PEM. Also, they have emissions that are not present with other fuel cell designs. As the hydrogen is removed from the methanol, carbon is released. The carbon and hydrogen combine with the oxygen at the outlet of the cell to form carbon dioxide and water.

These cells use a mixture of methanol and water that is introduced to a negatively charged electrode. This electrode immediately reacts and breaks the methanol molecules apart. The carbon and oxygen atoms from the methanol combine to form CO_2. The hydrogen atoms are separated into protons and electrons. The electrons move through an external circuit and return to the cell at a positive electrode. Once in the external circuit, they combine with the protons, which arrived there by passing through the membrane. At this point water is formed and exhausted from the cell.

Phosphoric Acid. The **phosphoric acid fuel cell** is the most commonly used fuel cell in commercial applications; it can operate at 37 to 42 percent efficiency. These fuel cells use liquid phosphoric acid **(Figure 11-8)** as the electrolyte with electrodes made of carbon paper coated with a platinum catalyst. The use of platinum means they are costly to manufacture. They produce the most power when they operate at a relatively high temperature (anywhere between 300 and 400°F [150 to 205°C]). The operation of the fuel cell is much the same as others; the catalyst separates the fuel into electrons and protons. The electrons move through an

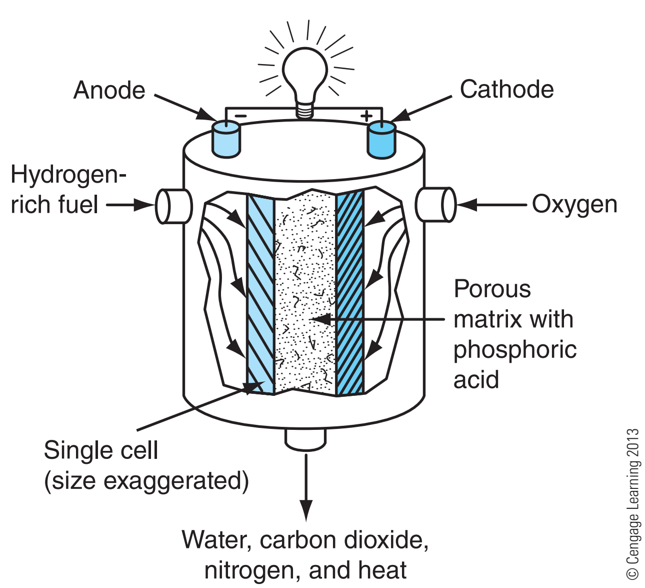

Figure 11-8 A phosphoric acid fuel cell.

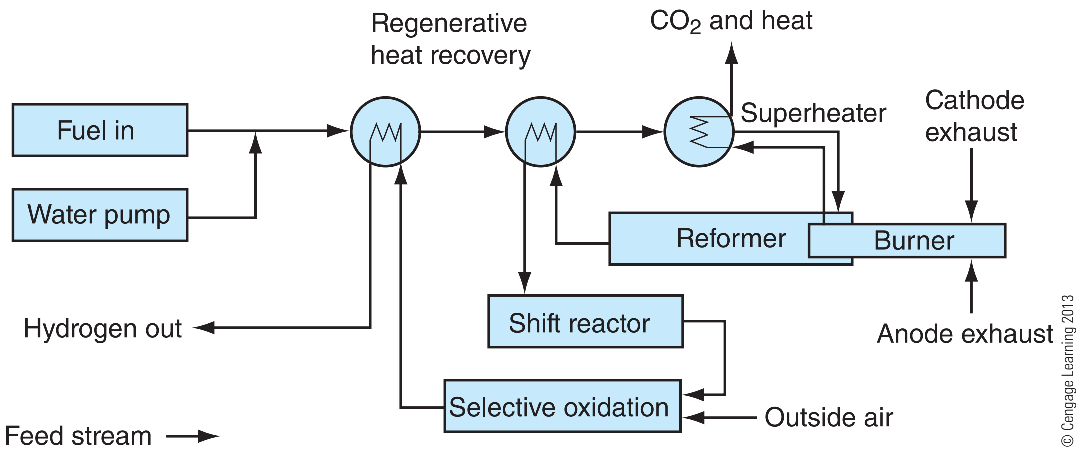

Figure 11-9 The flow diagram for converting methanol to hydrogen with a reformer.

external circuit, and the protons move to the cathode. At the cathode, the (electrons) oxygen and (protons) hydrogen ions join to form water. The water is emitted as steam, which can be used to power another electrical generating device. When this occurs, the efficiency of the fuel cell doubles. It is unlikely that this design of fuel cell will be used in an automobile because of the high temperatures, the challenges of producing varying outputs, and cost. It works fine when power output demands are constant.

Alkaline. The **alkaline fuel cell (AFC)** is the one used primarily by NASA. It is expensive, but highly efficient. In a spacecraft, the water (its exhaust) is used as drinking water for the space travelers. This fuel cell will undoubtedly never be used in automobiles because of its cost. It is also very sensitive to carbon dioxide, which means it does best where all CO_2 can be removed from the incoming supply of air. This fuel cell operates in the same manner as a PEM.

Alkaline fuel cells use a water-based solution of potassium hydroxide (KOH) as the electrolyte. The electrodes are coated with a catalyst, although due to the operating temperature and the purity of the incoming gases, platinum is not required.

Obstacles for Fuel Cell Vehicles

Fuel cells provide clean energy and are quite efficient, which is the main reason for considering their use
will be used on any large scale, certain obstacles must be overcome. The lack of a hydrogen infrastructure is one of the biggest obstacles. This is an obstacle of practicality and consumer acceptance, not of engineering. In order for a fuel cell vehicle to be practical, its fuel must be readily available.

Another problem related to fuel supply is storage. To be practical, any vehicle must have a decent driving range, one of at least 300 miles (483 km). To accomplish this, fuel cell vehicles must be able to store a lot of hydrogen. Many different methods of storage are being researched. Storing hydrogen in pressure tanks may be the answer; however, high pressures are required, and high-pressure tanks are very expensive. The typical fuel cell vehicle stores hydrogen at 5,000 psi (352 kg/cm) and has a driving range of about 150 miles (241 km). Doubling the pressure would nearly double the driving range. To double the pressure, stronger tanks are required, which adds to the cost of the tanks. Hydrogen storage is a major area for research and will be discussed in more detail later in this chapter.

Some FCEVs have on-board reformers **(Figure 11-9)** that extract hydrogen from gasoline, ethanol, or methanol. Storing these fuels requires less space and is much simpler than storing pure hydrogen. The objections to using a reformer are plentiful. A reformer has undesirable emissions, such as carbon dioxide. Using reformers does not reduce our dependence on fossil fuels. Reformers **(Figure 11-10)** are expensive,

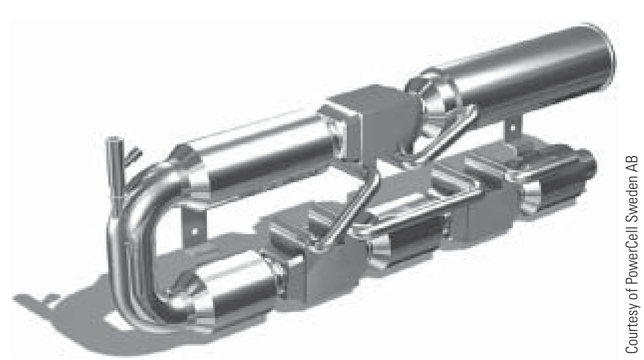

Figure 11-10 An example of a reformer.

slow, and require long run times before they can provide enough hydrogen to move a vehicle a few feet.

The cost of a fuel cell and its supporting systems is extremely high. It is estimated that the cost of one fuel cell vehicle is $1 million. Obviously, as more FCEVs are built, the cost will come down. Also, the advances made with hybrid vehicles that can be shared with FCEVs will also lower future costs. As it stands right now, very few consumers could afford to purchase a fuel cell vehicle. To gain public acceptance, the cost must be drastically reduced.

An issue that may seem to be an odd concern is noise. FCEVs are too quiet—so quiet that there are safety concerns. If the vehicles can be seen but not heard, their approach to the rear of pedestrians and bicyclists can present dangerous situations. This is an area that must be studied.

To control the output of a fuel cell and therefore the speed of the vehicle, advanced electronics are necessary. Much of this technology is already used in hybrid vehicles, but the uniqueness of the fuel cell demands additional new controls. FCEVs have high- and low-voltage systems, and electronic controls are necessary to allow the fuel cell to power both. These controls are in addition to the typical computer systems of other vehicle types. The traction motors used in a FCEV must be very efficient and able to respond to changing driving conditions. Hybrid motor technology is an area of constant study, and that technology can be shared with FCEVs.

Most fuel cells take some time to start, especially when they are cold. As mentioned before, freezing temperatures can kill a fuel cell. Frozen electrolyte or ice on the membrane can destroy it or at least stop the fuel cell from working. An exhaust system plugged with ice will shut down a fuel cell. This is an area of much research, and some manufacturers have had some success dealing with the problem. The basic thrust has been making sure all water is removed from the fuel cell after it has been shut down. This requires energy from a storage device. There is also research being done on mixing special coolants in the water. The fact that a fuel cell does not generate electricity until it has a temperature of 32°F (0°C) is an obstacle that needs to be overcome.

On the other side of the temperature scale, heat must be carefully controlled. Fuel cells become very hot while they operate, and they operate best within a particular temperature range. That range depends on the type of fuel cell. PEM cells operate best at a lower temperature than conventional ICEs. This presents a major challenge as it is more difficult to get rid of low heat than it is high heat. This means the cooling system must be more efficient than those used in conventional vehicles. Typically a PEM cell requires larger and/or more radiators. This means more space is needed in the vehicle just for the cooling system. This results in less useable space for passengers and luggage. When the space for the cooling system is added to required space for the fuel cell stack and other components, very careful planning of space is necessary **(Figure 11-11).** This becomes more of a challenge when one considers that the electronics and traction motors must also be kept cool. The cooling of these requires an additional

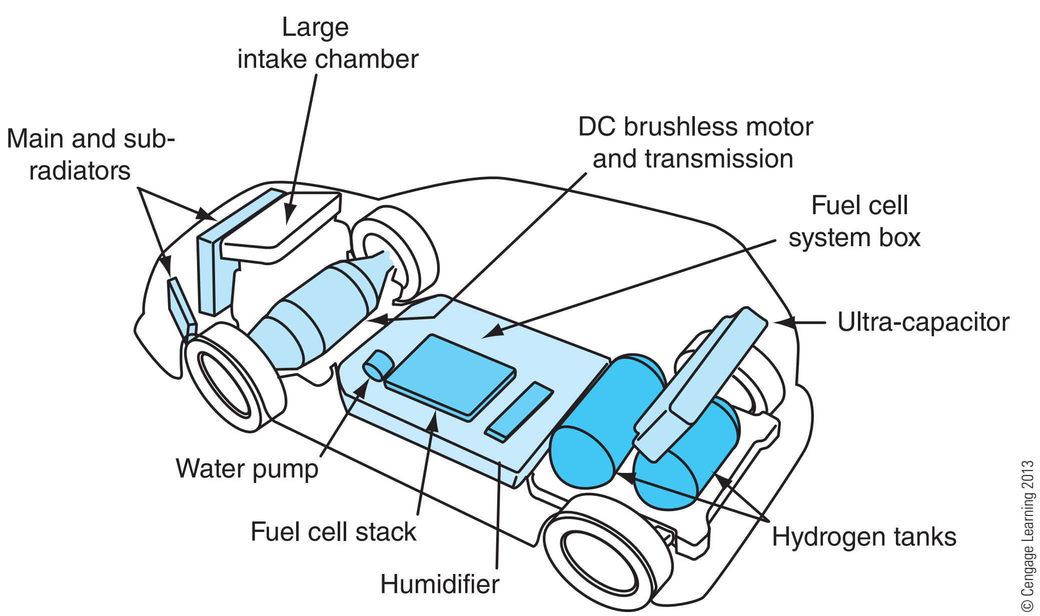

Figure 11-11 The layout of the components for the fuel cell system in a Honda FCX.

cooling system because they operate at a different temperature range than the fuel stack. An additional cooling problem enters when the vehicle is equipped with a high-voltage battery pack and/or ultracapacitors.

An obstacle that pertains to other fuel cell designs is the isolation of the extremely high temperatures of the fuel cell. For example, the solid oxide fuel cell operates at temperatures from 1,290 to 1,830°F (700 to 1,000°C). If this heat is not totally insulated from the passenger compartment, it could bake everyone and everything inside the vehicle.

Another heat-related problem is generated by the air compressor that feeds outside air into the fuel cell. As air is compressed, its temperature increases. The fuel cell works best within a specific temperature range, and the compressed air can heat up the cell beyond that range. To eliminate this, intercoolers must be added to the air compressor system. These, again, occupy space. There is also the problem of filtering the incoming air. Ideally, the incoming air would be free of all dirt and other contaminants. A filtering system occupies space and has an impact on the overall layout and design of the vehicle.

HYDROGEN

Hydrogen is full of energy because of its atomic structure. It has been used as a fuel for spacecraft and electrical generators. It is also used to manufacture reformulated gasoline, ammonia for fertilizer, and many different food products. And in the future, hydrogen may be the fuel for personal transportation. The automotive industry has long used the energy released by separating hydrogen from a substance and recombining it with oxygen. In a gasoline ICE, gasoline (a hydrocarbon) is forced, by heat, to combine with oxygen. The result is combustion, which releases energy. That energy is used as mechanical energy. In a fuel cell, the same basic thing happens, but the chemical energy is released as electrical energy.

What Is Hydrogen?

Hydrogen is the simplest and lightest of all elements.
(Figure 11-12). Hydrogen is a colorless and odorless gas. It is one of the most abundant elements on earth. However, it is only found in compound form. The combination of hydrogen and oxygen forms water. Fossil fuels are combinations of carbon and hydrogen, which is why they are called hydrocarbons.

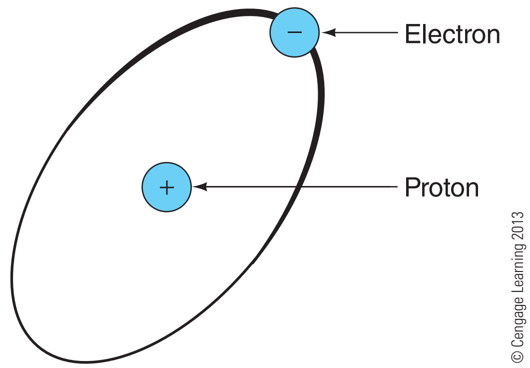

Figure 11-12 A hydrogen atom.

Sources of Hydrogen

Hydrogen is extracted from various substances through a process that pulls hydrogen out of its bond with another element or elements. Hydrogen is commonly extracted from water, fossil fuels, coal, and biomass. The two most common ways hydrogen is produced are steam reforming and electrolysis. Although FCEVs are considered zero-emission vehicles, there are some related emissions due to the production process. Hydrogen production is commonly done, but it is very costly. Currently it costs much more to produce hydrogen than it does to produce other fuels, such as gasoline. This, again, is an obstacle and the focus of much research.

Steam reforming is the most common method used to produce hydrogen. This process uses high-temperature steam to extract hydrogen from natural gas or methane **(Figure 11-13).** Methane is the simplest of all hydrocarbons and is readily available. Methane is the primary component of natural gas, which is found in oil fields, natural gas fields, and coal beds. This method is used to produce about 95 percent of the hydrogen that is available today. Steam reforming is currently the most cost-effective way to produce hydrogen. However, it relies on fossil fuels to create the steam and uses a fossil fuel as the source for hydrogen. Therefore, it does not reduce our dependence on fossil fuels, and it releases emissions during the process.

