CHAPTER 2

Advanced Internal Combustion Engine Technologies

LEARNING OBJECTIVES

After studying this chapter, you should be able to:

LO 2-1 Explore hybrid, plug-in, electric, and fuel cell vehicle propulsion and rechargeable energy management system technologies and operating modes.

LO 2-2 Examine the spark internal combustion engine and the four-stroke cycle.

LO 2-3 Explore advanced engine controls.

LO 2-4 Assess hybrid vehicle GDI engine technologies.

LO 2-5 Examine applications of homogeneous charge compression ignition engine technologies.

Hybrid Electric Vehicles

LO 2-1

Explore hybrid, plug-in, electric, and fuel cell vehicle propulsion and rechargeable energy management system technologies and operating modes.

When understanding how a hybrid electric vehicle (HEV) operates, you should think of a conventionally powered vehicle with an internal combustion engine (ICE), with the addition of a small battery pack operating together to provide an efficient powertrain system. The ICE is connected to a high-voltage generator that is used to generate electrical power to charge the battery pack within this type of application, thus extending the range of the battery pack (**FIGURE 2-1**). The generator is also used to provide electrical power to the electric drive motor. The electric drive motor and engine combine different levels of torque at given road speeds and loads for vehicle propulsion. Utilizing an ICE to generate power for a hybrid vehicle allows the HEV to have a comparable range to a conventionally powered vehicle. HEVs are a necessary intermediate step in the conversion of the automobile from a petroleum-powered vehicle to a fully electric one. Prior to the hybrid vehicle, the automobile was a series of different systems that somewhat worked together to allow the vehicle to operate properly (**FIGURE 2-2**). This worked well enough throughout the years with the electrical and mechanical systems working with little interaction. Each system operating independently of the others did not prove to be an optimal or efficient setup.

Prior to HEVs, vehicle powertrain systems did not work efficiently together. A lot of these inefficiencies are related to the varying speeds at which the engine and vehicle operate at, along with the chemical conversion of gasoline to mechanical motion. This energy conversion creates a lot of wasted heat that is released into the surrounding air. Controlling this waste of energy is key to increasing efficiency within a vehicle. The strategy of the powertrain control module (PCM) on an HEV is to control revolutions per minute (rpm) with the main purpose of generating power instead of propelling the vehicle. The vehicle drive wheels are connected to electric motors and the engine through a planetary gear set that provides the output torque to drive the vehicle (**FIGURE 2-3**). Having an engine that maintains a constant rpm is useful because it can be set to operate at the most efficient rpm for that design. Without the fluctuations of a conventional ICE, the HEV increases the efficiency of the ICE by maintaining a constant rpm. This constant rpm can minimize operator comfort issues and decrease wear on engine components.

To help minimize wasted energy, the HEV uses a regenerative braking strategy to recapture some of the energy that was lost during acceleration. Regenerative braking simply recaptures energy expended and uses that energy to recharge the battery pack (**FIGURE 2-4**). This only happens under the right conditions; when the vehicle is coming to a stop, the high-voltage controller changes the drive motor to a generator by orienting (retarding) the stator magnetic field to a slower frequency than the rpm of the rotor. Using the generator magnetic fields, vehicle braking will be applied to the vehicle by using negative torque on electric machine rotor, and a drive unit/transmission axle. The kinetic energy from the vehicle rotates the electric machine rotor, which permits the regenerative (magnetic) energy and negative torque to be produced, which reduces vehicle speed. The weight of the vehicle helps move the rotor within the generator field to generate electricity. Power generation is variable based on the potential sensed by the high-voltage controller, which is developed by the speed of the vehicle, by the braking requested by the driver, and by the type of system on the vehicle. Regenerative braking will be discussed in more depth throughout this title.

FIGURE 2-1 A hybrid electric vehicle (HEV) is the intermediate step between a conventional internal combustion engine (ICE) and a fully electric vehicle (EV). Because of its infrastructure and battery limitations, the HEV is preparing the driving public to get used to an electrified vehicle prior to full electrification.

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Plug-In Hybrid Electric and Extended Range Electric Vehicles

After the HEV, the next segue to a pure **battery electric vehicle (BEV)** is a **plug-in hybrid electric vehicle (PHEV)**. The PHEV has all of the same components as the HEV, but has a much larger battery pack that can be plugged into utility power for recharging (**FIGURE 2-5**). In the United States, the average driver travels 29 miles a day. Many PHEVs have an average range of 21 miles before the ICE even has to start. Minimizing the operation

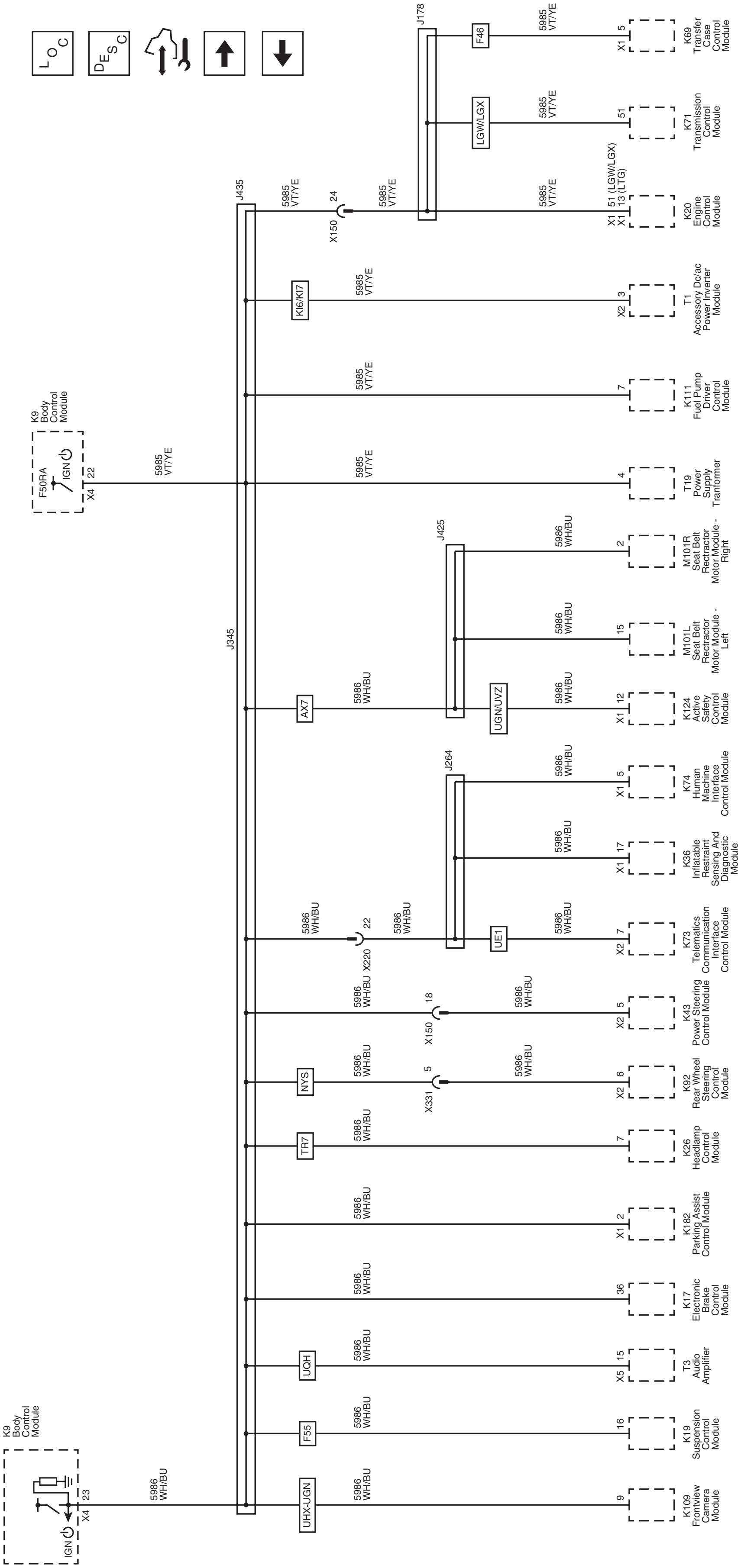

FIGURE 2-2 A conventionally powered vehicle has multiple systems that may not work well together because they all have a particular purpose. Original equipment manufacturers have integrated all of the systems together to increase fuel and operational efficiencies.

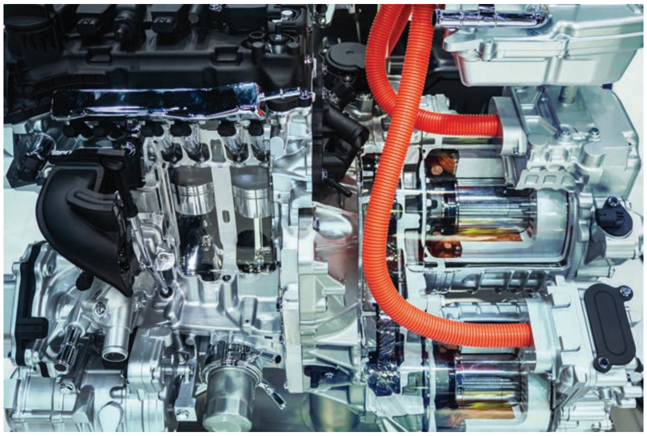

FIGURE 2-3 An HEV utilizes an ICE to generate power for the vehicle's low- and high-voltage system. The ICE is used primarily to operate the high-voltage generator to produce electrical power to operate the vehicle propulsion system and recharge the high-voltage battery pack, then the high-voltage system powers the propulsion system.

FIGURE 2-4 The regenerative braking system utilizes components that are already in the high-voltage system to generate electricity based on the vehicle in motion. The power used to make the stationary vehicle move to a particular speed can partially be recovered when the vehicle is decelerating. Energy does not disappear, it simply changes forms. Recapturing energy before or as it changes forms is an easy way to minimize the need for the battery pack to be charged externally.

FIGURE 2-5 The plug-in hybrid electric vehicle (PHEV) is a combination of an HEV and a battery electric vehicle (BEV). It has the plug-in features of a BEV and the extended range of an HEV. The PHEV is a necessary evolution from an ICE-equipped vehicle to a vehicle fully powered by electricity.

FIGURE 2-6 The propulsion system on a PHEV is much more complicated than that on a BEV. Integrating the ICE allows for extended range, but also increases costs for the owner of the vehicle. In a traditional ICE-powered vehicle, the owner only has to worry about the drivetrain of the vehicle for propulsion. In a PHEV, the owner has to worry about the drivetrain, high-voltage electronics, and the battery pack. The increased complexity dramatically increases the cost to repair.

of the ICE will further lessen the impact a vehicle has on the environment. PHEV systems emulate those on an HEV. Adding the charging element from home alternating current (AC) power allows the PHEV to operate primarily on battery voltage while also allowing the vehicle the ability to drive past the battery capacity.

The PHEV is a crucial step in transitioning drivers to plug in their vehicles on a regular basis. As vehicles transition to being fully electric, drivers will have to change the way they operate their vehicles. Planning out trips to take advantage of charging opportunities and looking for areas with higher populations of charging stations will progressively become part of the public's mindset. The issue that most drivers have with a PHEV is the premium cost for a vehicle that still has an ICE to maintain (**FIGURE 2-6**). This dual-purpose vehicle costs more to maintain and repair than a typical BEV.

Battery Electric Vehicles

As the BEV increases its market share within the automotive market, both consumer and technician must change the way they approach them. A BEV application eliminates the ICE completely and relies on the battery pack for propulsion power (**FIGURE 2-7**). Eliminating the ICE decreases the vehicle's weight and its need for

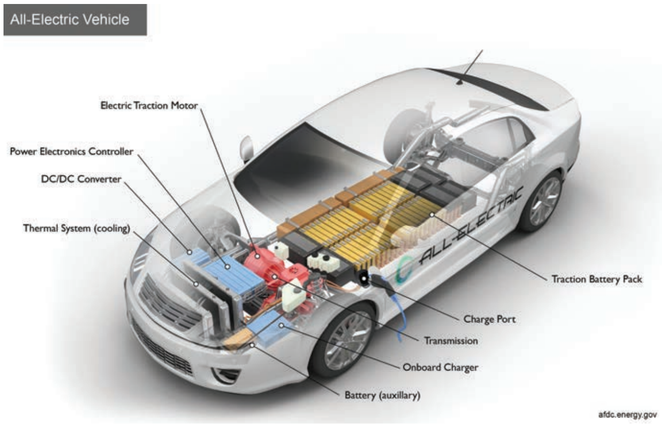

FIGURE 2-7 The BEV drivetrain is simplified to a battery pack, controller, and drive motors. This simplification makes entry into the automotive market easier than a conventional ICE-powered vehicle, which is why there are multiple companies providing BEVs for consumers.
Courtesy of AFDC/U.S. Department of Energy.

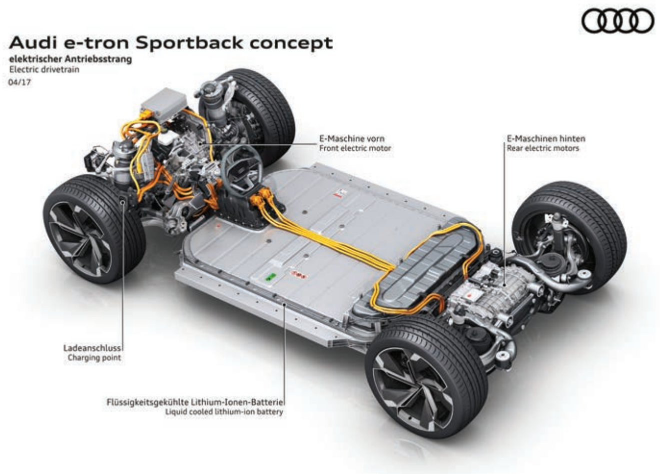

FIGURE 2-8 Having room to put components where they are needed allows the manufacturer to increase the safety of the vehicle as well as provide proper aerodynamically designed body panels.
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FIGURE 2-9 For a long time, controlling the occupants' comfort has consumed a vehicle's energy. Prior to having the ability to control the cabin temperature with the vehicle switched off, a vehicle would have to utilize a large portion of energy to bring down the high temperatures within the cabin once it was switched on. Maintaining cabin temperature at all times decreases the power consumption throughout the operation of the vehicle. These power savings can then be used to power the vehicle down the road.
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regular maintenance. With increased room, the vehicle can now have larger electric motors, larger battery packs, and more room to situate those components in the ideal locations (**FIGURE 2-8**). Issues with a BEV come down to the range capacity of the battery pack. Without the availability of an ICE to generate power any time it is needed, the vehicle must become more efficient than it was previously. To help increase this efficiency, the whole vehicle is integrated together; the systems all work together and regenerative braking increases to help increase or maintain the battery pack's **state of charge (SOC)**.

Vehicle aerodynamics take on a larger portion of a BEV application because it is uncommon for operators to be able to simply pull over and quickly fill up the battery pack. Squeezing every bit of efficiency out of the vehicle design is necessary to keep the vehicle operating properly. Total vehicle integration has changed the way that a BEV must be developed. The commonality across models is being minimized and a more specialized vehicle infrastructure is being implemented in this type of application. From smart vehicle options like cabin temperature maintenance while the vehicle is off (**FIGURE 2-9**) to over-the-air updates to repair software bugs, the BEV is the next evolution of the personal transportation industry.

Fuel Cell Electric Vehicles

Fuel cell technology has been a slow growing technology in the automotive space; its implementation into a mobile platform is just now gaining market share. This renewed interest comes with environmental concerns over the use of petroleum products, production wastes in rare earth minerals mined for high-capacity battery pads in BEVs, and the abundance of hydrogen within the world. Currently, the majority of **fuel cell electric vehicle (FCEV)** operation is within public transport or municipality operations. A majority of these types of vehicles operate a set route, so infrastructure can be planned and made available along the vehicle's route (**FIGURE 2-10**). The technology behind creating power for an FCEV involves combining hydrogen and oxygen. The byproduct of the joining of these atoms is H_2O, or water. Hydrogen is the most abundant element in the universe. The hydrogen present on Earth is found in water more than any other place, which makes access fairly easy for locations across the globe.