A cleaner, but more costly, method for producing hydrogen is electrolysis. In this process, electrical

rates into hydrogen and oxygen. The hydrogen atoms collect at a negatively charged cathode and the oxygen atoms collect at the positively charged anode. Producing hydrogen by electrolysis costs approximately 10 times more than using steam reforming. However, the process does result in pure hydrogen and oxygen.

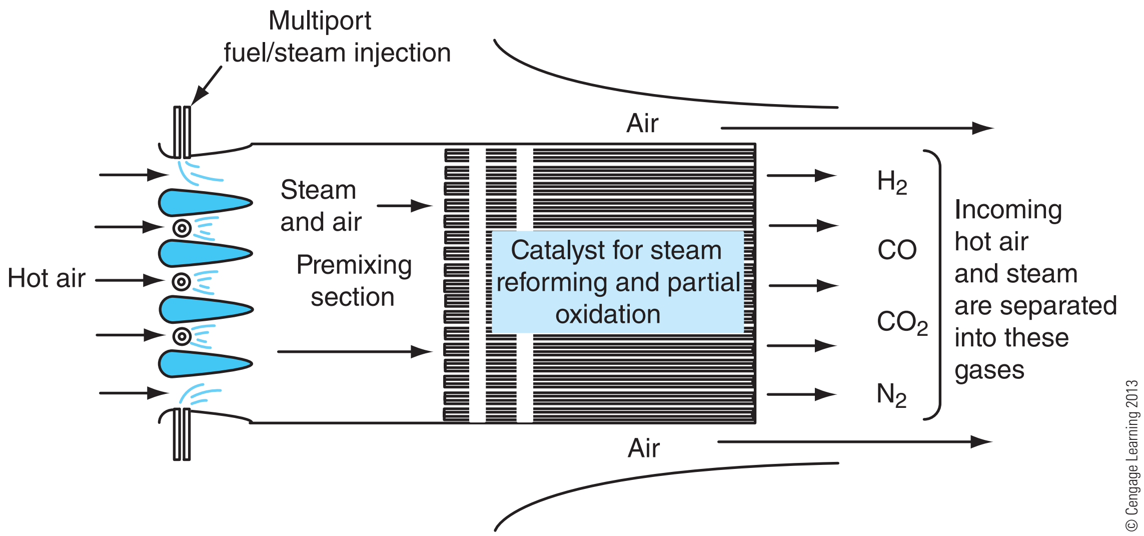

Figure 11-13 Basic view of how a steam reformer produces hydrogen.

The use of solar energy to separate the atoms in water is being heavily researched. Water is a renewable resource, and light from the sun is readily available. Basically, the sun's light is collected at photovoltaic cells and converted to electricity. That electrical energy is then passed through the water to begin electrolysis. This process is called **photo electrolysis**. Another photolytic process is also being researched. **Photo biological methods** rely on the activities of some algae and bacteria that produce hydrogen when exposed to light **(Figure 11-14).**

Biomass (plants or agricultural waste) may provide an economical alternative to fossil fuel–based hydrogen production. By gasifying or burning biomass with high heat, we can separate the biomass into hydrogen and other gases. Biomass can also be used to provide the heat to cause the separation. This means the process uses no fossil fuels.

Some concept FCEVs rely on reformers that extract hydrogen from a fossil fuel directly on the vehicle. Three fuels are commonly used: gasoline, methanol, and natural gas. Reformers make the vehicle more practical because the fuel supply is easily replenished. However, reformers have some emissions issues, are costly, and consume valuable vehicle space. There is also an issue of the purity of the fuels that will be reformed. Many of these fuels have a substantial amount of sulfur. The sulfur can contaminate the catalysts used in the fuel cell and may not be totally filtered out of the hydrogen during the reforming process.

Hydrogen Fuel for ICEs

There is a lot of energy available in hydrogen. Some automobile manufacturers are experimenting

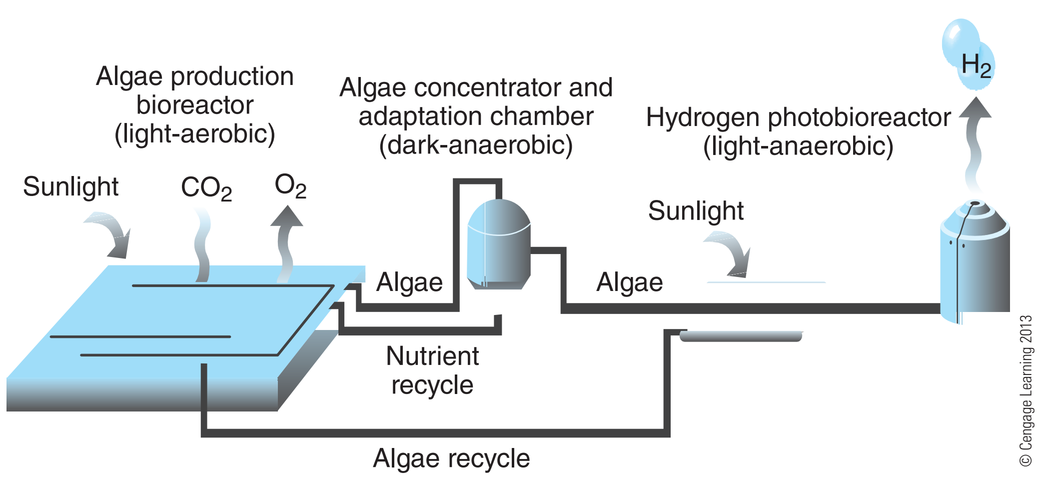

Figure 11-14 The principle of photo-biological hydrogen production.

with fueling internal combustion engines with pure hydrogen. Research is also being done with adding hydrogen to other fuels. In both of these cases, exhaust emissions are reduced without a great decrease in power output; in some cases, the power has actually increased. The basic engine needs few modifications to use hydrogen, which means switching to this fuel would not be costly. In addition to these benefits, hydrogen-fueled ICEs may be the impetus for building a solid infrastructure for dispersing hydrogen as a fuel.

Three major auto manufacturers have developed and tested hydrogen-fueled internal combustion engines. These vehicles actually have bi-fuel capabilities. Of particular interest is BMW's bi-fueled V12 engine, which uses liquefied hydrogen or gasoline as its fuel **(Figure 11-15).** When running on hydrogen, the engine has zero carbon dioxide emissions. To prove the feasibility of the engine, BMW took a specially equipped car out to its high-speed test track in Miramas, France. There the car set nine international speed records for hydrogen-driven vehicles. To store the liquefied hydrogen, the storage tank is kept at a constant temperature of –423°F (–253°C). At this temperature, the liquid hydrogen has the highest possible energy density.

Ford and Mazda have also developed vehicles with hydrogen power. Mazda has experimentally used it in its rotary engine, claiming the design is ideal for using hydrogen. The concept vehicles from both manufacturers are also bi-fuel vehicles. One of the engines converted by Ford is its 2.3L, I-4 engine. Engine modifications include a higher compression ratio, special fuel injectors, and a modified electronic control system. When running on hydrogen, the engine is more than 10 percent more efficient than when it runs on gasoline. Another benefit is emissions levels that are near zero.

Photo courtesy of BMW of North America, LLC

Figure 11-15 BMW's hydrogen powered V12 ICE.

Because the fuel contains no carbon, there are no carbon-related emissions (CO, HC, or CO_2). Typically, an engine running on hydrogen produces less power than a same-sized gasoline-powered engine. So Ford added a supercharger with an intercooler to the engine to compensate for the loss of power.

Infrastructure and Storage

Other than manufacturing costs, the biggest challenge for hydrogen-powered vehicles, whether with a fuel cell or an engine, is the lack of an infrastructure. These vehicles need to be able to be refueled quickly and conveniently. The use of reformers may be the short-term answer to this problem. However, reformers add more weight and technical complexity to a vehicle. Also, the reformed hydrogen is not free of contaminants. Some of what could be in the hydrogen may poison the fuel cell and cause it to underperform.

Honda is developing a home energy station that extracts hydrogen from natural gas. These stations will allow owners of hydrogen-powered vehicles to refill their tanks at home **(Figure 11-16).** The stations are also capable of supplying electricity, hot water, and heat for the home. The stations use electrolysis to extract the hydrogen and solar energy as the source for electrical current.

In-Vehicle Storage

Hydrogen contains more energy per unit of weight than any other fuel, but it contains much less energy by volume. This makes storing enough hydrogen for an acceptable driving range very difficult. Naturally, you can store more in a larger container, but that container would consume more space and add considerable weight to the vehicle. In-vehicle hydrogen storage is another area of much attention for researchers and engineers.

In most concept FCEVs, hydrogen is stored either as a liquid or as a compressed gas **(Figure 11-17).** When stored as a liquid, hydrogen must be kept very cold. Keeping it that cold adds weight and complexity to the storage system. At cryogenic (icy cold) temperatures, more hydrogen can be stored in a given space. Cryo-

Shuttle. However, liquid storage has some safety issues that are not present with compressed hydrogen storage. The tanks required for compressed hydrogen need to be very strong, which translates to very heavy and very expensive to manufacture **(Figure 11-18).** Also, higher pressures mean more hydrogen can be packed into the

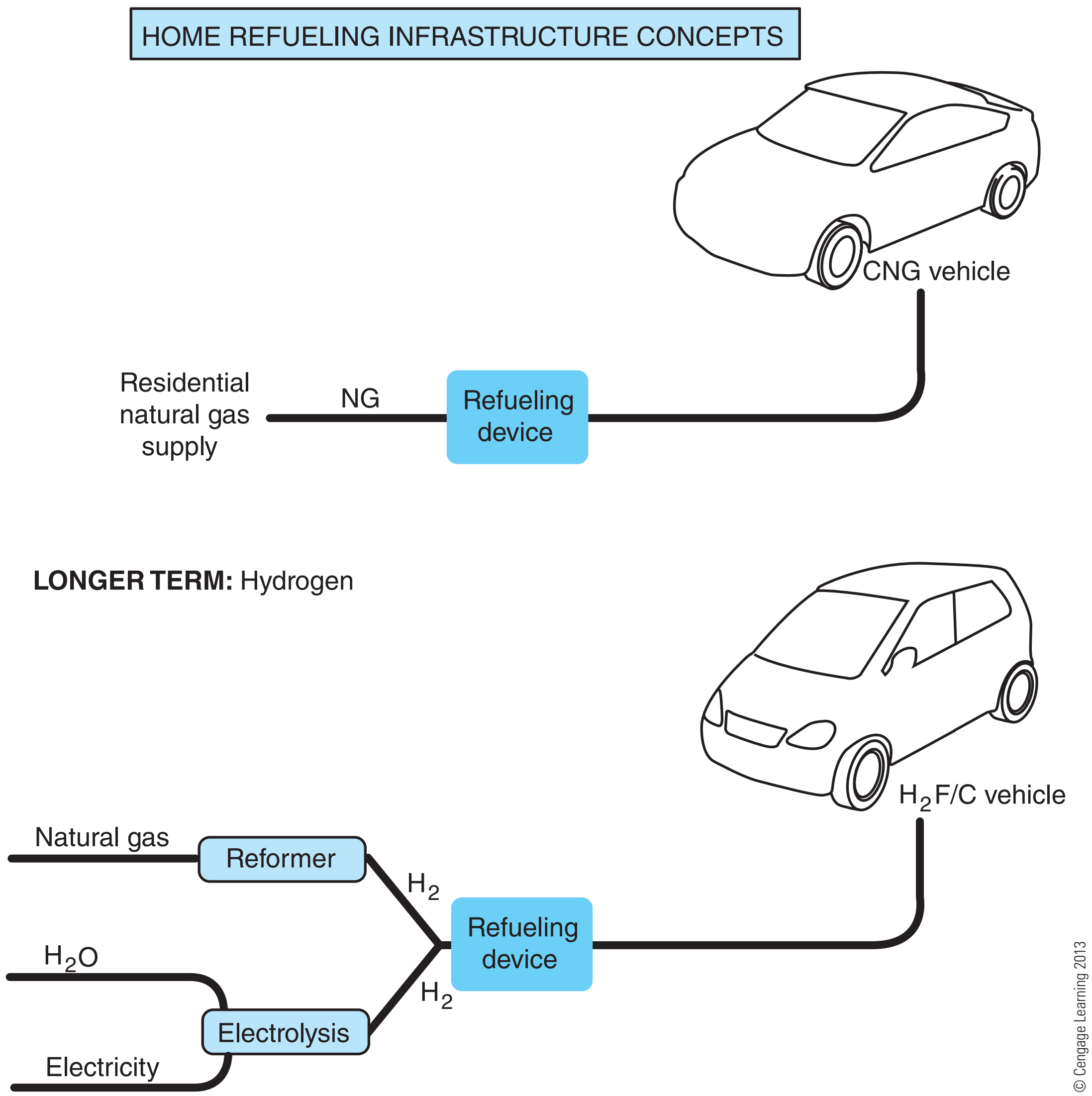

Figure 11-16 Creating a home-based hydrogen-refueling center.

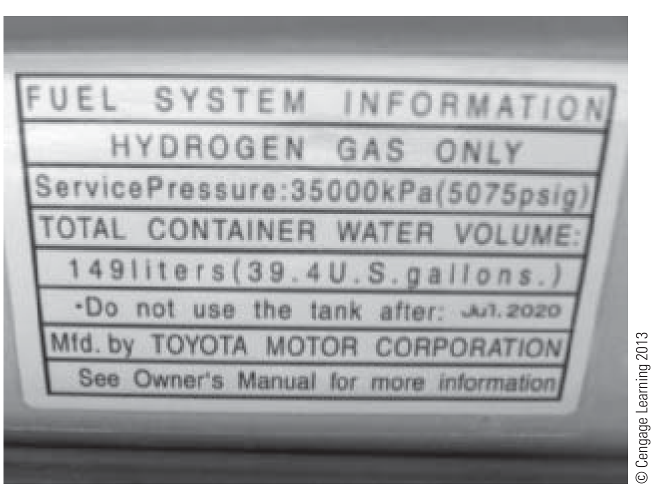

Figure 11-17 This sticker defines the amount and form of the stored hydrogen fuel.

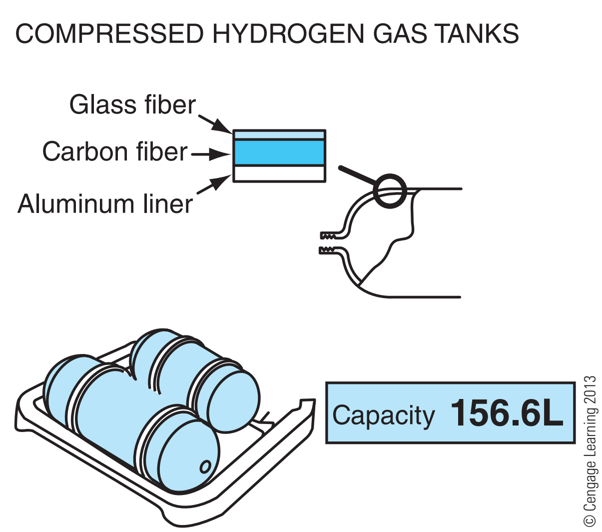

Figure 11-18 In-vehicle storage tanks for compressed hydrogen.

tank, but the tank must be made stronger before the pressure can be increased.