Harnessing the power of hydrogen requires quite of bit of technology to convert it to useful power for vehicle

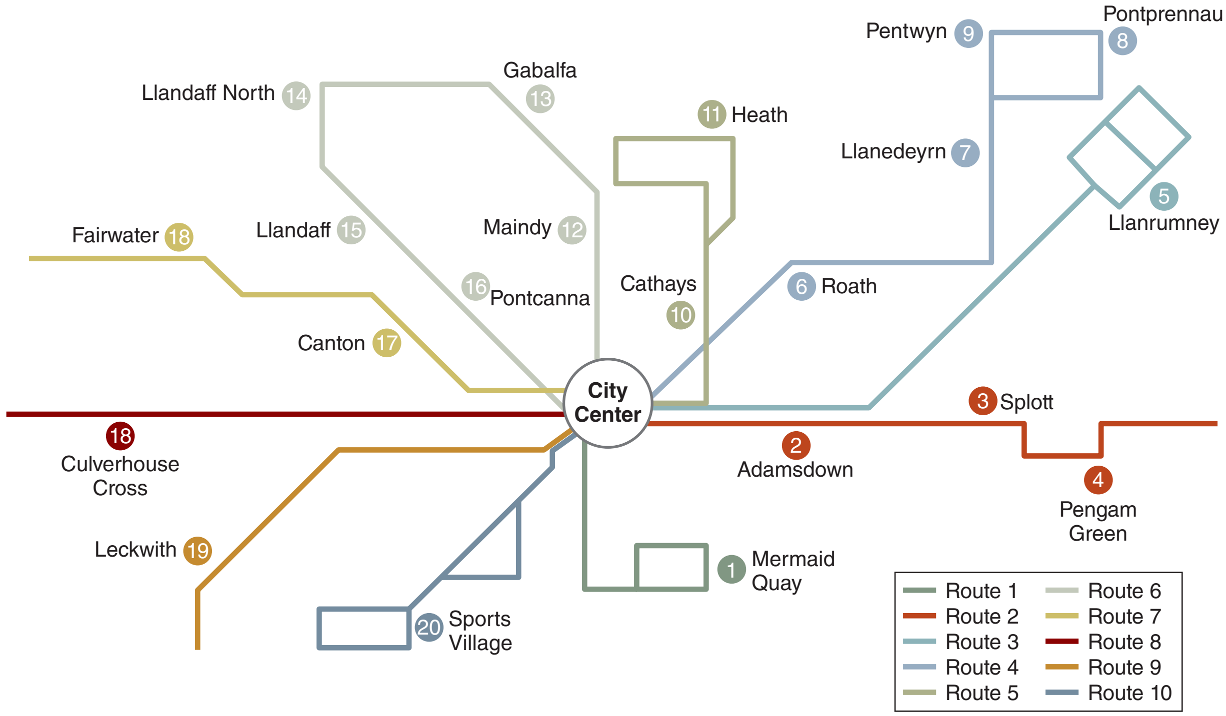

FIGURE 2-10 With the absence of dedicated infrastructure across the country, fuel cell electric vehicles (FCEVs) are currently set along dedicated routes. These vehicles have been used for municipalities as they usually have a set route that services a city.

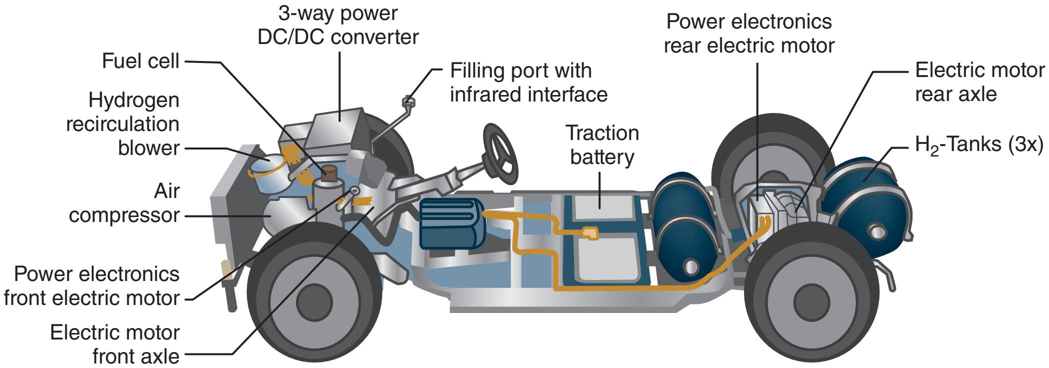

FIGURE 2-11 The FCEV uses the combination of oxygen and hydrogen to generate electricity that it then stores in the battery pack for use with its electric propulsion motors. This situation requires the vehicle to have a constant source of hydrogen to generate the electricity it needs to operate the powertrain components.

propulsion, but it is a simple process. To use hydrogen to power a vehicle, the hydrogen must be combined with oxygen. When that combination happens within the fuel cell, the output is water and electricity. The electricity is fed to a battery pack present on the vehicle, which then powers the vehicle's propulsion motors (**FIGURE 2-11**). This is similar to an HEV in that there is a power source (fuel cell); fuel (hydrogen) is fed into a conversion device; and the output is electricity, which charges the battery pack. As fuel cell technology accelerates, the need for an intermediate battery pack will start to wane. Simplifying the conversion from hydrogen power to propulsion will continue, and increasing efficiencies will always take precedence as doing more with less is the direction that society is following.

The Four-Stroke Otto Cycle

LO 2-2

Examine the spark internal combustion engine and the four-stroke cycle.

A four-stroke engine design may be either an in-line, V-type arrangement, or opposed cylinder. The **spark ignition (SI) engine** used in today's vehicles operates on the **four-stroke Otto cycle**. The four-stroke engine receives its name from the fact that the piston must travel the distance of the cylinder, known as stroke, four times to complete one engine cycle. During the four strokes, the crankshaft makes two complete revolutions. Only one of the

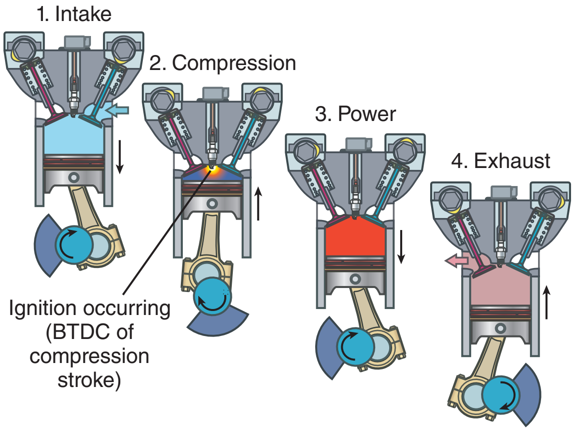

FIGURE 2-12 The basic four-stroke cycle.

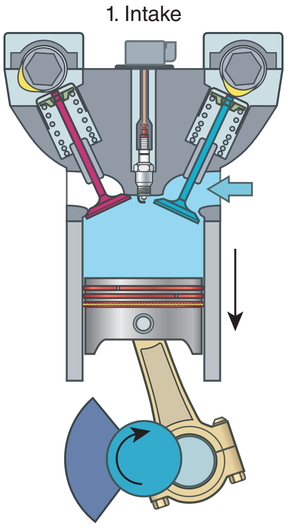

FIGURE 2-13 The intake stroke is where the vacuum (negative pressure) draws in the air and fuel mixture into the cylinder from the opening of the intake valve.

crankshaft's rotations, however, develops power; the other rotation consumes power. The four strokes that are required to make one cycle are intake, compression, power, and exhaust. All of these events are necessary for the engine to function correctly. In actual operation, these four events can and usually do overlap each other or occur at the same time.

The strokes operate in 180 degrees of crankshaft rotation for simplicity; however, this is not an actual representation of engine operation. When the piston in a cylinder is at the position farthest away from the crankshaft (centerline of the journal), it is at **top dead center (TDC)**. When the piston in the cylinder is at a position closest to the crankshaft, this is bottom dead center (BDC). When the piston moves from TDC to BDC or from BDC to TDC, one stroke has occurred (**FIGURE 2-12**). Two or more strokes are called reciprocating motion, meaning an up-and-down motion within the cylinder. Another name for a piston engine is a reciprocating engine.

Basic Four-Stroke Operation

To have a combustion event, the intake and exhaust of fuel and fumes requires that the engine perform a certain set of tasks. These tasks are categorized into a type of operation. In this case, we are talking about the basic four-stroke operation of an internal combustion engine. These tasks include intake, compression, power, and exhaust events. Certain events happen in each stroke; the following text describes these events in detail.

Intake Stroke

The first stroke in a four-stroke Otto cycle is the intake stroke. The air-fuel mixture starts to be introduced into the combustion chamber with the piston at TDC as the intake stroke begins. The intake valve is partially open as it prepares to open fully during the final stages of the exhaust stroke (valve overlap). Valve overlap is the time when both the intake and exhaust valves are open and is necessary due to the degrees of crankshaft rotation that are required to open the intake valve. The piston is moving down the cylinder from TDC to BDC (**FIGURE 2-13**). As the piston moves down the bore, it creates a larger volume area above the top of the piston. As the volume above the piston increases, it creates a pressure lower than atmospheric (a partial vacuum) in the cylinder. It is commonplace to assume that the vacuum created here is solely responsible for the cylinder filling to reach maximum volumetric efficiency (VE), but that assumption is only partially correct. Piston velocity plays a crucial part in increasing airflow and cylinder filling. The calculation to determine piston speed uses piston stroke, rod length, piston pin offset, and rpm. As a piston reaches its maximum velocity (approximately 70–80 degrees after top dead center [ATDC]), the greatest pressure difference exists between atmospheric pressure and cylinder pressure. This difference in pressure increases airflow substantially. With the intake valve opening, higher outside air pressure (atmospheric) forces an air charge that usually draws fuel (unless in a gasoline direct-injection engine) into the cylinder. As the piston continues traveling down the cylinder, the exhaust valve fully closes while the intake valve, which is fully open, begins to close as the piston reaches BDC. When the piston reaches the bottom of its travel, or BDC, pressure no longer increases, so the pressure differential is now almost equal, slowing airflow inertia. The intake valve is still open slightly after BDC, using the momentum from the incoming intake charge to continue filling the cylinder, even though the piston speed slows at BDC. Holding the intake valve open enhances VE.

Compression Stroke

The compression stroke follows the intake stroke and begins near BDC when the intake valve(s) close and the

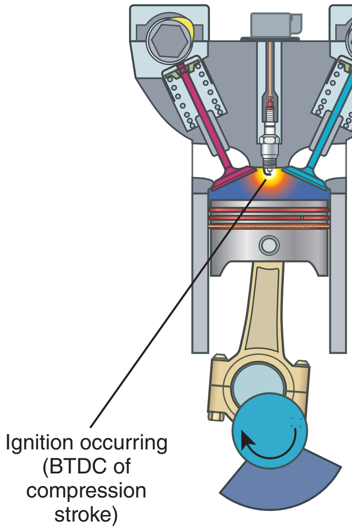

FIGURE 2-14 The compression stroke is where the cylinder is compressing the atoms within the air and fuel mixture into a smaller space. This is done to fully maximize the ignition, fully converting the chemical potential energy into mechanical energy that can be utilized for propulsion or power generation.

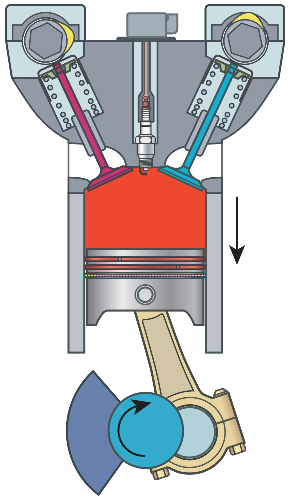

FIGURE 2-15 The power stroke is where the energy conversion happens. The chemical fuel is combined with the air in the cylinder. When this combination happens, the mixture ignites. The piston moves, providing a path for the expanding gases from this atom combination event, and the piston is connected to the crankshaft through a connecting rod. As the piston is moved within the cylinder, the crankshaft starts to turn, completing the energy conversion event.

piston starts moving up the cylinder bore. As the piston reaches BDC, two events occur simultaneously: the intake valve almost closes, and the piston speed slows substantially. The intake valve closes fully after BDC. With both valves fully closed, the cylinder is now completely sealed. The piston then begins the trek back to TDC on the compression stroke, squeezing the air-fuel mixture into a smaller volume, which elevates the pressure and temperature in the cylinder (**FIGURE 2-14**). The cylinder pressure continues to increase until the piston reaches TDC, where the air-fuel charge has reached its design limits, or maximum compression ratio. The base compression ratio is determined during engine design and is fixed. Remember that the intake and compression processes started with approximately 15 psi (1 bar) of atmospheric pressure exerted on the air-fuel charge. Compression of the air-fuel mixture facilitates igniting the charge and makes combustion (burning of fuel) more complete and efficient. This event is crucial because the burn needs to be regulated—and not be an explosion, which is detonation. A result of detonation is engine damage, usually melted ring lands. Accurately controlled burning returns the piston at maximum velocity to BDC.

Power Stroke

The power stroke is the third stroke, the only stroke during the four-stroke Otto cycle that generates power, or when internal combustion occurs. Both valves remain closed as the piston reaches TDC of the compression stroke. A spark of more than 20,000 volts, created by the ignition coil jumping the spark plug gap, begins the power stroke by igniting the compressed air-fuel mixture with the piston approaching TDC with both valves closed. The air-fuel mixture burns rapidly, reaching temperatures as high as 4,500° F (2,482.2° C). The expanding gases quickly force the piston back down the bore by creating a large pressure area across the top of the piston from combustion (**FIGURE 2-15**). The exhaust valve starts to open before the piston has reached BDC. The majority of the gas pressure from combustion diminishes between 45 and 90 degrees of crankshaft rotation ATDC. When the crankpin reaches 90 degrees ATDC, recovery of most of the power is complete, and cylinder pressures are low. The exhaust valve begins to open as the piston travels back down the bore before bottom dead center (BBDC), aiding in expelling exhaust gases by increasing the time during which the valve is open. Opening the exhaust valve during the power stroke also assists in reducing cylinder pressure and pumping losses. Pumping losses occur because the mechanical movement of the components in the engine requires power to operate, which decreases the available power to use at the flywheel.

Exhaust Stroke

The final stroke of the four-stroke Otto cycle is the exhaust stroke. As the power stroke ends, the piston moves from BDC back to TDC to expel the burned gases from the cylinder through the open exhaust valve(s). During the exhaust stroke, several other engine operations are taking place simultaneously.