Other storage technologies are being developed. Two of these technologies getting the most attention are systems based on metal hydrides and carbon nanotubes. The use of metal hydrides offers the possibility of storing three times more hydrogen in a given volume than when it is compressed. The metal hydrides, normally powdered magnesium–based alloys, collect hydrogen atoms and hold them at low temperatures. When the metal hydrides are heated, the hydrogen is released until heat is removed from the metal. Carbon nanotubes are microscopic tubes of carbon that can store hydrogen in their pores. Because the surface of these tubes is quite irregular, the actual surface area is larger than the size of the tubes. The use of metal hydrides and carbon nanotubes may help solve the hydrogen storage problem for the future.

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Figure 11-19 The sticker says this vehicle is a fuel cell hybrid vehicle and defines the purpose of the major components.

PROTOTYPE FCEVs

Fuel cell vehicles for everyday use are still years away; however, there are many fuel cell prototypes and concept vehicles on the road all over the world **(Figure 11-19).** All of these are part of the ongoing research that is taking place. Every major manufacturer has built at least one type of FCEV, and many have developed a new model nearly every year. These vehicles are testing different technologies in a real-world setting. It is difficult to predict exactly how a mass-produced FCEV will be equipped, but it is certain that some of the technology used in today's prototypes will be part of that final design. In addition, much of what was learned from the experiences of EVs and HEVs will also be part of the future FCEV.

There are three basic configurations that describe the design of an FCEV powertrain **(Figure 11-20).** The powertrain of a basic fuel cell vehicle is referred to as the direct-supply system. With this design, the energy from the fuel cell is delivered directly to the electric traction motor(s). Vehicles with this configuration do not have regenerative braking, and propulsion power depends entirely on the output of the fuel cell.

In a battery hybrid powertrain system, the energy from the fuel cell is sent to the motor(s), the battery

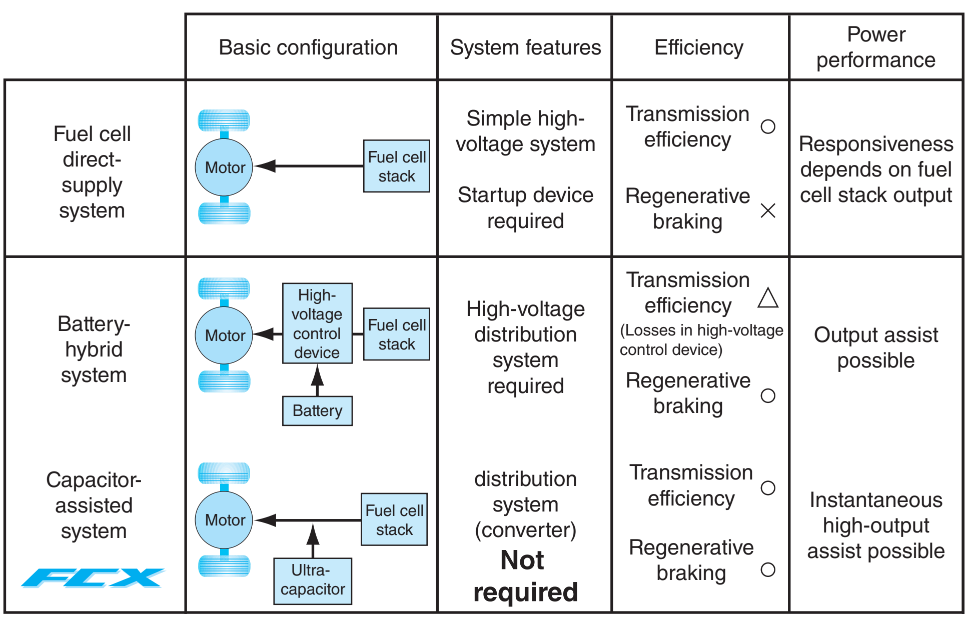

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Figure 11-20 Honda's view of the different powertrain configurations for FCEVs.

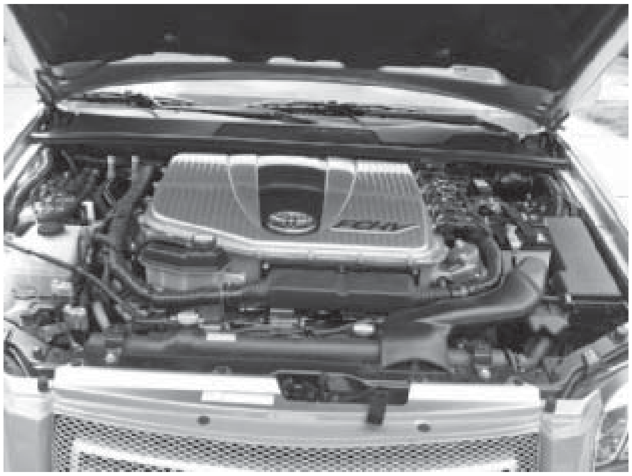

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Figure 11-21 The fuel cell and related electronic parts consume all of the space under the hood of this vehicle.

pack, or both. This configuration can use regenerative braking. The battery can also supplement the fuel cell's energy to improve performance. This system requires more electronic controls than the direct-supply system **(Figure 11-21).**

The third configuration uses ultra-capacitors rather than a battery. The ultra-capacitors are charged by the fuel cell and regenerative braking. Ultra-capacitors charge and discharge quickly, which allows the powertrain to respond quickly to changing conditions. Complex electronic systems are also required for this type of system.

Fuel supply is also a factor in the design of an FCEV. Storage tanks and reformers take up space and are costly. It is the ability to feed a fuel cell for a long time that increases the vehicle's driving range. There are also variations in the electric traction motors used in the prototypes. Some use a motor from an EV or HEV, whereas others have motors located at the wheels. Some have a combination of both.

All FCEVs have a low-voltage system to energize and operate lights, accessories, and the various control modules. This means that all FCEVs need a DC/DC converter to reduce the high voltage from the fuel cell. In addition, because a fuel cell generates DC voltage, an inverter is not needed unless the traction motors and the accessories require AC voltage.

To
vehicles, examples will be presented of some of the vehicles from some manufacturers. The examples are just a sampling of what has been developed. Many of the manufacturers that are working on fuel cell vehicles are also developing hybrid vehicles and other alternatives that will reduce our dependence on fossil fuels.

Daimler

Daimler started developing fuel cell vehicles in 1994 and has produced well over 100 vehicles for testing purposes. These vehicles include cars, buses, and vans. Their vehicles were part of the NECAR (New Electric Car) and NEBUS (New Electric Bus) initiatives. Its FCEVs are on the roads in the United States, Europe, China, Australia, Japan, and Singapore. At each location, feasibility studies are being made while the vehicles are being used in varying driving and climate conditions.

Through continuous research, Daimler has been able to extend driving range, minimize the space required for the fuel cell components, and improve cold weather starting and operation. To minimize the space requirements, engineers have fit the entire fuel cell drive system into the floor. Doing this allowed them to convert a small car, the Mercedes-Benz A-class, and small SUVs into FCEVs and still have room for passengers and luggage **(Figure 11-22).**

A current prototype is a Mercedes B-class F-Cell that has a 136-HP (100-kW) electric motor. This is a hybrid vehicle; it uses battery power to start the vehicle and to assist the fuel cell in delivering power to the electric motors during acceleration. The battery pack is recharged by the fuel cell and by regenerative braking. The hydrogen is stored at 10,000 psi, and the car has a driving range of about 280 miles.

General Motors Corporation

General Motors has made a huge commitment to the development of FCEVs. In fact, it had a stated goal to design and validate a fuel cell propulsion system by 2010, one that would be competitive with current

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Figure 11-22 Mercedes-Benz A-class F-Cell passenger cars, like the one seen here, are being operated by customers in Singapore, Japan, Germany, and the United States.

vehicles with regard to cost, reliability, and performance. This goal was not accomplished, as it was held back by GM's bankruptcy and other financial problems. However, progress has continued, as is evident by some of GM's latest prototypes.

GM's venture into fuel cell technology began in 1997 with the introduction of a fuel cell–powered Opel Sintra. This is a European-only minivan. The fuel cell Sintra was followed up, in 1998, by a fuel cell–powered Zafira, which was the replacement vehicle for the Sintra. This model vehicle was the initial test bed for early GM fuel cell vehicles. The first Zafira FCEV used a methanol reformer and a Ballard fuel cell. It had a decent driving range of 300 miles (483 km). This original FCEV, and the Zafira, served as the basis for three generations of what GM called its HydroGen series. Each generation used a GM-developed PEM fuel cell. The HydroGen1 and 3 (there was no true HydroGen2) relied on liquid cryogenic hydrogen and had a range of 250 miles (400 km). The HydroGen1 was based on the battery hybrid configuration, whereas the HydroGen3 was direct supply. The advanced HydroGen3 was also based on the direct-supply configuration (sent to testing one year after the original HydroGen3), which relied on high-pressure (10,000 psi [703 kg/cm]) hydrogen storage. Its range was lower than that of the previous generations, but it used less fuel overall.

Using what it learned from the HydroGen series, GM tested a fuel-cell-powered Chevrolet S-10 pickup in 2001, which combined several of the technologies used previously. This S-10 pickup had a low-power fuel cell from GM and used the battery hybrid configuration. It also had a gasoline reformer to supply the required hydrogen. The driving range for this truck was 240 miles (386 km). Due to the low output from the fuel cell, the vehicle had a lower top speed and milder acceleration than previous GM FCEVs.

After these experiments, GM worked to minimize the required space and increase fuel economy. In 2002, it introduced its "skateboard" concept **(Figure 11-23).** In this design, all of the fuel cell–related components are packed into a carbon fiber structure that also serves as the chassis for the vehicle. The first such vehicles were the AUTOnomy and the Hy-wire. These vehicles featured many futuristic concepts, including total drive-by-wire systems. The concept was based on the idea of developing a propelled chassis that any body style or configuration could be placed upon.

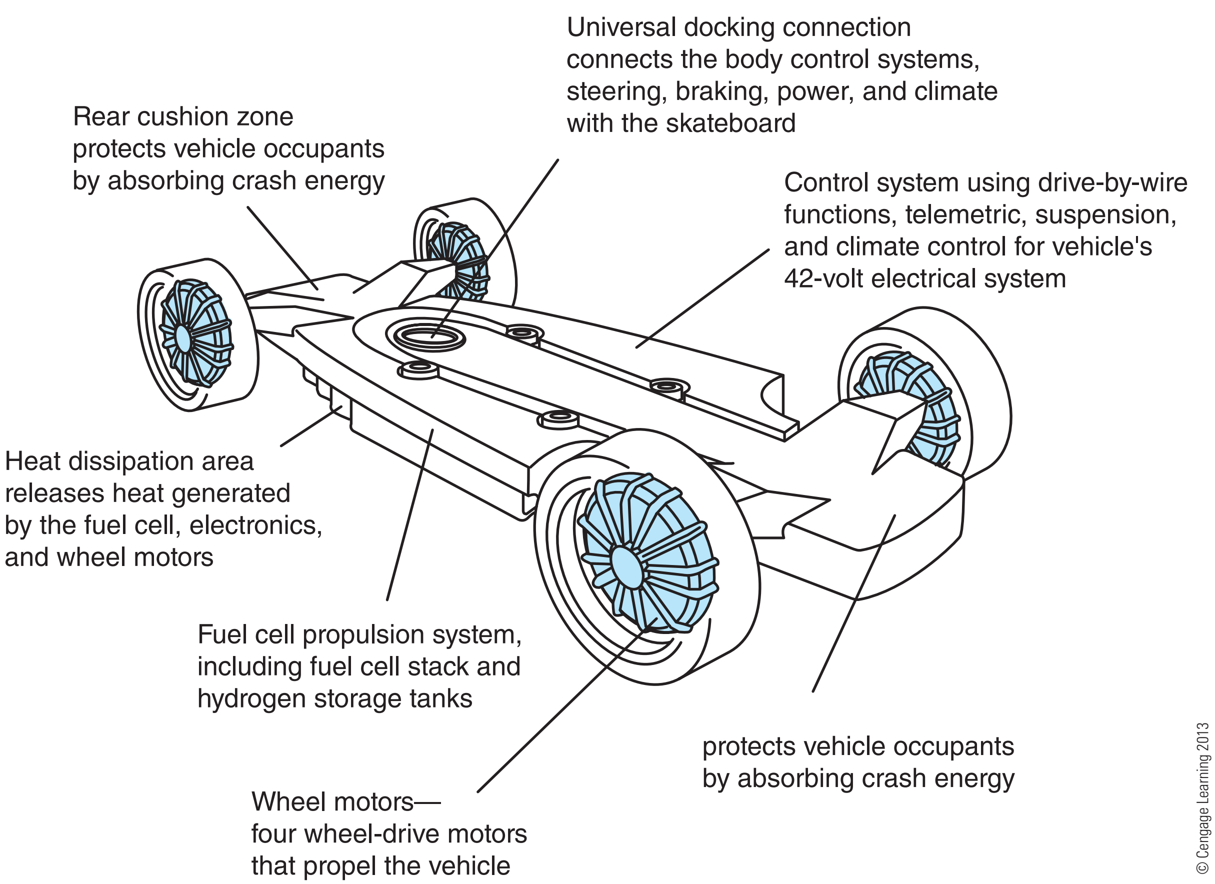

Figure 11-23 The basic layout of General Motors' skateboard chassis.

The recent concept GM fuel cell vehicle is the Sequel. The Sequel uses the technologies that worked well in the AUTOnomy, Hy-wire, and the advanced HydroGen3. This battery hybrid fuel cell vehicle uses a lithium-ion battery to provide extra electrical energy to the three electric motors during acceleration and to capture energy during braking. A transverse-mounted, three-phase AC motor drives the front wheels, and 2 three-phase AC wheel hub motors drive the rear wheels. There is a separate inverter for each motor. The electrical system includes three separate systems with three different voltages. A high-voltage system provides energy for the traction motors; the 42-volt system supplies energy for the brakes, steering, air conditioning, and other by-wire systems; and the 12-volt system is used for the conventional accessories and lights.

The fuel cell stack, hydrogen and air processing subsystems, high-voltage distribution system, and hydrogen storage tanks are housed in the skateboard. The storage tanks are designed to hold compressed hydrogen at 10,000 psi (703 kg/cm).

Recently, GM unveiled a fuel-cell-powered version of its Chevrolet Volt. In this concept car, the generator was replaced by a fuel cell. To accommodate the hydrogen storage tanks, the battery pack was made half of its original size. It also uses a more advanced fuel cell design, and the vehicle is lighter. The lithium-ion battery pack can be recharged by plugging it in, by the fuel cell, or through regenerative braking.

When the car is first started, it is powered by the fuel cell. When more power is needed, the battery pack provides additional energy to the traction motor. When the battery is not operating the motor, it is being recharged.

Toyota

Much of what Toyota has learned with its hybrids is transferable to its fuel cell vehicles. In fact, many of the same components can be transferred as well. Toyota's first FCEV, the RAV 4 FCEV, used a Toyota-developed PEM fuel cell and was configured as a battery hybrid FCEV. There were two generations of the RAV 4 FCEV; the first stored the hydrogen in metal hydrides, and the second had a methanol reformer. The
310 miles (500 km).

As Toyota continued to make advancements in hybrid technology, it applied the technology to new fuel cell prototypes and concept vehicles. To take a quick look at how hybrid technology and components are used in a fuel cell vehicle, consider the latest

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Figure 11-24 A Toyota FCHV.

FCHV (Toyota Fuel Cell Hybrid Vehicle), which is based on the Highlander **(Figure 11-24).**

The vehicle is a battery hybrid FCEV and is propelled by 109-HP (80-kW) electric motors. The compressed fuel is stored in four hydrogen fuel tanks at 10,000 psi (700 kg/cm). The vehicle uses the same nickel-metal hydride 21-kW battery pack as the Prius, including all of the associated electronics. The FCHV has a driving range of about 500 miles.

A power control unit is in the engine compartment and is a slightly modified version of that used in the Prius. It monitors the current operating conditions and determines when to use the battery, fuel cell, or both to propel the vehicle and to charge the battery. This is the same strategy used in hybrid vehicles. However, in the FCEV the fuel cell and its output replace the engine.

Honda

Honda, the other major manufacturer of hybrid vehicles, also has been busy with fuel cell vehicle research. Unlike Toyotas, the hybrid system used in Hondas does not easily adapt to an FCEV. However, many of the controls and features do transfer rather nicely. Plus, Honda has much experience with battery electric vehicles and DC brushless motors. Honda started its venture into fuel cell vehicles in 1989 and has been road-testing vehicles since 1999, when it introduced the FCX. Through the years, Honda has had four versions of this original model, the FCX-V1, V2,

continued with new models, but those are referred to as the FCX.

The original two versions were released in the same year and were quite different from each other. V1 was a battery hybrid fuel cell vehicle that used a Ballard Mark 700 series PEM fuel cell. Hydrogen was stored

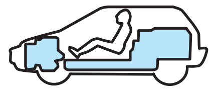
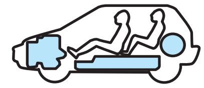
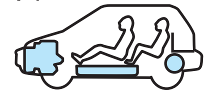
	V1 	V2 	V3 	V4 
Fuel	Pure hydrogen	Methanol	Pure hydrogen	Pure hydrogen
Energy storage	Metal hydride	Reformer	Compressed hydrogen gas (25 MPa)	Compressed hydrogen gas (35 MPa)
Motor power	49 kW	49 kW	60 kW	60 kW
Fuel cell stack	Ballard	Honda original	Honda original and Ballard	Ballard
Passengers	2	2	4	4 plus trunk

Figure 11-25 A comparison of the original FCX series from Honda.

in metal hydride. V2 was a direct-supply FCEV and used a Honda-developed PEM fuel cell with a methanol reformer. These two versions were developed to test the two different configurations and storage systems. What Honda learned from these two was then applied to V3, which is the basis for all subsequent fuel cell prototypes.

The FCX-V3 was equipped with a conglomeration of components from other Honda vehicles. It used the basic body and chassis from the EV-Plus, including its electric motor, transmission, and braking system. It was fitted with a modified version of Honda's hybrid electronic control system. To store the hydrogen, the V3 was fitted with high-pressure tanks used in Honda's natural gas–powered Civic. Some components are unique to the FCX and have since been used in other models. One of the components unique to the FCX is an ultra-capacitor, which replaces the battery that was used in the V1. The benefits of using an ultra-capacitor are many, but the major benefits are the instantaneous response times for discharge and charge and a capacitor's ability to directly feed a DC motor without regulation or inverter. Both an inverter and a voltage regulator consume electrical energy, and eliminating them increases driving range.

A Ballard Mark 700 series fuel cell was used with the

performance and to capture energy from regenerative braking. Hydrogen was stored at 3,600 psi (253 kg/cm).

A year later in 2001, the FCX-V4 was introduced. This was an ultra-capacitor hybrid. It used a Ballard Mark 900 series fuel cell and stored hydrogen at 5,000 psi (352 kg/cm). This resulted in an improvement in driving range: it could travel 185 miles (300 km) on a tank of fuel.

In 2002, the FCX was displayed. It was based entirely on the FCX-V4. However, it had several improvements, enough to increase the driving range by nearly 40 miles (64 km). This extended range was largely due to increased storage space for the compressed hydrogen. There were also other refinements that brought about the increase in range, as well as an increase in top speed and acceleration. The FCX became the first fuel cell vehicle certified by the Environmental Protection Agency (EPA), and during this certification the FCX was rated at the equivalent of 52 mpg on the highway and 49 mpg in the city.

As the FCX evolved, the biggest changes, until 2012, were in the overall packaging of the fuel cell system. In 2003, Honda consolidated all components of the fuel cell system into the chassis **(Figure 11-26)** and developed several editions based on that. All designs used an ultra-capacitor, Ballard Mark 900 series fuel cell, and compressed hydrogen storage. The fuel cell system box, as it sits in the chassis, contains the fuel cell stack, humidifier units, a water pump, and many electronic components. Because the PEM fuel cell needs to run at relatively low temperatures, the vehicles are fitted with three separate radiators. The

trols are under the hood. The assembly of ultra-capacitors is behind the rear seat. All of these packaging changes make the FCX a more practical automobile.

In 2007, Honda announced that it would begin production of its next-generation FCX within three to four years, and it is currently available for lease.

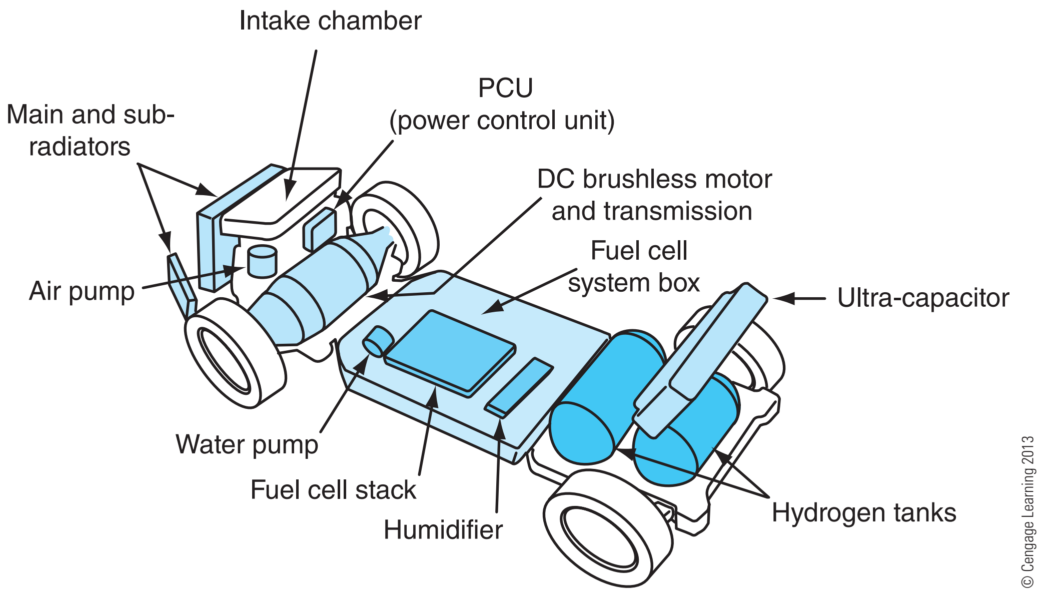


Figure 11-26 The layout of the fuel cell powertrain in a late-model Honda FCX.

Figure 11-27 A Honda Clarity, which is an FCEV.

This vehicle, called the Clarity, is not for sale but can be leased for three years to those who are interested.

The Honda FCX Clarity **(Figure 11-27)** is powered by a 100-kW V-Flow fuel cell stack, a lithium-ion battery pack, and a 95-kW electric motor, and it has a 5,000 psi compressed hydrogen gas storage tank that yields a range of 270 miles. Honda uses its latest design of fuel cell, one that is compact but powerful, and can operate

been developed to control water flow because this is critical to fuel cell efficiency and startup times. This new fuel cell is a PEFC (polymer electrolyte fuel cell). Oxygen and hydrogen flow from the top to the bottom of the fuel cell stack, and the fuel cells are arranged vertically to achieve efficient packaging. However, the biggest improvement to the fuel cell is that it is designed to allow gravity to get rid of the unwanted water in the system. By disposing of the water built up during operation, Honda's fuel cell is capable of starting in temperatures as low as –22°F (–30°C).

The fuel cell stack has metal separator structures that are easier to make, thereby reducing overall costs. Costs are further reduced by the use of an aromatic electrolyte membrane that also increases the fuel cell's efficiency through a broad range of temperatures. This new FCX uses Honda's ultra-capacitor and three separate electric motors. One motor drives the front wheels, and there is one motor at each rear wheel. This arrangement minimizes the space required for the drive system. The new FCX also has a special material in its hydrogen storage tanks. This material, not described at this time, doubles the storage capability of a tank and allows the new FCX to have a range of nearly 350 miles (563 km).

These vehicles are also equipped with a satellite-linked navigation system that displays the locations for all existing hydrogen-fueling stations within its database.

Others

developing fuel cell and/or hybrid vehicles. It is impractical to describe or list all of the prototypes they have developed, or are in the process of developing. The following is simply a description of where some of them have focused their attention and what they have introduced.

Figure 11-28 A Ford Focus FCV.

Figure 11-29 A Hyundai "Blue" concept car.

Audi. Audi has developed the Q5 HFC (Hybrid Fuel Cell) concept vehicle. Its PEM fuel cell can provide up to 133 horsepower on its hydrogen stored in two high-pressure cylinders at 10,000 psi. The SUV is fitted with two 60-HP electric motors located near the drive wheels. This is a hybrid FCEV, and its storage battery is a 1.3-kWh lithium-ion battery pack.

Ford Motor Company. Ford's venture into FCEVs is best defined by its Ford Focus FCV **(Figure 11-28).** The latter edition is a battery hybrid that uses a Ballard Mark 900 series PEM fuel cell. It relies on a nickel-metal hydride battery pack to capture energy during regenerative braking. The vehicle stores 5,000 psi of compressed hydrogen gas, and its powertrain has an electric motor rated at 87 HP and 170 ft.-lb of torque.

Nissan. The first fuel cell prototype from Nissan was the 2002 Nissan X-TRAIL. This vehicle used a PEM fuel cell manufactured by UTC. It had a 100-miles (161-km) driving range and was a battery hybrid. Hydrogen was stored at 5,000 psi (352 kg/cm). This model was followed by the Nissan Xterra-FCV, which is a direct-supply system that uses a Ballard Mark 900 stack. Nissan announced in 2005 that it would be producing its own fuel cells and its own high-pressure storage tanks. The fuel cell features new electrodes with geometric designs to increase efficiency and reduce the size of the unit.

Hyundai Motor Company. UTC Fuel Cells and Hyundai have been working together to develop an advanced PEM fuel cell capable of starting and operating

perimented quite heavily with electric and fuel cell vehicles. They are referring to this line of cars as the "Blue" line **(Figure 11-29).**

Volkswagen. Volkswagen has a fuel cell vehicle called the Bora HyMotion. Hydrogen is stored at cryogenic temperatures, which allows the vehicle to have a driving range of about 220 miles (355 km). The top speed of this vehicle is 90 mph (145 km/h), and it is capable of accelerating from 0 to 60 mph (0 to 97 km/h) in less than 12.5 seconds, both of which are good for an FCEV.

OTHER ALTERNATIVES

In an attempt to reduce our dependence on fossil fuels and to decrease the harmful emissions from our transportation systems, manufacturers are exploring many different avenues besides alternative fuels, hybrid vehicles, and fuel cells. Many of these are very futuristic, but others are here now or will be in the near future. This look at the future is certainly not inclusive, as many manufacturers chose not to share their current projects, and there are many different technologies being studied.

The future of the automobile (how it will look, what fuel it will use, what will supply the power, etc.) is totally undecided. The only thing that is certain is that it will emit far fewer pollutants, rely less on fossil fuels, go farther on a gallon (or equivalent) of fuel, and cost more.

ICE Modifications

As far as alternative fuels are concerned, Ford has had many available model vehicles that can run on E-85 fuel (85 percent ethanol and 15 percent gasoline), which is primarily a renewable fuel. Other manu-

gines. Other manufacturers, particularly Honda, are working on compressed natural gas (CNG) vehicles. CNG vehicles still depend on fossil fuels, but their emission levels are lower than those of gasoline-powered vehicles. And of course, there are a few manufacturers fueling their engines with hydrogen.

In the very near future, more vehicles will be equipped with systems already found in some vehicles, such as direct injection, variable valve timing, cylinder cutoff systems, stop-start capability, and 42-volt systems. The higher voltage allows more components to be electrically powered rather than belt driven. This reduces the load on the engine and makes it more efficient.

An old technology may be used in the future. Although it has been around for many years, electronics may allow it to be practical today. Homogeneous Charge Compression Ignition (HCCI) for gasoline engines relies on cylinder heat and pressure to ignite the air-fuel mixture. In this system, there are no spark plugs and therefore there is no ignition system. With HCCI, the air-fuel mixture is the same throughout the entire combustion chamber. In typical ICEs, there are pockets within the cylinder where the mixture is leaner or richer than the rest of the mixture. Because the mixture is uniform, a cleaner combustion takes place, which results in lower emissions and more efficient fuel usage. The mixture is self-ignited, similar to the ignition in a diesel engine. Once ignition begins, nearly all of the mixture ignites immediately. Without an ignition system, the timing of ignition is difficult to control. Advances made in electronics may provide the precise control required to use HCCI in the future.

Zero-Emissions Vehicles

Many believe the world would be a much better place if the roads were filled with zero-emission vehicles. To the unknowing this is possible now, and the only thing that stops us is "Big Oil." As we have seen throughout this book, achieving zero emissions from an automobile is no easy task, and the obstacles do not seem to come from the oil companies. The obstacles are primarily cost and practicality. Currently, there are four different powerplant systems that can provide a zero-emission vehicle:

- Battery electric vehicles
- Flywheel energy storage vehicles
- Fuel cell electric vehicles
- Air engine vehicles

Keep in mind that some of these do have associated emissions in the production of the fuel or the electrical energy

The basics of three of these powerplant systems have already been covered in this book. Air engines have not.

Scuderi Air-Hybrid Engine. The Scuderi Cycle, named after its inventor Carmelo Scuderi, is also

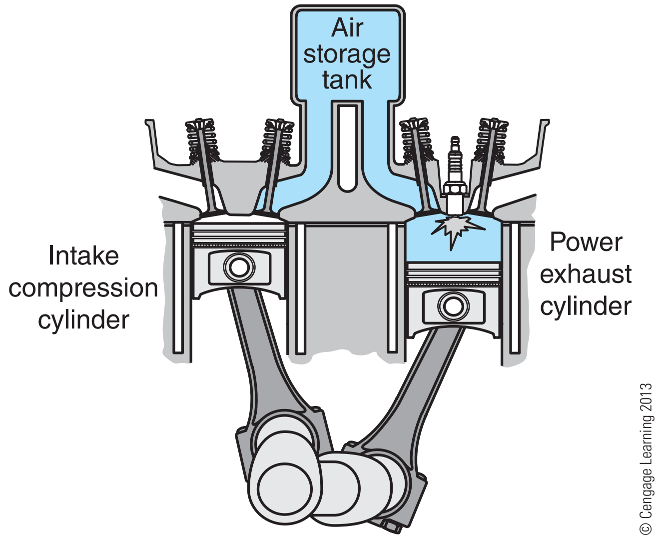


Figure 11-30 A Scuderi Air-Hybrid engine.

called a split-cycle. The name describes the action of two paired pistons; one is used for intake and compression and the other for power and exhaust. This allows the engine to fire every rotation of the crankshaft, just like a two-stroke engine. But this engine does not have the same disadvantages as a two-stroke.