Due to camshaft design, the exhaust stroke actually begins before the piston reaches BDC during the downward movement of the piston from the power stroke, as

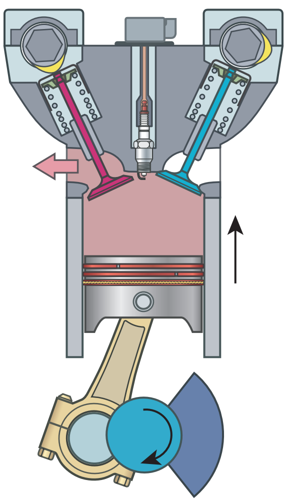

FIGURE 2-16 After the combustion event, the cylinder has exhaust gases present, which must be removed before the cycle can be started over. The exhaust stroke happens as the exhaust valve opens and the piston pushes the exhaust gases into the exhaust manifold.

discussed earlier. Although combustion has ceased, pressure remains in the cylinder from the combustion event. The exhaust valve opens, releasing cylinder pressure through the exhaust port. Then the piston travels back up the bore to TDC, forcing out the remaining gases that are in the cylinder (**FIGURE 2-16**). The exhaust valve is opening rapidly as the piston begins its ascent. As piston velocity increases, the exhaust valve needs to be fully open to reduce resistance (pumping losses), which hampers power and fuel economy. Valve overlap increases the cylinder fill during the intake stroke, a result of the negative pressure (vacuum) in the cylinder—which is a process known as *scavenging*. The vacuum created allows more air-fuel mixture to fill the cylinder and ensure that the exhaust gases purge efficiently. Delaying exhaust valve closure until after the piston has reached TDC and begun its descent takes advantage of the exhaust gas velocity, increasing cylinder scavenging. Delaying exhaust valve closure and starting to open the intake valve on the exhaust stroke (valve overlap) also aids in reducing pumping losses.

This completes the four-stroke Otto cycle. Note that the crankshaft has completed two full rotations (720 degrees) during the complete four-stroke cycle while the camshaft(s) have completed only one rotation (360 degrees). The piston has traveled from TDC to BDC four times, or strokes, to complete one cycle—hence the name four-stroke cycle. The timing of these events is similar, no matter which type of engine is using the cycle.

Engine Conversion to Mechanical Motion

A combustion engine is a device that transforms the chemical energy stored in a fuel into heat energy and then converts a portion of that heat energy into mechanical work. Most ICEs are incredibly inefficient at turning burned fuel into usable energy, despite current automotive engine designs that include forced induction, lightweight engine materials, variable valve lift and timing, stop/start technology, etc. Most gasoline combustion engines average around 20 to 30% thermal efficiency. Diesel engines are typically higher, approaching 40%.

There are several ways to find the efficiency of an engine. *Thermal efficiency* is the percentage of energy that is converted to mechanical work, taken from combustion. It is a measurement of an engine's efficiency at turning burned fuel into usable energy, expressed as a percentage. The thermal efficiency of a typical low-compression engine is about 26%. Highly modified engines or race engines typically have a thermal efficiency of about 34%. Increasing the mechanical efficiency also increases the ability of the engine to convert thermal energy into mechanical motion. *Mechanical efficiency* is the percentage of energy that an engine produces after subtracting mechanical losses such as friction and rotational losses, compared to what the engine would deliver without any loss of power. The mechanical efficiency of the majority of engines is about 94%. Identifying those areas of inefficient mechanical operation allows the designers of the ICE to maximize efficiency and minimize chances of failure.

Thermal Efficiency

An approximate rule of thumb is that nearly one-third of the fuel energy goes out the exhaust pipe as lost heat. Another one-third of the fuel energy is lost to the cooling and lubrication systems that carry damaging heat away from the engine (coolant, oil, and surrounding airflow). This leaves roughly only one-third of the energy (best case) available for power output, which is reduced further by tire rolling resistance. After totaling all the losses, only about 20 to 30% of the energy from the fuel consumed in a modern conventional automotive engine is left to propel the vehicle, depending on the drive cycle (city, highway, or combined). Engine and driveline inefficiencies consume the remaining energy or are used to power the vehicle's accessories.

Automotive manufacturers continue to strive for improved fuel efficiency by using and developing advanced technologies that will find their way into a technician's service bay. Forced induction, **gasoline direct injection (GDI)**, water injection, and increased use of the Atkinson engine design are current examples. Greater use of friction- and thermal-reducing metallic, aluminum, and ceramic engine components; lower-friction piston rings; engine oil; and other vehicle lubricants is normal. Manufacturers continue to develop new technologies that may or may not make it into production vehicles in the future. An example is a new free piston engine: The free piston engine linear generator (FPEG) from Toyota Central in Maine has a claimed thermal efficiency for the device approaching 42%; it is under development and could power hybrids in the future.

Atkinson-Cycle and Miller-Cycle Engines

Despite its predicted demise, the gasoline ICE has been and will continue to be, at least in the near future, the choice of automotive engine power plants. As guidelines for emission and fuel economy standards continue to increase, modifications to the ICE have been taking place and will continue to do so. The Atkinson and Miller engines are two examples of a never-ending quest for efficiency. Atkinson-style engines in use today originated from hybrid applications (**FIGURE 2-17**). As valve timing and engine control module (ECM) controls have advanced, Atkinson-style engine use has expanded to some non-hybrid automobiles, featuring engines that can run in the **Atkinson cycle** on a part-time operating basis, improving fuel economy while in this mode. Atkinson-style engines may be as much as 10% more efficient than a typical Otto-style engine. Some Mazda models offer this technology, referred to as Skyactiv technology.

The Atkinson-style engine increases its efficiency over an Otto-style engine by reducing pumping losses. To regulate power, the traditional airflow into the engine is restricted with a throttle plate. This restriction of airflow creates a partial vacuum (low pressure, less than atmospheric) in the intake manifold. By maintaining this low pressure in the intake manifold, drawing air into the cylinders is more difficult, forcing the piston to work harder and thus wasting energy.

FIGURE 2-17 Some hybrid models use the Atkinson cycle because they are a stationary engine that does not have the violent rpm swings found in a conventional engine. The increased efficiency of this four-stroke strategy allows for increased fuel efficiencies that are not found in an Otto four-stroke engine.
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The Atkinson-style engine relies on many of the same principles as the Otto-style engine and still maintains the basic four-stroke cycle design with intake, compression, power, and exhaust. The differences, however, are the use of a longer stroke and the operation of the intake valve. Current Atkinson-cycle technology modifies the Otto-cycle engine operation. The Atkinson cycle is also known as the "five-stroke cycle" because it includes the intake backflow. The five cycles, then, are intake, compression, ignition, power, and exhaust. Backflow is the partial expulsion of cylinder gases into the intake manifold to eliminate pumping losses, reducing effective compression ratio.

The Atkinson engine reduces the power lost due to the energy required to compress the air-fuel mixture in a typical Otto-cycle ICE. By lowering the compression ratio, the Atkinson engine reduces the power required by the crankshaft to push the piston up the bore, increasing overall engine efficiency. The **Miller-cycle engine** and the Atkinson-cycle engine are both variations on the traditional four-stroke SI engine. These engines operate more efficiently but produce lower power outputs for the same displacement. Both engine designs offer poor, low-rpm performance.

In a conventional four-stroke cycle, the compression and the power (expansion) strokes are the same length. One method used to increase engine efficiency is to increase the stroke and raise the expansion ratio, which increases the compression ratio. Increasing the compression ratio requires additional energy to overcome the increase, offsetting some of the gains made in efficiency. There is also a limit as to how high the compression ratio can escalate. Increasing compression too much may result in high enough cylinder temperatures to prematurely ignite the air-fuel mixture before the ignition spark occurs.

The Atkinson-style engine is another approach to increase engine efficiency. The Atkinson-style engine used in modern vehicles is a variation on the true Atkinson-cycle engine developed in 1882. The original design incorporated a complex arrangement of levers and a unique crankshaft design. Modern Atkinson-style engines accomplish the most vital qualities of the Atkinson cycle, reducing pumping losses and decreasing fuel consumption by lowering the effective compression ratio.

The Miller-style and Atkinson-style engines in use today use valve timing variations that keep the intake valve open longer than usual. The intake valve does not close at the end of the intake stroke, as it typically would. The valve remains open well past when the piston is at BDC of the intake stroke and into the compression stroke. As the piston rises for the compression stroke, the intake valve remains open. Holding the intake valve open longer shortens the compression stroke, lowering the effective compression ratio. Reducing the compression stroke shortens the distance that the piston has to compress the air-fuel mixture. To help offset the reduced effective compression ratio, the power stroke remains long. Delaying the opening of the exhaust valve until the piston is closer to BDC lengthens the power stroke. Extending the duration of the power stroke allows the combustion gases to expand more. Therefore, the pressure created by the expansion of the burning gases acts on the piston longer, applying pressure to the crankshaft for a prolonged time, and increases efficiency. Holding the intake valve open longer not only reduces the dynamic compression ratio, but also lowers manifold vacuum (normal), reduces pumping losses (parasitic drag), and increases efficiency.