A crossover passage allows the compressed air from the intake/compression cylinder to move to the power/exhaust cylinder. Fuel is then injected and ignited to produce the power stroke. Ignition, however does not take place until the piston is after TDC. The movement of the compressed air from one cylinder to another removes the stress on the piston and forces the compressed air into the next. This allows the energy from the combustion process to push the piston down at a point of low resistance.

One modification to this engine would include an air storage tank above the crossover **(Figure 11-30).** If the release of the air was controlled, the release of additional air could boost performance. To fill the storage tank, the power cylinder is turned off during deceleration, and all of the compressed air in the compression cylinder moves up to the tank. To achieve maximum efficiency, the compression cylinder turns off, and high-pressure air from the storage tank is supplied to the power cylinder. This reduces the power losses that normally occur during the compression

from the compression cylinder to the power cylinder and the rest is stored in the tank.

Air Engine. A pure **air engine** is an emission-free piston engine that uses compressed air as its fuel **(Figure 11-31).** The engine relies on the expansion of

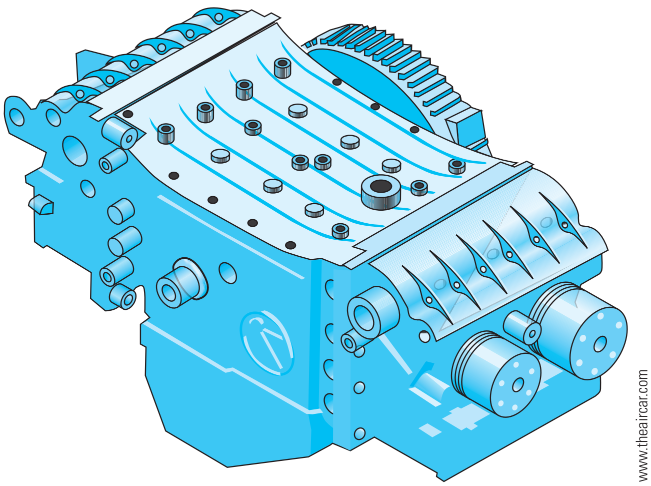


Figure 11-31 A compressed air engine.

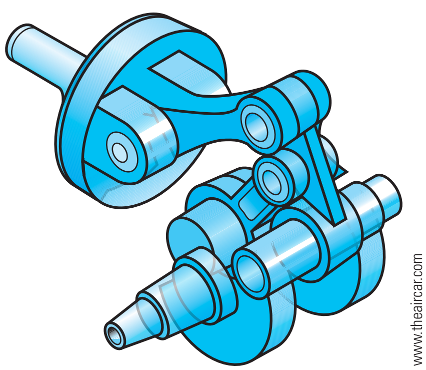


Figure 11-32 Compressed air from a tank is used to move the pistons in an air engine.

compressed air to drive the pistons in a modified engine **(Figure 11-32).** One leading company in the development of air engines is Moteur Development International (MDI). They are based in Spain and have offices in the United Kingdom, Spain, Portugal, Latin America, and Canada. The MDI engine was developed in 2001.

The actual operation of the engine can be somewhat confusing, but the basics are simply that compressed air is used to force a piston down in the same way as the pressure increase in an ICE cylinder. The expansion of the compressed air relies on outside heat and the increase and decrease of the temperature of that air. The engine uses a unique connecting rod and crankshaft assembly that allows the pistons to be held at top dead center for 70 degrees of the cycle. By this means, pressure is allowed to increase in the cylinder, and the pressure on the piston is increased. The exhaust from this system is very cold air, which can be used to cool the passenger compartment. This is a zero-emissions engine, and it has a driving range that is about twice that of a battery electric vehicle. These engines can be used with a conventional ICE (two separate engines). The ICE can drive an air compressor to replenish the pressure in the air tanks and extend the driving range of the vehicle.

Diesel Engines

Diesel engines in cars and light trucks will become more common soon. There are many reasons for this, one of which is that low-sulfur diesel fuel will be available in the United States. Diesel vehicles are very common in Europe and other places where cleaner fuels are available. Diesel engines achieve better fuel economy than gasoline engines of the same size. With new technologies and the cleaner fuels, their emissions levels can be comparable to the best of gasoline engines. Plus, diesel hybrids could achieve fuel mileage ratings well beyond today's best.

Emissions have always been an obstacle to diesel cars, and new, stricter emissions standards will go into effect shortly. Many of the new diesel vehicles will have an assortment of traps and filters to clean the exhaust before it leaves the tailpipe; others will use **selective catalytic reduction** (SCR) systems. In fact, most diesel cars will be using SCR within the next few years. SCR is one of the keys to providing cleaner-running diesel engines.

SCR is a process in which a reductant is injected into the exhaust stream and then absorbed onto a catalyst **(Figure 11-33).** This action breaks down the

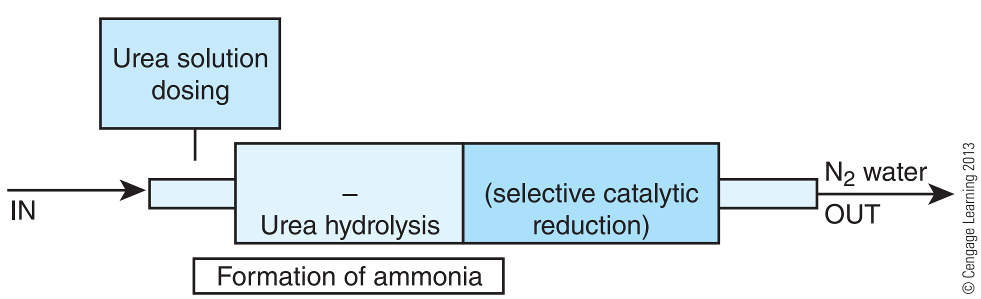


Figure 11-33 Selective catalytic reduction is a process in which a reductant is injected into the exhaust stream and then absorbed onto a catalyst.

exhaust's NO_x to form H_2O and N_2. A reductant removes oxygen from a substance and combines with the oxygen to form another compound. In this case, oxygen is separated from the NO_x and is combined with hydrogen to form water. The common reductants used in SCR systems are ammonia and urea water solutions. The problem with these reductants is again the lack of an infrastructure. The tanks that hold the reductant must be able to be refilled. When the tanks are empty, the emission levels will not be satisfactory. Alternatives to ammonia and urea are being studied in hopes that a suitable reductant that is readily available can be found.

The reductant is injected into the exhaust stream over a catalyst. These special catalytic converters work well only when they are within a specific temperature range. The engine's control unit is programmed to keep the temperature of the exhaust within that range. Also, the amount of reductant sprayed into the exhaust must be proportioned to the amount of exhaust flow. The amount of reductant sprayed is controlled by the engine's control module.

VW TDI Engines. Volkswagen has sold more diesel cars in the United States than any other manufacturer. **TDI** or **Turbocharged Direct Injection** is a design of diesel engines which features turbocharging and direct fuel injection **(Figure 11-34),** developed by Volkswagen. In the TDI engine the fuel injectors spray fuel directly into the main combustion chamber of each cylinder. In older diesels, the fuel was sprayed into a

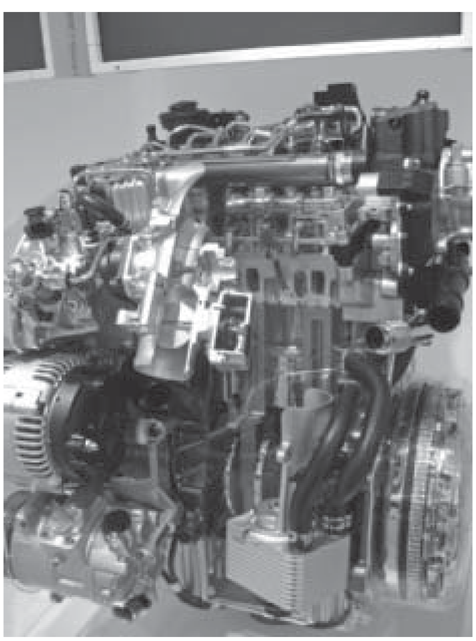


Figure 11-34 A Volkswagen TDI engine.

Figure 11-35 A VW Golf TDI clean diesel.

precombustion chamber because there was not enough fuel pressure to offset the high pressures in the cylinder after compression. This 2.0L four-cylinder engine produces 140 HP at 4,000 rpm and 236 ft.-lb of torque at only 1,750 rpm.

These are called clean diesels **(Figure 11-35)** because they do not emit the soot that characterizes many diesels. Some VW diesels rely on the urea technology to treat the exhaust. Others have a particulate filter in the exhaust system. The filter traps harmful particulates, including nitrogen oxide and hydrocarbons. As particulates accumulate in the filter, its backpressure increases. Once the backpressure sensor sees that the pressure is too high, the system is commanded to inject additional amounts of fuel into the cylinders. This temporary condition cleans the filter.

Steam Hybrid

Another older technology that is being looked at for the future is steam power. BMW has built and tested an auxiliary drive system that uses steam to assist the engine. The heat to create the steam comes from the heat of the exhaust. This idea was first patented in 1914, and steam engines were around years before that. The original ideas had many disadvantages, one being the space required to hold the water and to house the heat-recovery system. BMW seems to have solved these problems and has been able to achieve more than

15 percent in fuel consumption. The real advantage of this system is that the heat has no cost associated with it. The required heat is normally wasted and transferred to the atmosphere.

The steam auxiliary drive system, called the Turbosteamer, can be installed on any engine as long as there

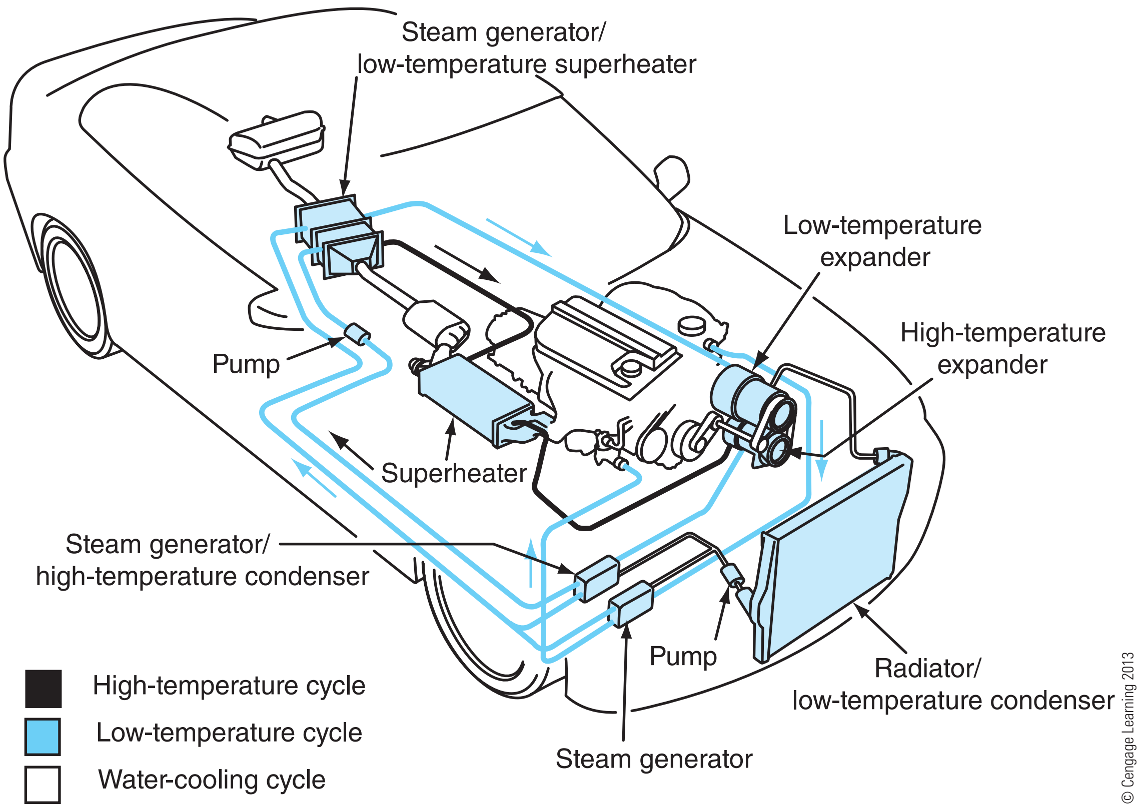


Figure 11-36 BMW's Turbosteamer.

is room in the engine compartment. There are two fluid circuits in the system **(Figure 11-36).** The circuit used to assist the engine is the high-temperature circuit. The fluid moves around the exhaust system and heat exchangers.

The primary high-temperature circuit moves the fluid through heat exchangers positioned behind the catalytic converter. By capturing more than 80 percent of the exhaust's heat, the water is heated to 1,022°F (550°C). The resultant steam is transferred to an expansion unit, which changes the steam into mechanical energy. The expansion unit then drives pulleys that are connected to the engine's crankshaft. There the mechanical energy assists the rotation of the crankshaft. The remaining steam moves to the second circuit, which also serves as the engine's cooling system. This circuit is filled with engine coolant and absorbs the steam's heat and transfers it and the engine's heat outside the vehicle, just as a traditional cooling system would.

Review Questions

1. *True or False:* All fuel cell vehicles have regenerative braking and 12-volt auxiliary systems.

2. Which of the following statements about hydrogen is true?

   A. A hydrogen atom is one proton and two electrons.

   B. Hydrogen is one of the heaviest elements known and is full of energy.

   C. Fossil fuels are combinations of carbon and hydrogen.

   D. Hydrogen is produced in a fuel cell when water is broken down into its basic elements.

3. *True or False:* A PEM fuel cell needs to operate at very high temperatures.

4. What characteristics of an ultra-capacitor allow it to work well in a fuel cell drive system?

5. Why is water control so important to the effectiveness of a PEM fuel cell?

6. Which of the following CANNOT be used as a source for the production of hydrogen?

   A. Gasoline
   B. Methanol
   C. Carbon dioxide
   D. Natural gas

7. The type of fuel cell that will undoubtedly be used first in an automobile is the:

   A. Proton exchange membrane fuel cell
   B. Solid oxide fuel cell
   C. Molten carbonate fuel cell
   D. Alkaline fuel cell

8. Currently there are four different powerplant systems that can provide a zero-emissions vehicle. Name them.

9. What two substances are commonly used as a reductant in SCR systems for diesel engines?

10. Which of the following statements about fuel cells is NOT true?

    A. A single fuel cell produces very low voltage, normally less than 1 volt.
    B. A fuel cell produces electricity through an electrochemical reaction that combines hydrogen and oxygen to form water.
    C. A fuel cell is composed of two electrodes coated with a catalyst and separated from each other by an electrolyte and from the case by separators.
    D. In a fuel cell, catalysts are used to ignite the hydrogen; this causes a release of electrons or electrical energy.

Glossary

A/F (air/fuel) ratio A ratio expressing the amount of fuel mixed with air, by weight, that enters the combustion chamber in an internal combustion engine.

absorbed (or absorptive) glass mat A technique for producing sealed lead-acid batteries. The electrolyte is absorbed in a matrix of glass fibers, which holds the electrolyte next to the plate, and immobilizes it, preventing spills.

AC see *alternating current (AC)*.

accelerator pedal A device used to control the throttle opening, and thereby intake air, on an internal combustion engine.

accessory power module (APM) Part of GM's EV1 that contains a power supply which works with the auxiliary battery to energize various accessories.