Because some of the intake gases push back from the cylinder into the intake manifold, Miller and Atkinson engines can use a larger throttle opening for a given amount of power. When the ECM injects fuel into the engine during the intake stroke, some of the air-fuel mixture in the cylinder pushes back into the intake manifold because the intake valve remains open during compression stroke (reversion). Naturally, this reduces power generation because less air-fuel mixture is available to combust. Some manufacturers incorporate a surge tank in the intake manifold to store the reversion of the air-fuel mixture, the positive crankcase ventilation (PCV), and the exhaust gas recirculation (EGR) gases. Storing reversion gases is unlike most modern engines, where the intake manifold moves air, PCV, and EGR gases only during fuel injection into the cylinder. Due to the flow and storage of the combination of gases and fuel in an Atkinson-style engine, the intake manifold may get quite dirty from carbon deposits (a normal condition). Low-speed and high-speed driving habits may increase intake deposit formation.

The Atkinson-cycle engine is efficient within a particular operating range (the engine "sweet spot" of peak torque rpm), typically between 2,000 and 4,500 rpm, but its overall power output and torque are lower than a conventional ICE. This type of engine is less useful as a primary energy source due to reduced power density, but it is ideal for applications such as a series-parallel hybrid vehicle, where it can work in tandem with a battery-driven electric motor and charge the high-voltage battery.

A major benefit of the Atkinson-style engine is the reduction of pumping losses; it reduces the level of pumping losses that occur in an Otto-cycle engine, resulting in increased fuel economy. During low to part-load operation in a typical Otto-cycle engine, the throttle plate restricts airflow into the engine to control engine rpm. Reducing the amount of air that enters the engine also decreases the amount of fuel required to maintain the desired air-fuel ratio of 14.7:1. A closed, or partially closed, throttle reduces airflow and air pressure in the intake manifold. When air pressure is reduced in the intake manifold, it falls below atmospheric pressure, creating a vacuum. However, reducing airflow also negatively *reduces* VE as the piston struggles to draw air into the cylinder past the closed throttle plate. An Atkinson-style engine reduces the effect of the closed throttle plate by increasing its opening and controlling airflow with valve timing. Opening the intake valve earlier and holding it open longer reduces the internal engine resistance to airflow. Increasing the throttle opening beyond a typical Otto-cycle engine reduces the work of the piston in the bore during the intake stroke, increasing unrestricted airflow in the engine. The additional airflow increases cylinder filling during low-rpm operation, increasing VE and fuel economy.

In addition, the lower maximum operating rpm allows engine components to be lighter than a conventional ICE. Lighter and smaller components reduce friction and increase engine efficiency. Also, the crankshaft is mounted slightly off-center from the cylinder bores. This position reduces the thrust load on the piston, thereby reducing the power lost from friction.

The Miller-cycle engine is similar to an Atkinson-style engine; however, it adds a supercharger and leaves the intake valve open during part of the compression stroke (**FIGURE 2-18**). As the cylinder compresses the mixture, the intake charge is being compressed against the supercharger pressure, which increases the efficiency of the engine. Increasing the air density helps reduce the loss of power that is inherent in the Atkinson cycle.

FIGURE 2-18 The Miller-cycle engine is based on the Atkinson-style engine but employs a supercharger and a delayed intake valve closing feature. These two features allow it to increase efficiency by up to 15%.
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The Miller-cycle engine adds an engine-driven supercharger to increase VE and boost power output when required. When the engine is operating at low load and speed, supercharger boost is not necessary. A clutch disengages the drive of the supercharger (similar to some air-conditioning [A/C] compressors), preventing unnecessary drag on the engine. Engaging the clutch when extra power is required engages the supercharger, boosts the amount of air drawn into the engine, and supercharges the cylinder.

In a hybrid application, the ability of the engine to accelerate quickly and produce increasing power is not necessary. HEVs require semi-constant power generation, past the battery pack capacity, which requires the engine to operate in a narrow rpm range. This rpm range will match the power output of the power generator attached to the engine. Optimal power output may change, based on need by the vehicle. This "controlled" environment allows for a highly efficient ICE and high-power output at all times. Only utilizing the ICE for power generation means the engine does not operate all of the time, unlike a conventional ICE-powered vehicle, thus extending the need for regular maintenance.

Advanced Engine Controls

LO 2-3

Explore advanced engine controls.

The ability to control the advance and retard of the cam timing is a huge benefit to engine performance. Retarded timing provides greater engine efficiency when large amounts of air are flowing into the engine at higher rpm. Advanced timing is useful when the engine needs high torque during lower engine rpm operations. In past applications, an engine designer would have had to decide which valve timing best served the operating range of the engine and then designed the camshaft for that purpose. What if an electronic module could manage optimum valve timing for widely differing engine demands, such as in a vehicle used both for commuting and rallying or racing? Well, today's automobiles do almost that by using electronically controlled, hydraulically assisted variable valve timing while the engine is operating. Twin camshafts are advanced or retarded through the use of cam phasers or actuators. The phaser typically takes the place of the standard cam gear or pulley and uses oil pressure from the engine oil pump to move (some advance, some retard) the camshafts when commanded by the powertrain control module (PCM).

When utilizing this type of phasing, the HEV can fine-tune engine operation while generating power for the battery pack and providing propulsion. This fine-tuning will allow the engine to meet optimal efficiency while the engine is running, extending the mileage of a tank of fuel (**FIGURE 2-19**). Changing the timing of the engine allows for easier engine startup and quicker acceleration and deceleration of the engine. When using **variable valve timing (VVT)**, the PCM can control emissions output of the engine; it has the ability to control harmful nitrides of oxygen (NOx) and other emission output of the ICE (**FIGURE 2-20**). Connecting the VVT-equipped ICE with the hybrid drive systems allows for a more efficient transfer of power from petroleum products to the electric drive motors that move the vehicle.

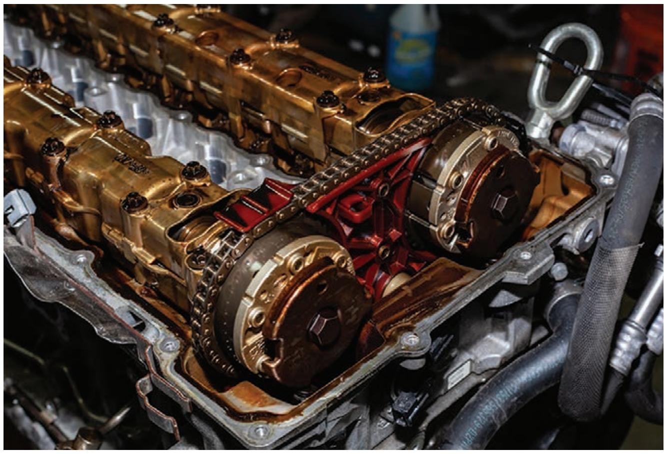

FIGURE 2-19 Utilizing variable valve timing (VVT) when operating a hybrid ICE, the powertrain control module (PCM) can adjust the valve events to coincide with increased efficiency, based on demands on the ICE, while the vehicle moves down the road.

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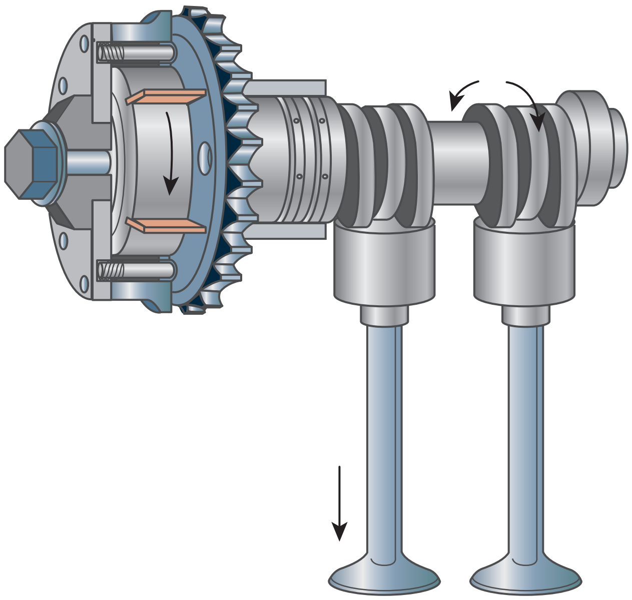

FIGURE 2-20 When the VVT is actuated, EGR is not needed to help cool the cylinder. Adjusting the valve events as the engine is operating allows the PCM to control the temperature within the cylinder to minimize nitrides of oxide (NOx) production.