Active Control Engine Mount (ACM) A powerplant mounting system that is designed to suppress the natural vibrations of the driveline by instantly changing the damping of the mounts.

active mass The substance used in a positive or negative electrode of a battery or fuel cell which creates current flow by an electrochemical reaction.

active material The specific material at the positive or negative electrode of a battery or fuel cell that takes part in the charge and discharge reactions of the device.

Active Noise Control (ANC) A system that monitors low-frequency engine noise in the passenger compartment and sends out an equal but opposite noise to effectively cancel the engine noise.

additives Chemicals added to fuel in very small quantities to improve and maintain fuel quality. Detergents and corrosion inhibitors are examples of gasoline additives.

advanced technology vehicle (ATV) A vehicle that combines engine/power/drivetrain systems to improve fuel economy. This includes hybrid power systems and fuel cells, as well as some specialized electric vehicles.

AFC (alkaline fuel cell) A fuel cell with an alkaline electrolyte; can only be operated with pure oxygen.

aftermarket
the original purchase, such as adding equipment not a part of the original purchase.

air conditioning (A/C) The process of adjusting and regulating, by heating or refrigerating, the quality, quantity, temperature, humidity, and circulation of air in a space or enclosure; to condition the air.

air engine An emission-free piston engine that uses compressed air as its fuel.

air pollution Unwanted particles, mist, or gases put into the atmosphere as a result of motor vehicle exhaust, the operation of industrial facilities, or other human activity.

air toxics Toxic air pollutants defined under Title II of the Clean Air Act (CAA), including benzene, formaldehyde, acetaldehyde, 1-3 butadiene, and polycyclic organic matter (POM).

alcohol fuels A class of liquid chemicals that have certain combinations of hydrogen, carbon, and oxygen, and that are capable of being used as fuel.

alcohols Organic compounds that are distinguished from hydrocarbons by the inclusion of a hydroxyl group. The two simplest alcohols are methanol and ethanol.

aldehydes A class of organic compounds that can be produced from the oxidation of an alcohol (the removing the hydrogen atoms from the alcohol).

alkaline battery A primary battery that uses an alkaline aqueous solution as its electrolyte.

alkaline fuel cell (AFC) The type of fuel cell used by NASA. These cells use a water-based solution of potassium hydroxide (KOH) as the electrolyte and electrodes coated with a catalyst.

alternating current (AC) An electric current that reverses its direction of flow from positive to negative at regular intervals, typically 60 times per second.

alternative fuels Fuels for internal combustion engines that can be used in place of gasoline or diesel fuel. The term includes blends of other fuels with gasoline or diesel fuel. The most common alternative fuels are methanol, ethanol, compressed natural gas (CNG), liquefied natural gas (LNG), liquefied petroleum gas (LPG), and hydrogen.

alternative-fuel vehicle (AFV) A vehicle that does not use a typical form of energy for operation: electricity, E85, propane, natural gas, and others.

ambient The surrounding atmosphere; encompassing on all sides; the environment surrounding a body but undisturbed or unaffected by it.

as the outdoor air temperature around a building.

American Wire Gauge (AWG) A standard method of denoting the diameter of electrically conducting wire.

ampere/amperage (Amp) Standard unit used to measure electric current; proportional to the quantity of electrons

flowing through a conductor past a given point in 1 second. Amperage is calculated by dividing watts by volts.

ampere-hour (AH) rating This rating is based on the total number of amperes the battery can supply in a 20-hour period at a fixed rate of discharge. If a battery is rated at 200 ampere-hours, it can supply 10 amperes per hour for 20 hours.

anode The positive electrode at which oxidation (loss of electrons) takes place in a liquid solution. Depending on the current direction, each of the two electrodes can become an anode in secondary cells. The negative electrode is then the anode when discharging.

ANSI American National Standards Institute, the national organization that coordinates development and maintenance of consensus standards and sets rules for fairness in their development. ANSI also represents the United States in the development of international standards.

aromatics Hydrocarbons based on the ringed six-carbon benzene series of related organic groups. Benzene, toluene, and xylene are the principal aromatics, commonly referred to as the BTX group. They represent one of the heaviest parts of gasoline.

ash A nonorganic, nonflammable substance left over after combustible material has been completely burned.

assist hybrid vehicle A vehicle that cannot be powered only by the electric motor. The electric motor helps or assists the engine to overcome increased load. At all other times, the vehicle is powered by the ICE.

AT–PZEV Advanced Technology–Partial Zero Emission Vehicle.

Atkinson cycle During the Atkinson cycle, the intake valves are kept open for awhile during the compression stroke; this reduces the actual displacement and the power output of the engine.

atom The smallest unit of an element, consisting of a dense, positively charged nucleus (of protons and neutrons) orbited by negatively charged electrons.

auxiliary power outlet (APO) An AC power outlet available in some hybrid pickup trucks and SUVs. They are designed to power tools and other electrical appliances.

base The part of a transistor that controls the amount of current that flows to or from the emitter or collector.

battery A container, or group of containers, holding electrodes and an electrolyte for producing electric current by chemical reaction and storing energy. The individual containers are called "cells." Batteries store direct current (DC) voltage.

battery condition monitor (BCM) An electronic assembly that monitors state of charge, temperature, and other vital battery readings.

battery ECU Monitors the charging condition of the HV battery.

battery life Number of cycles or miles an EV will travel on one battery pack before the pack must be replaced.

battery pack monitor (BPM) A device that monitors state of charge, temperature, and other vital battery readings.

battery smart unit A device used to monitor the voltage, current flow, and temperature of the battery pack. It may also have a leak detection circuit that watches for excessive current drain. Serial communication is used to transfer the digital signals from the battery smart unit to the electronic control unit.

BEAN Body Electronic Area Network. A form of communication used in a multiplexed system.

belt alternator/starter (BAS) A combination motor/generator that is driven by the engine's crankshaft via a drive belt. It replaces both the engine's alternator and starter motor.

benzene A type of colorless liquid hydrocarbon that can be used as a fuel.

bi-fuel vehicle A vehicle with two separate fuel systems designed to run on either an alternative fuel or gasoline or diesel, using one fuel at a time; may be referred to as a dual-fuel vehicle.

biodiesel A biodegradable fuel for use in diesel engines. It is produced by organically derived oils or fats. It may be used as a replacement for or as a component of diesel fuel.

biomass Renewable organic matter that can be used as a source of energy, such as plants, wood chips, bales of straw, liquid manure, organic wastes, agricultural crops, crop waste residues, wood, animal and municipal waste, aquatic plants and fungal growth.

Brake System Control Module (BSCM) A control unit that calculates the required braking force for slowing down and stopping a vehicle. Based on these calculations, it controls regenerative braking and the hydraulic brake system.

British thermal unit (Btu) The standard measure of heat energy. It takes one Btu to raise the temperature of 1 pound of water by 1 degree Fahrenheit at sea level. One Btu is equivalent to 252 calories, 778 foot-pounds, 1,055 joules, and 0.293 watt-hours.

bus bar A conductor that serves as a common connection for two or more circuits. It may be in the form of metal bars or cables.

butane A hydrocarbon gas found in the earth along with natural gas and oil. Butane turns into a liquid when it is put under pressure.

button cell A miniature cell. A button- or coin-shaped battery whose diameter is greater than its height.

California Air Resources Board (CARB) A state agency that regulates the air quality in California. Air quality regulations established by CARB are often stricter than those set by the federal government.

CAN bus see *controller area network (CAN) bus*.

capacitance The unit of measure for a capacitor's ability to store an electric charge.

capacitor A device for holding and storing a surge of

capacity Amount of electrical energy a cell or battery contains expressed in ampere/hours.

carbon dioxide (CO_2) A colorless, odorless, nonpoisonous gas that is a normal part of the air. Carbon dioxide is exhaled by humans and animals and is absorbed by green growing things and by the sea. It is sometimes referred to as a "greenhouse gas."

carbon monoxide (CO) A colorless, odorless, highly poisonous gas made up of carbon and oxygen molecules formed during combustion. It is a major air pollutant on the basis of weight.

carcinogens Potential cancer-causing agents. They include industrial chemicals found in food additives, pesticides, fertilizers, drugs, toys, household cleaners, toiletries, and paints.

catalyst A material that facilitates or accelerates a chemical reaction while retaining its own properties and without being consumed.

category 3 (CAT III) A classification of test equipment. Meters classified as CAT III are required for testing electric drive vehicles because of the high voltages, three-phase current, and potential for high transient voltages.

cathode The positive electrode. The electrode at which a reduction reaction (gain of electrons) occurs.

CCM Convenience Charge Module. The 110-volt charger provided in the trunk of the EV1.

cell A primary galvanic unit, which converts chemical energy directly into electric energy. Normally made up of a positive and a negative electrode, a separator, and electrolyte.

cell, cylindrical Cells whose heights are equal to or greater than their diameters.

cell, secondary Rechargeable battery cell.

Celsius A temperature scale based on the freezing (0 degrees) and boiling (100 degrees) points of water. Abbreviated as C and formerly known as Centigrade. To convert Celsius to Fahrenheit, multiply the number by 9, divide by 5, and add 32.

charge/charging Refilling a battery with electrical energy.

charge inlet The location on an electric vehicle where the recharger is connected.

charging process The supplying of electrical energy for conversion to stored chemical energy at a battery or capacitor.

charging station The device that provides a connection from a power source to a battery for charging.

chassis ground The use of the vehicle's frame and/or body as a common connection to the negative terminal of a battery.

chemical energy The energy generated when a chemical combusts, decomposes, or transforms to produce new compounds.

circuit The path for electrical current. It normally includes a load and control.

circuit breaker A circuit protection device that opens when excessive current is present in its circuit.

clamp

spikes. It is typically installed in parallel to a coil, creating a bypass for the electrons during the time the circuit is opened.

clean fuel vehicle Refers to vehicles that use low-emission, clean-burning fuels, which include ethanol, hydrogen, liquefied petroleum gas, methanol, natural gas, and reformulated gasoline.

closed circuit An electrical circuit that has a completed path from the negative of the battery to the positive terminal.

coin cell A miniature cell. A button- or coin-shaped battery whose diameter is greater than its height.

cold cranking amps (CCA) rating A common method of rating most automotive starting batteries. This rating is based on the load, in amperes, that a battery is able to deliver for 30 seconds at 0°F (−17.7°C) without its voltage dropping below a predetermined level.

collector The portion of a bipolar transistor that receives the majority of electrical current.

combustion Rapid oxidation, with the release of energy in the form of heat and light.

compressed natural gas (CNG) Natural gas that has been condensed by high pressure, typically between 2,000 and 3,600 pounds per square inch.

compression ignition A form of ignition that initiates combustion in a diesel engine. It is caused by the rapid compression of air within the cylinders that generates the required heat to ignite the fuel as it is injected.

conductance A battery's ability to conduct current. It is a measurement of the plate surface available in a battery for chemical reaction.

conductance test A test that measures conductance and provides a reliable indication of a battery's condition and is correlated to battery capacity. Conductance can be used to detect cell defects, shorts, normal aging, and open circuits, which can cause the battery to fail.

conduction The transfer of heat energy through a material by the motion of adjacent atoms and molecules without changing the position of the particles.

conductive charging A 110V or 220V recharging method that uses conventional metal-to-metal contact to transfer electricity from a charger to a battery.

conductor A device that readily allows for current flow.

continuity A term used to describe the presence of a completed circuit between two points.

continuously variable transmission (CVT) A transmission that automatically changes torque and speed ranges without requiring a change in engine speed. A CVT is a transmission without fixed forward speeds.

controller A device used to manage the flow of electricity from batteries to motor(s).

controller area network (CAN) bus A commonly used multiplexing protocol for serial communication. The communication wire is a twisted-pair wire.

convection Heat transfer by the movement of air.

convenience charger An integral charger carried on board EVs. These chargers have a standardized connection that

outlet.

converted or conversion vehicle A vehicle originally designed to operate on gasoline or diesel that has been modified to run on an alternative fuel or electricity.

converter Drops high-voltage direct current to DC 12V in order to supply electricity to body electrical components, as well as to recharge the 12V battery.

corrosion inhibitors Additives used to inhibit corrosion in the fuel systems.

counter-EMF (CEMF) A force that is created in a rotating armature. The faster the armature spins, the more induced voltage is present in the armature. The induced voltage opposes or is counter to the battery's voltage. This limits the current through the armature windings.

CP Charge port. Located at the nose of the EV1, it is where the paddle is inserted to commence inductive charging.

cranking amps (CA) rating A method of rating automotive starting batteries. This rating is based on the load, in amperes, that a battery is able to deliver for 30 seconds at 32°F (0°C) without its voltage dropping below a predetermined level.

crude oil Petroleum as found in the earth, before it is refined into various oil products.

cryogenic Cold, frost. When applied to gases, it refers to low temperatures where the gases are in their liquid phase.

current The number of electrons flowing past a given point in a given amount of time.

cycle A cycle is one complete charge/discharge sequence of a battery.

cycle life Number of cycles a battery will undergo before it no longer can provide its designed electrical power.

cylinder idling system A system used by Honda that stops combustion in selected cylinders in some of their gasoline engines.

cylindrical battery A battery whose height is greater than its diameter.

cylindrical cell A type of electrochemical cell in which the electrodes are rolled together and fit into a metal cylinder. A separator soaked in an electrolyte is placed between the plates.

Data Link Connector The connector used to connect equipment into a vehicle's computer system for the purpose of diagnostics.

dedicated vehicle A vehicle that operates only on one fuel.

deep cycling A term used to describe the repeated process of a battery discharging and being recharged frequently.

deep discharge A qualitative term indicating the discharge of a significant percentage of a battery's capacity (50 percent or more).

delta winding A type of stator winding connection that connects three windings in series and has the appearance of the Greek letter delta. AC generators with delta windings are capable of putting out higher amperages.

density The mass of a unit volume of a substance.

depth of discharge The ampere-hours discharged from a cell
capacity under the same specified conditions.

Diagnostic Trouble Codes (DTCs) Numerical codes generated by an electronic control system to indicate a problem in a circuit or subsystem or to indicate a general condition that is out of limits.

dielectric material A substance that serves as an insulator of electricity.

diesel fuel Fuel for diesel engines obtained from the distillation of crude oil. It is composed of hydrocarbons, and its efficiency is measured by cetane number.

diode A simple semiconductor device that permits the flow of electricity in one direction but not in the opposite direction.

direct current (DC) Electricity that flows continuously in one direction.

direct-methanol fuel cell (DMFC) A type of the PEM fuel cell that uses liquid methanol as the fuel, rather than hydrogen.

discharge Withdrawal of electrical energy from a cell or battery.

discharge rate The rate at which a cell or battery is discharged.

DLC3 Data link connector 3.

DMFC see *direct-methanol fuel cell (DMFC).*

drain Withdrawal of current from a cell or battery.

driveline efficiency The amount of energy produced in an engine or motor that is used for propulsion and is not wasted.

duty cycle The length of time a device is turned on compared to the time it is off. Duty cycle can be expressed as a ratio or as a percentage.

dynamometer An instrument for measuring mechanical power.

E85 E85 is a blend of 85 percent ethanol and 15 percent gasoline. E85 is commonly available and is a renewable energy source.

ECM Engine control module. Often part of the powertrain control module. The module controls the operation of various engine systems.