To ensure proper operation, the ICE and high-voltage electrical propulsion system are monitored by the PCM and hybrid drive controller.

Several inputs are used to ensure that the ECM is able to control the timing accurately. These are the same inputs used by the PCM to control fuel delivery and ignition system timing. The PCM also must know oil temperature to ensure that the oil viscosity is not too thick or thin. Based on input from an oil temperature sensor, the PCM either allows or disables variable valve timing; the viscosity of the oil must be correct for accurate valve timing. The PCM must know the amount of engine load to determine the need for an advance or retard of cam timing. To calculate engine load, the PCM primarily uses the following inputs:

- Mass airflow sensor or manifold absolute pressure sensor
- Throttle position sensor
- Intake air temperature sensor
- Engine coolant temperature sensor
- Crankshaft position sensor
- Oil pressure sensor
- Rpm
- Voltage requirements of the vehicle
- Hybrid drive system needs

The PCM relies on feedback to ensure that the cams are rotating as commanded; the camshaft position sensor (CMP) is used for this function. The output of the PCM is delivered to the cam timing solenoid. The cam solenoid allows oil pressure to move into the cam phaser. The solenoid is turned on and off with a pulse-width modulation (PWM) signal. PWM is the variable rapid (in milliseconds) time-based on/off switching of a direct current (DC) signal. The longer the solenoid device is turned off, the less it opens; the longer it is turned on, the more it opens. In this way, the solenoid can regulate the amount and direction of oil flow to the cam phaser to alter camshaft/valve timing.

Analyze Engine Cylinder Operational Control Systems

To help the transition from a conventional ICE-powered vehicle to a BEV, original equipment manufacturers (OEMs) have tried to provide options similar to a "normal" engine but have features that increase mileage and decrease emissions. One of these types of systems is cylinder deactivation (**FIGURE 2-21**). Cylinder deactivation goes by various names like Chevrolet's **Active Fuel Management (AFM)** and Chrysler's **Multiple Displacement System (MDS)** (**FIGURE 2-22**). These types of systems are used on push-rod–equipped V8 engines. When the PCM determines the time is right, usually under a light throttle cruising condition, it actuates an oil control solenoid located in the valley of the engine (**FIGURE 2-23**). This actuation limits the oil flow to the lifter and the related valve, not allowing the valve to operate. While this is happening, the PCM shuts off the ignition and fuel to those cylinders it is disabling to take the load off the engine.

FIGURE 2-21 Cylinder deactivation helps improve the vehicle's fuel mileage, along with giving the operator the ability of the larger V8 engine, when needed. This is almost like an adjustable engine present within the vehicle.

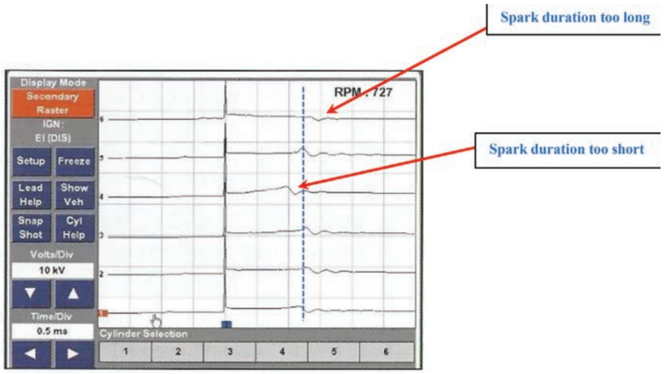

FIGURE 2-22 The control system that disables the cylinders is primarily oil driven on the Dodge or Chevy applications. The PCM controls the ability of the engine to actuate the valve, which leads to the combustion event in the cylinder. The PCM turns the valve off, which minimizes the fuel used in the engine.

Along with deactivating cylinders through lifter control, modifying the amount of valve lift is another common way to adjust the performance of the engine, based on the operational situation. **Variable valve lift (VVL)**, in its various forms, allows the PCM to customize the amount of valve lift, as well as the timing of the event (**FIGURE 2-24**). When the PCM decides that increased or decreased power is desired for ICE operation, it actuates a lever or a solenoid to mechanically control fluid flow to the change mechanism. This change allows the engine to increase power or change the way the combustion event happens within the cylinder. This can change the

FIGURE 2-23 Controlling the oil flow to the lifter will allow the lifter to operate, or not. All that controls it is a simple electronic solenoid that must be electrically actuated by the PCM.

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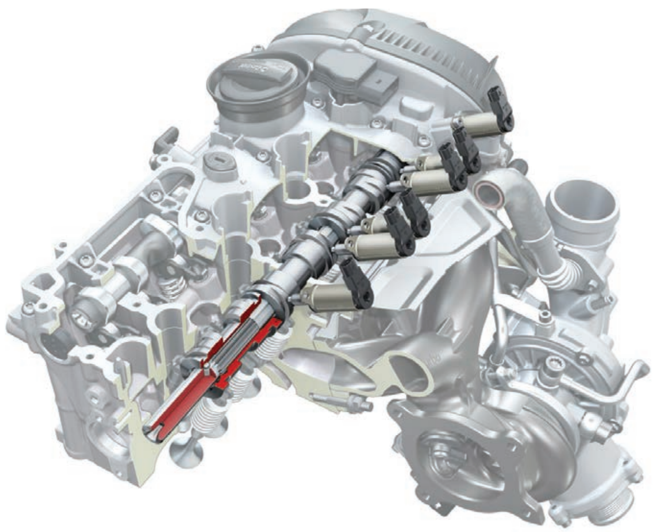

FIGURE 2-24 Variable valve lift (VVL), coupled with VVT, allows the PCM to determine the exact situation that the engine needs to be put in to be the most efficient and create the most power possible.

© Audi AG.

four-stroke Otto cycle into more of an Atkinson type of event, which can increase efficiency, when desired.

Variable Compression/Lift Technologies

This section will highlight two different technologies that are used to help adapt the ICE to the needs of the driver and increase power/mileage along the way. The first type of technology is **Fiat's MultiAir® system**. This system utilizes a typical ICE with special valve train control to adjust the way the events happen within the

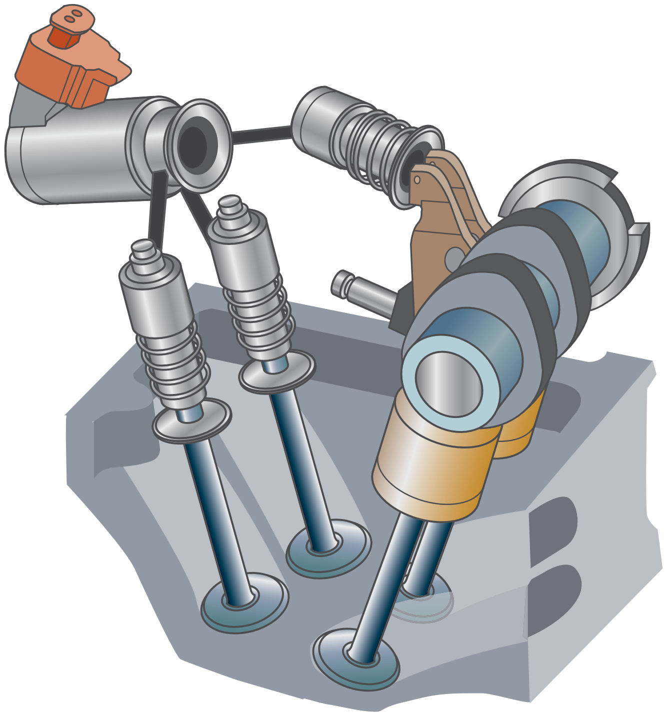

FIGURE 2-25 The MultiAir® system relies on quality engine oil present in the engine, as well as proper maintenance being conducted to maintain clearances within the valve train. With poor maintenance or engine oil that does not meet specifications, the operation of this system will be compromised.