ECU Electronic control unit. An electronic unit that monitors and controls a system or subsystems.

efficiency The ratio of the useful energy delivered by an engine or motor to the energy supplied to it over the same period of time.

electric generator A device that converts heat, chemical, or mechanical energy into electrical energy.

electric motor-assisted power steering (EMPS) system The EMPS is a variable-ratio, speed-sensitive power steering system. The EMPS provides steering assist when the engine is on and when it is off.

electric propulsion motor An AC or DC electric motor designed for vehicle propulsion.

electric resistance heater A device that produces heat through electric resistance.

Electric Throttle Control System-intelligent (ETCS-i) Intake airflow for the engine is controlled by a throttle assembly that responds to the throttle pedal and the operating

electric vehicle (EV) A vehicle that is propelled exclusively by electric power.

electrically inert A substance is not conductive, nor will it affect an electronic circuit.

electricity A form of energy that is produced by the controlled movement of electrons.

electro-hydraulic brakes An electrically powered braking system with no engine-related vacuum sources for power assist.

electro-hydraulic power steering (EHPS) An electric motor–driven, variable-assist power steering system.

electrochemical reactions Chemical reactions that produce free electrons.

electrode A conducting structure within a cell in which electrochemical reactions take place.

electrolysis A process that breaks a chemical compound down into its elements by passing a direct current through it.

electrolyte Normally an aqueous salt solution that permits ionic conduction between the positive and negative electrodes in a battery cell.

electromotive force (EMF) The force created by the presence of voltage.

electrons The particles in an atom that have a negative charge.

element A substance consisting entirely of atoms with the same atomic number.

emissions Exhaust emissions are the pollutants emitted by the engine through the tailpipe. High exhaust emissions lead to smog, poor air quality, and global warming.

emitter A portion of a transistor from which electrons are emitted, or forced out.

energy The capacity for doing work.

energy density A battery's rated energy per unit of volume. Measured in units of watt-hours per liter (Wh/L).

energy management Smart on-board systems that optimize driving range and allow the powering of electrical accessories.

energy storage box (ESB) The name for the battery in GM hybrids.

Environmental Protection Agency (EPA) A U.S. federal agency charged with protecting the environment. It is responsible for regulating exhaust emissions in automotive and other vehicles.

ETCS-i see *electric throttle control system-intelligent.*

ethanol Also known as ethyl alcohol or grain alcohol. It can be produced from the fermentation of various sugars from carbohydrates found in agricultural crops and cellulosic residues from crops or wood. Used as a gasoline octane enhancer and oxygenate, and can also be used in higher concentrations in alternative-fuel vehicles.

ethyl tertiary butyl ether (ETBE) A fuel oxygenate that can be added to gasoline and used as an oxygenate in reformulated gasolines.

EV (electric vehicle) A vehicle powered solely by electricity. Energy is normally provided by batteries, but it may also

extended range EV An electric vehicle that uses an additional source to provide electrical energy when the battery is nearly depleted.

Fahrenheit A temperature scale in which the boiling point of water is 212 degrees and its freezing point is 32 degrees. To convert Fahrenheit to Celsius, subtract 32, multiply by 5, and divide the product by 9.

farad (F) The standard measure of capacitance. A 1-farad capacitor can store 1 coulomb of charge at 1 volt.

fast charging A battery recharging process that uses high current delivered for a short time.

fission A release of energy caused by the splitting of an atom's nucleus. This is the energy process used in nuclear power plants to make the heat needed to run steam-powered generators.

fixed-value resistors Resistors whose value does not or cannot change.

flexible-fuel vehicle (FFV) A vehicle that can operate on either methanol or ethanol and regular gasoline or any combination of the two from the same tank.

flux density The number of flux lines per square centimeter.

flux field The magnetic field formed by magnetic lines of force.

flywheel energy storage A system comprised of a large, heavy flywheel suspended by magnetic bearings and connected to a motor/generator. Kinetic energy is stored as the flywheel spins with the motor. The flywheel's momentum keeps it rotating while it spins the generator to produce electrical energy.

flywheel power storage see *flywheel energy storage.*

forward bias A positive voltage that is applied to the P-material and a negative voltage that is applied to the N-material in a semiconductor.

fossil fuel Fuel that was formed in the earth from remains of living organisms. These include oil, coal, natural gas, and their by-products.

frequency The number of cycles that an alternating current moves through in 1 second.

fuel A substance that can be used to produce heat.

fuel cell An electrochemical engine with no moving parts in which hydrogen and oxygen combine in a controlled manner to directly produce an electric current and heat.

fuel cell stack An assembly of several hundred fuel cells connected in series and layered or stacked next to each other. Each fuel cell produces electricity, and the combined output of the cells is used to power a vehicle.

full hybrid A hybrid vehicle that is able to run on the engine, the batteries, or a combination of the two.

full-wave rectification The conversion of the total AC voltage signal to a DC voltage signal.

fuse An electrical device used to protect a circuit against accidental overload or unit malfunction.

fusible link A type of fuse made of a special wire that melts to open a circuit when current draw is excessive.

gallon A unit of volume. A U.S. gallon has 3.785 liters.

gas Gaseous fuel (normally natural gas) that is burned to produce heat energy. The word also is used to refer to gasoline.

gasohol Refers to gasoline that contains 10 percent ethanol by volume.

gasoline A light petroleum product obtained by refining crude oil and used as a motor vehicle fuel.

greenhouse effect A warming of the earth and its atmosphere that results from the trapping of solar radiation by CO_2, water vapor, methane, nitrous oxide, chlorofluorocarbons, and other gases.

grids The basic framework of the lead-acid battery plates. They are the lead alloy framework that supports the active material of the plate.

gross vehicle weight (GVW) The maximum allowable fully laden weight of the vehicle and its payload.

ground The negatively charged side of an electrical circuit. A ground can be a wire, the negative side of the battery, or the vehicle chassis.

ground wire A wire that connects a component to the negative side of the battery through the vehicle's chassis. The use of the ground wire eliminates the need to run a separate wire from the component to the negative terminal of the battery.

half-wave rectification The conversion of half of the total AC voltage signal to a DC voltage signal.

HC adsorber and catalyst system (HCAC) A system used on early Priuses to capture hydrocarbons in the exhaust when the three-way catalytic converter was cold and basically ineffective.

heat engine An engine that converts heat to mechanical energy.

heat pump An air-conditioning unit that is capable of heating by refrigeration. It transfers heat from one object to another. It operates in the opposite way to function as air conditioning.

heavy-duty vehicle Generally, a vehicle that has a GVWR of more than 26,000 lb.

high-voltage (HV) battery The unit that supplies voltage to the traction motor in an electric drive vehicle. The battery is an assembly of many batteries or battery cells.

horsepower A unit for measuring the rate of doing work. One horsepower equals about three-fourths of a kilowatt (745.7 watts).

HV High voltage.

HV battery see *high-voltage (HV) battery.*

HVAC Heating, ventilation, and air conditioning. A system that provides heating, ventilation, and/or cooling.

hybrid vehicles Vehicles that have two or more sources of energy.

Hybrid Vehicle Control Unit (HV ECU) The electronic control unit that monitors and controls the operation of the hybrid system.

hydraulic hybrids Similar to hybrid electric vehicles, except energy for the alternative power source is stored in tanks of hydraulic fluid under pressure. These vehicles have a hydraulic propulsion system.

hydrocarbons (HC) Any compound that contains hydrogen and carbon. Most often refers to the pollutant HC, which results from incomplete combustion.

hydrogen H is the chemical symbol for hydrogen. It is the lightest element on the periodic table of elements and the most abundant element in the universe.

hydrometer Instrument for measuring the density of liquids in relation to water. This tool is commonly used to measure the state of charge in a lead-acid battery by measuring the specific gravity of the electrolyte.

IGBT see *insulated gate bipolar transistor (IGBT).*

impurities Trace elements that are added to electrically inert materials to produce a semiconductor.

induction The process of producing electricity through magnetism rather than direct flow through a conductor.

induction motor A type of AC motor in which power is supplied to the rotor by means of electromagnetic induction.

inductive charging A recharging method that transfers electricity from a charger to a battery through a magnetic field.

infrastructure Refers to the recharging and refueling network necessary to distribute a fuel.

initial charge The first charging process after the electrolyte has been poured into a dry battery.

injectors Valves that allow fuel under pressure to enter an engine's intake manifold or combustion chambers.

insulated gate bipolar transistor (IGBT) A solid state device that converts DC voltage into three-phase AC voltage to power an electric motor or other device.

insulation resistance tester A tester that measures the amount of voltage that can leak through the insulation of a wire or cable.

insulator A material that does not allow for good current flow.

integrated motor assist (IMA) The motor/generator assembly used in Honda hybrids that fits between the engine and the transmission.

integrated starter alternator damper (ISAD) Similar to Honda's IMA, this unit replaces the flywheel, generator, and starter motor. It is placed between the engine and transmission in some hybrid vehicles.

intelligent-Dual & Sequential Ignition (i-DSI) system A system that relies on two spark plugs per cylinder and the firing sequence of each is controlled by an electronic control module through its inputs.

intelligent power unit (IPU) A power unit that controls the amount of electricity flowing to and from a battery pack or other electrical device based on the current operating conditions.

inverter A device that converts AC electricity to DC electricity and DC to AC.

ion An electrically charged particle or molecule.

joule A unit of work or energy. One thousand fifty-five joules equals a British thermal unit.

kerosene A colorless, low-sulfur oil product that burns without producing much smoke.

kilovolt (kV) One thousand volts (1,000).

kilowatt (kW) The international unit to measure power (not just electrical), a kilowatt equals 1,000 watts. One kW equals 1.34 horsepower, and 746 watts equals 1 horsepower.

kilowatt-hour (kWh) The standard unit for measuring quantities of energy that are consumed over time. Specifically, it is 1 kilowatt supplied for 1 hour.

kinetic energy Energy in motion.

Kinetic Energy Recovery System (KERS) A system that captures and stores the kinetic energy of a vehicle during a change in the vehicle's speed.

lead-acid battery A battery that uses lead oxide and spongy lead electrodes with sulfuric acid as an electrolyte.

LEV see *low-emission vehicle.*

linear air-fuel (LAF) sensor An exhaust oxygen sensor that is capable of measuring oxygen content when an engine is running very lean air-fuel mixtures.

lineman's gloves Electrically insulated gloves. These gloves must be worn whenever working on or around high-voltage circuits.

liquefied gases Gases that have been changed into liquid form. The most common liquefied gases are natural gas, butane, butylene, ethane, ethylene, propane, and propylene.

liquefied petroleum gas (LPG) A mixture of hydrocarbons found in natural gas and used primarily as a home heating fuel and motor vehicle fuel.

liquefied natural gas (LNG) Natural gas that has been condensed to a liquid, typically by cooling the gas.

lithium-ion battery A battery in which lithium is used as the electrochemically active material and the electrolyte is a liquid that conducts lithium ions.

lithium polymer battery A battery in which lithium is used as the electrochemically active material and the electrolyte is a polymer or polymer-like material that conducts lithium ions.

LNG see *liquefied natural gas (LNG).*

load The amount of electric current drawn from a power source to operate a circuit or device.

load test A battery test conducted to determine how well a battery performs under a load.

low emission vehicle (LEV) A vehicle certified by the California Air Resources Board to have emissions from 0 to 50,000 miles no higher than 0.075 grams/mile (g/mi.) of nonmethane organic gases, 3.4 g/mi. of carbon monoxide, and 0.2 g/mi. of nitrogen oxides.

low-maintenance battery A battery design that uses the same basic materials as a maintenance-free lead-acid battery, but has vent holes and caps, which allow water to be added to the cells when needed.

LPG see *liquefied petroleum gas (LPG).*

M85 A blend of 85 percent methanol and 15 percent unleaded regular gasoline used as a fuel.

M100
methanol vehicles.

maintenance-free battery A type of sealed lead-acid battery that does not have a provision for adding water to the cells.

malfunction indicator light (MIL) A warning lamp in a vehicle's instrument panel that lets the driver know when the vehicle's electronic control units detected a problem.

MCFC Molten carbonate fuel cell. A fuel cell with a molten alkaline carbonate electrolyte.

methane A light hydrocarbon that is the main component of natural gas and marsh gas. It is the product of the anaerobic decomposition of organic matter.

methanol Also known as methyl alcohol or wood alcohol. A liquid fuel formed by catalytically combining CO with hydrogen under high temperature and pressure.

methyl tertiary butyl ether (MTBE) An ether manufactured by reacting methanol and isobutylene. The resulting ether has high octane and low volatility. MTBE is a fuel oxygenate.

MIL see *malfunction indicator light (MIL).*

mild (micro) hybrid A vehicle equipped with stop-start technology combined with regenerative braking. The electric motor/generator never drives the wheels or adds power to the drivetrain.

miles per kilowatt-hour (MPkWh) The unit of measure for fuel efficiency of electric vehicles. The equivalent of miles per gallon for liquid-fueled vehicles.

mobile source emissions Emissions resulting from the operations of any type of motor vehicle.

molten carbonate fuel cell (MCFC) A type of fuel cell that uses a liquefied carbonate salt as its electrolyte. This fuel cell operates at very high temperatures.

Monroney label A label required in the United States to be displayed in all new automobiles that includes the listing of certain information about the vehicle.

motor controller An electronic device that reads accelerator and brake pedal positions and controls the operation and speed of an electric motor.

motor control module (MCM) A control module that determines whether the motor(s) should operate as a generator or motor, and what should the power usage or output be.

motor power inverter (MPI) The unit that converts the direct current from a battery or capacitor into alternating current for the traction motors. The inverter also changes the AC generated by the motors into DC to charge the batteries.

MPa Megapascals. The metric unit of measure for pressure. One MPa corresponds to a pressure of 10 atmospheres (10 bar).

MTBE see *methyl tertiary butyl ether (MTBE).*

natural gas Hydrocarbon gas found in the earth, composed of a mixture of gaseous hydrocarbons, primarily methane, occurring naturally in the earth and used principally as a fuel.

neutron An uncharged particle found in the nucleus of every atom except that of hydrogen.

to accelerate 1 kilogram at 1 meter per second.

nickel-cadmium battery (NiCad) A battery made with a nickel electrode and a cadmium electrode and uses potassium hydroxide as the electrolyte.

nickel-metal hydride battery (NiMH) A battery made with nickel hydroxide and hydride alloys. The electrolyte is potassium hydroxide.

nitrogen oxide (NO_x) One of the regulated exhaust emissions of an internal combustion engine. NO_x is produced by the combination of nitrogen and oxygen due to the high temperatures reached in the combustion process.

nitrogen-oxide-adsorptive catalytic converter This type of catalytic converter is used on some lean-burn engines, in addition to a conventional three-way catalytic converter, to keep NO_x emission levels low.

NO_x see *nitrogen oxide (NO_x).*

NPN transistor A bipolar transistor whose base–emitter junction is forward biased and the base–collector junction is reverse biased.

octane rating A measure of a gasoline's ability to resist ignition by heat.

OEM see *original equipment manufacturer (OEM).*

ohm A unit of measure of electrical resistance. One volt can push a current of 1 ampere through a resistance of 1 ohm.

Ohm's law A basic law of electricity expressing the relationship between current, resistance, and voltage in any electrical circuit.

OPEC The acronym for the Organization of Petroleum Exporting Countries, which was founded to unify and coordinate the petroleum policies of its members.

open circuit An electrical circuit that has a break in the wire.

open-circuit voltage (OCV) The no-load voltage of a cell or battery measured with a high-resistance voltmeter.

open-loop fuel control A system in which the air-fuel mixture is preset with no feedback correction signal to optimize fuel metering.

operating voltage The voltage that is used by a device to make it function or operate.

original equipment manufacturer (OEM) A manufacturer that certifies that all of its vehicle components have been installed under its direct supervision by its own assembly processes and are covered by the manufacturer's full warranty protection.

oxides of nitrogen Various compounds of oxygen and nitrogen that are formed in the cylinders during combustion and are part of the exhaust gas.

oxygenate A prime ingredient in reformulated gasoline. The increased oxygen content given by oxygenates promotes more complete combustion, thereby reducing tailpipe emissions.

oxygenated fuels Fuels blended with an additive to increase oxygen content, allowing more thorough combustion for reduced carbon monoxide emissions.

ozone A type of oxygen that has three atoms per molecule instead of two. Ozone is a poisonous gas, but the ozone layer in the upper atmosphere shields the earth from deadly ultraviolet radiation from space.

PAFC see *phosphoric acid fuel cell.*

parallel circuit In this type of circuit, there is more than one path for the current to follow.

parallel HEV A drivetrain in which both the motor and the engine can apply torque to move the vehicle. The motor can act in reverse as a generator for braking and to charge the batteries.

parasitic drain The electric drain on a battery while the vehicle is not operating and the ignition switch is in the OFF position.

particulate matter (PM) Unburned fuel particles that form smoke or soot. A chief component of exhaust emissions from heavy-duty diesel engines.

particulate trap Diesel vehicle emission control device that traps and incinerates diesel particulate emissions after they are exhausted but before they are expelled into the atmosphere.

PCM see *powertrain control module.*

PCS Power control system. See also *power control unit.*

PCU see *power control unit.*

PEB see *power electronics bay.*

PEMFC see *proton exchange membrane (PEM) fuel cell.*

petroleum Oil as it is found in its natural state under the ground.

phosphoric acid fuel cell The most commonly used fuel cell in commercial applications. These fuel cells use liquid phosphoric acid as the electrolyte with electrodes made of carbon paper coated with a platinum catalyst.

photo biological method A process, currently being studied, that produces hydrogen when certain algae and bacteria are exposed to light.

photo electrolysis The process during which the sun's light is collected at photovoltaic cells and converted to electricity. That electrical energy is then passed through water to begin electrolysis.

photovoltaic cells Also called "solar cells." These convert solar energy to electrical energy.

PIM Power inverter module. See also *power inverter.*

planetary carrier Part of a planetary gear set. The carrier has a shaft for each of the planetary pinion gears. The carrier and pinions are considered one unit—the mid-sized gear member. The planetary pinions surround the sun gear and are surrounded by the ring gear.

planetary gear unit A combination of three gears in mesh; two of the gears have external teeth and the third has internal teeth.

planetary pinion gears Small gears fitted into the planetary carrier of a planetary gear set.

plug-in hybrid electric vehicles (PHEVs) Full hybrids with larger batteries and the ability to recharge from an electric power grid. They are equipped with a power socket that allows the batteries to be recharged when the engine is not running.

PNP transistor A bipolar transistor whose base–emitter junction is reverse biased and whose base–collector junction is forward biased.

polyvinyl ether (PVE) oil A highly viscous refrigerant oil that contains soft adhesive resins, or nonadhesive elastomers.

potentiometer A variable resistor commonly used as a tracking device or position sensor.

power The rate at which energy is released. Power is measured in kilowatts for an electric vehicle.

power control unit The electronic unit responsible for controlling the amount of electricity flowing to and from the battery and charging systems.

power density A battery rating for the amount of power available per unit of volume. Measured in watts per liter (W/L).

power electronics bay The assembly that contains the voltage source and PCU in many hybrid vehicles.

power inverter Converts the high power of a DC battery pack into the pulsed AC required for powering the electric motor.

power-split device The basic name for the CVT transmission used in Ford and Toyota hybrid vehicles. This device is based on planetary gears and divides the output of the engine and the electric motors to drive the wheels or the generator.

powertrain control module The module that monitors and controls most of the functions of an internal combustion engine and its supporting systems.

PPM Parts per million. The unit commonly used to represent the degree of pollutant concentration where the concentrations are small.

primary battery A cell or battery designed to deliver its rated capacity once and be discarded; not designed to be recharged.

prismatic cells Electrochemical cells with flat electrodes placed into a box with electrolytic separators placed between them.

propane A gas that is both present in natural gas and refined from crude oil. It is used for heating, lighting, and industrial applications.

propulsion system The combination of the powertrain and battery system, which converts stored electrical energy into mechanical energy in a vehicle.

proton exchange membrane (PEM) fuel cell The most commonly used fuel cell in vehicles. This fuel cell easily allows for adjustable outputs, is compact, and is capable of providing high outputs.

pulse width modulation (PWM) The characteristic of a continuous on-and-off cycling of a solenoid for a fixed number of times per second. While the frequency of the cycles remains constant, the ratio of on-time to total cycle time varies, or is modulated.

range The distance that a vehicle can travel on a charge or fuel refill.

rate of charge Amount of energy in a set period of time that is being added to a battery. This is commonly expressed as a ratio of the battery's rated capacity to the charge duration in hours.

reactance The opposition of a circuit component to a change
or inductance.

recombinant battery A completely sealed maintenance-free lead-acid battery that uses an electrolyte in a gel form.

reformulated gasoline (RFG) Gasoline that has had its composition and/or characteristics altered to reduce vehicular emissions of pollutants, particularly pursuant to the EPA regulations under the CAA.

regenerative braking A method that captures a vehicle's kinetic energy while it is slowing down or being stopped. This captured energy is used to charge batteries and/or an ultra-capacitor.

regulator A device used to control the input and/or output of something.

Reid vapor pressure (RVP) A standard measurement of a liquid's vapor pressure in psi at 100°F. It is an indication of the propensity of the liquid to evaporate.

relay This is an electromagnetic switch that uses a low-current circuit to control a high-current circuit.

reluctance A force created by the magnetic fields that results from current passing through a conductor. This force opposes the current flow and therefore limits the amount of current that can flow through a coil of wire.

renewable energy A form of energy that is never exhausted because it is renewed by nature. Typical sources include energy produced by wind, hydroelectric, geothermal, or solar heat power stations, solar cells, and biomass.

renewable resources Renewable energy resources are naturally replenishable. Renewable energy resources include biomass, hydro, geothermal, solar, and wind.

reserve capacity (RC) rating A battery rating system that expresses the length of time, in minutes, that a fully charged starting battery at 80°F (26.7°C) can be discharged at 25 amperes before battery voltage drops below 10.5 volts.

resistance The ability of something to resist the flow of current and to turn some of it into heat. Resistance is measured in ohms.

resolver A sensor that monitors the position of the magnetic fields of the rotor.

retrofit To change a vehicle or engine from the way it was built. This is usually done by adding equipment such as conversion systems.

reverse bias A positive voltage applied to N-material and a negative voltage applied to the P-material in a semiconductor.

rheostat A variable resistor typically used to control the action of a device.

ring gear The internally toothed gear in a planetary gear set; it is the largest of the gears in the gear set.

rolling losses The amount of energy lost as a result of tire rolling resistance.

rolling resistance coefficient A measure of the drag created by friction between the tires of a moving car and the pavement.

root mean square (RMS) A common expression for stating the amount of alternating current measured by a meter.

SAE viscosity number A system established by the Soci-

transmission and differential lubricants according to their viscosities.

sealed lead-acid A type of lead-acid battery in which a special mat material saturated in electrolyte is placed between the battery's plates. There is no free liquid in the battery. Gases produced by the chemical reactions in the battery are "recombined" within the battery.

secondary battery A cell or battery designed to be recharged.

selective catalytic reduction (SCR) A process in which a reductant is injected into the exhaust stream of a diesel engine and then absorbed onto a catalyst, which breaks down the NO_x to form H_2O and N_2.

self-inductance The ability of an inductor to collect and store energy when it is in a magnetic field.

semiconductor A material that is not a good conductor or a good insulator but can function as either when certain conditions exist.

sensor A device used to monitor the activity or condition of a component or system.

separator Material used as insulation between electrodes of opposite polarity.

series circuit An electrical circuit that only allows current to flow through one path.

series HEV The series vehicle components include an engine, a generator, batteries, and a motor. The engine does not drive the vehicle directly. Instead, it drives the generator, which charges the battery to supply power to the electric motor that propels the vehicle.

series-parallel circuit An electrical circuit that has the characteristics of both a series and a parallel circuit.

service plug A device used to shut off the high-voltage circuit of the HV battery when it is removed for vehicle inspection or maintenance.

shift position sensor Converts the shift lever position into an electrical signal that is sent to a control module.

sine wave The resultant wave from AC voltage. The amount the pattern on an oscilloscope moves up and down is equal within one cycle.

slow charging A battery recharging process that uses low current delivered for a long period of time.

smart charging The use of computerized charging stations that constantly monitor the battery so charging is done at the best rate and temperature to prolong battery life.

smog A mixture of smoke and fog. The term is commonly used to refer to air pollutants.

SOC see *state of charge.*

SOFC see *solid oxide fuel cell.*

solar cell A photovoltaic cell that converts light into electricity.

solar energy Heat and light radiated from the sun.

solar power Electricity generated from solar radiation.

solenoid An electromagnetic device that changes electrical energy into mechanical energy. This is not a motor, as a solenoid does not work continuously; movement only occurs at initial energizing or de-energizing.

solid
ramic anode, ceramic cathode, and a solid electrolyte. Its high operating temperatures eliminate the need for expensive catalysts, and therefore these cells have low production costs.

spark ignition engine An internal combustion engine in which combustion begins by the initiation of an electrical spark.

specific energy A battery's rated energy per unit weight. Measured in units of watt-hours per kilogram (Wh/kg).

specific power A battery's rated power per unit weight. Measured in units of watts per kilogram (W/kg).

starting battery The low-voltage battery used to start the engine and power low-voltage circuits in most hybrid vehicles.

state of charge (SOC) A rating, expressed in a percentage, of the current capacity of a battery.

stator The stationary member of an AC motor or generator. It is made up of a number of conductors that serve as an electromagnet or collect the voltage induced by the rotating magnetic field.

steam reforming A common procedure for extracting hydrogen from hydrocarbons.

stepped resistors A variable resistor that has fixed resistance values at specific points.

SULEV Super ultra low emission vehicle.

sulfur dioxide (SO_2) An EPA criteria pollutant.

sun gear A gear located in the center of a planetary gear set; the smallest of the gears in the set.

super-capacitor An advanced capacitor design that can capture very high amounts of electrical energy that is captured during the change of vehicle speed.

superconductor A synthetic material that has very low or no electrical resistance.

synchronous motor An electric motor that has a constant speed, regardless of the load placed on it.

synfuel Fuel that is artificially made rather than found in nature.

System Main Relay (SMR) A relay controlled by a low-voltage source that ultimately controls the high-voltage system. This is present in some hybrid vehicles.

tapped resistors Resistors designed to have two or more fixed values, available by connecting wires to the several taps of the resistor.

TDI Turbocharged Direct Injection, the name of VW's clean diesel engine.

thermistor A solid-state resistor that changes its resistance according to its heat.

three-phase voltage A power system comprised of three conductors carrying voltage waveforms that are out of phase with each other. Normally the phase difference is 120 degrees.

TMED see *transmission-mounted electrical device (TMED).*

torque The amount of twisting force exerted on a shaft or other item. It is measured in foot-pounds.

toxic emission Any pollutant that can negatively affect human health or the environment.

tractive force The amount of power available from the drivetrain. It is calculated by multiplying the engine's torque by the overall gear ratio.

tractive resistance The forces that work against the movement of a vehicle, such as rolling resistance and aerodynamic drag.

transformer A device that transfers electrical energy from one circuit to another through the transformer's windings.

transistor An electronic device produced by joining three sections of semiconductor materials. A transistor is very useful as a switching device, functioning as either a conductor or an insulator.

Transmission Control Module (TCM) A control module that directly controls the operation of a transmission/transaxle.

transmission-mounted electrical device (TMED) An electric motor mounted in or on a transmission.

trickle charge A method of recharging in which a battery is either continuously or intermittently connected to a constant current supply that maintains the battery in a fully or almost fully charged condition.

Turbocharged Direct Injection see *TDI.*

turbocharging A way to increase the quantity of intake air to an internal combustion engine. It uses the pressure of exhaust gases to spin a turbine and impeller that forces air into the engine.

TWC Three-way catalytic converter.

two-mode hybrid system A hybrid transmission that fits into a standard housing and is basically two planetary gear sets coupled to two electric motors. This results in a continuously variable transmission and motor/generators for hybrid operation. This also allows for two distinct modes of hybrid drive operation: low speed/low load and cruising at highway speeds.

ULEV Ultra low emission vehicle.

ultra-capacitor see *super-capacitor.*

unleaded gasoline Gasoline that does not contain tetraethyl lead and is in compliance with federal and state regulations.

valve-regulated lead-acid (VRLA) battery A type of recombinant battery in which the oxygen produced on the positive plates is absorbed by the negative plate. That, in turn, decreases the amount of hydrogen produced at the negative plate. The combination of hydrogen and oxygen produces water, which is returned to the electrolyte.

Variable Cylinder Management (VCM) A system with the capability of shutting down various cylinders of the engine when they are not needed.

variable fuel vehicle (VFV) A vehicle that has the capability of running on any combination of gasoline and an alternative fuel. Also called a flexible fuel vehicle.

variable resistor A resistor that allows for a change in resistance based on the physical movement of a control. The control can be moved by an individual or a component.

variable valve timing and lift control for economy (VTEC-E) An electronic system that controls intake valve opening to provide for the optimum fuel economy regardless of overall engine performance.

Variable Valve Timing-intelligent (VVT-i) An electronic system that controls intake valve opening to provide for the optimum performance and fuel economy according to operating conditions.

volatile organic compound (VOC) An emission regulated by the EPA. These compounds are reactive gases that are released during combustion or the evaporation of fuel. VOCs react with NO_x in the presence of sunlight and form ozone.

volt A unit of measurement of electromotive force. It is the amount of force required to drive a steady current of 1 ampere through a resistance of 1 ohm.

voltage Electrical pressure resulting from a difference in electrical potential between one point and another.

voltage drop This term represents the amount of electrical energy that is changed to another form of energy as current passes through an electrical load.

watt A unit of measure of electric power.

watt-hour One watt of power expended for 1 hour.

wye configuration A type of stator winding connection that connects three windings in parallel and has the appearance of the letter *Y.* AC generators with wye windings are capable of putting out higher voltages.

xylene A petroleum-based hydrocarbon used to increase the octane rating of gasoline. It is photochemically reactive and, when present in exhaust emissions, contributes to the formation of smog.

zener diode A diode that allows reverse current to flow above a set voltage limit.

ZEV Zero Emissions Vehicle.

zinc-air battery A battery constructed with a zinc electrode and an air electrode that uses potassium hydroxide as the electrolyte.

Resources

The following websites have information about electric drive vehicles. Some of these are very technical, while others are simply fun and informational.

http://evalbum.com
www.acpropulsion.com
www.acterra.org
www.avere.org
www.cafeelectric.com
www.calcars.org
www.cengage.com
www.driveclean.ca.gov
www.eaaev.org
www.electricdrive.org
www.etikkit.com
www.evadc.org
www.evco.ca
www.evparts.com
www.evproject.com
www.evworld.com
www.hybridcars.com
www.hybrid-diagnostics.com
www.kta-ev.com
www.lusciousgarage.com
www.manzanitamicro.com
www.metricmind.com
www.MixedPower.com
www.nedra.com
www.priuschat.com
www.priusplus.org
www.shepinc.com

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