engine. The four-stroke Otto cycle happens regularly to allow the power to be developed when needed. When the situation is right and fuel mileage can be saved, the PCM changes the way the intake valve opens to increase the open time, reducing pressure within the cylinder. This infinite adjustability of the valve train is accomplished by hydraulic pressure contained in the actuator piston on top of the intake valve (**FIGURE 2-25**). This disconnection of the physical camshaft with the valve allows for use of the camshaft lobe to generate pressure for the actuation event and the hydraulic pressure to control the amount the valve lift can affect that event. As the PCM pulses the solenoid that controls the pressure to open the valve, the valve can open as little or as much as the solenoid allows the hydraulic pressure in. This infinite ability to change the valve event changes as the needs of the engine change.

The next technology that we are exploring is **Nissan's Variable Compression (VC)** engine. This type of technology has the ability to change the compression ratio of the engine while the engine operates (**FIGURE 2-26**). This change of compression ratio allows the PCM to decide whether the engine needs to produce more power or minimize power and increase mileage output. As the engine operates, the PCM determines whether or not to go into fuel-saving mode, so it rotates the actuator and moves the upper link to put the piston back in line with the piston, thus minimizing the angle and decreasing friction (**FIGURE 2-27**). As the PCM determines the engine needs to output more power, it rotates the actuator to a more upward location

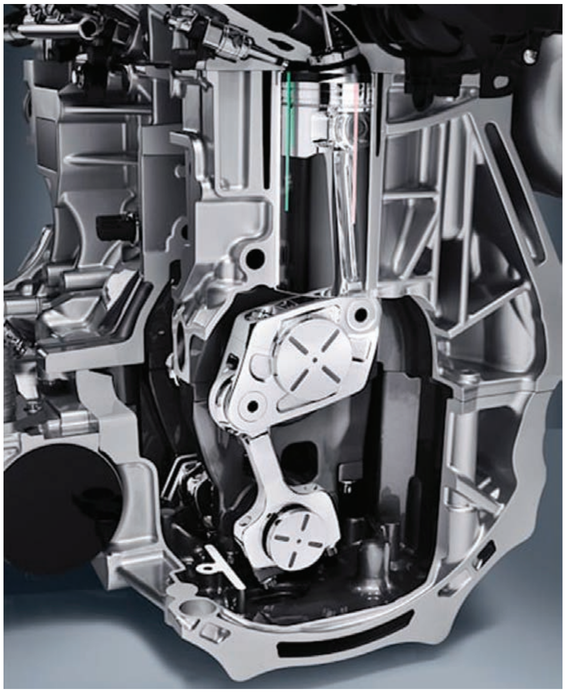

FIGURE 2-26 The Nissan Variable Compression (VC) engine has the ability to change the compression ratio when the PCM determines the desired output of the engine, based on the driver's input. This is a new technology that has a lot of moving components that must work together to function properly.

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to increase compression, thus increasing power output of the engine. There are a lot of components that are moving to make this event happen, which is why regular maintenance is a requirement.

Gasoline Direct Injection Engines

LO 2-4

Assess hybrid vehicle gasoline direct injection (GDI) engine technologies.

When looking at ICEs that power HEVs, the technician must understand the operation of various types of technologies. The ICE can decrease emissions and increase power output to propel the vehicle. Coupling the increased efficiency of the ICE with an electric vehicle (EV) powertrain, the HEV can minimize the emissions output of the gasoline engine. Operation of this combination of technologies keeps the HEV operating with minimal disturbance to the vehicle operator. This conversion of a normally powered automobile to an HEV allows the driving public to get used to operating an EV while still maintaining the ability to fill up at any local fuel station.

The next evolution of the gasoline engine is gasoline direct injection (GDI). This is a combination of both an SI engine and a compression ignition (CI) engine. The ability to produce more power with less emissions is possible because this engine uses higher compression ratios and more

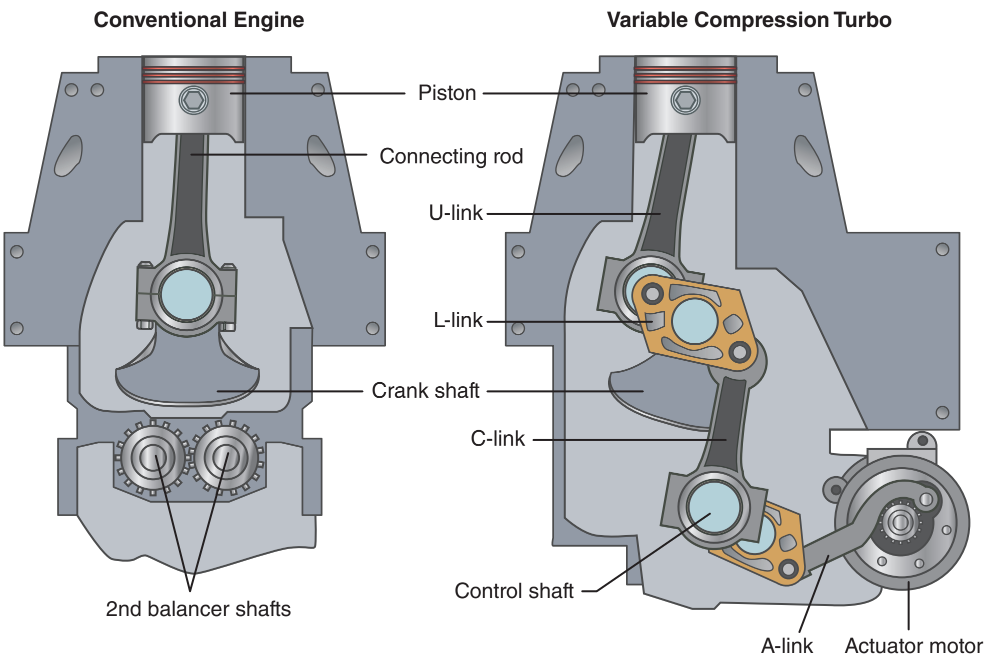

FIGURE 2-27 The VC engine uses an actuator motor and linkage to limit the upward movement of the piston in certain situations. This type of application requires proper maintenance to maintain all of these moving components.

FIGURE 2-28 The gasoline direct injection (GDI) engine has some minor differences from a typical SI engine. The major differences are the design of the piston face and the position of the fuel injector.

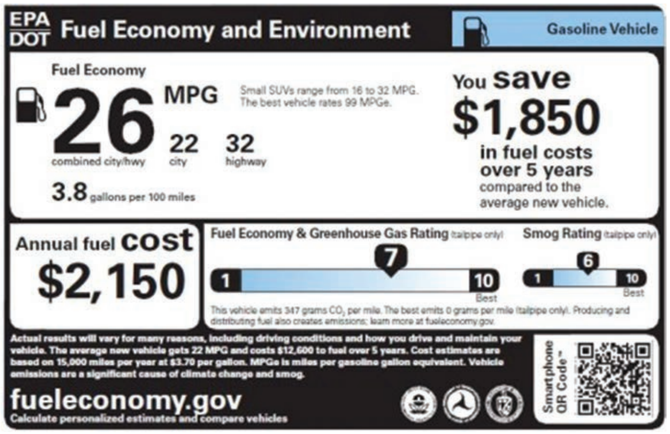

FIGURE 2-29 The increased efficiency of GDI has helped encourage manufacturers to adopt this new technology. With government mandates on vehicles' fuel efficiency, this is the next step in ongoing progression toward more efficient automobiles.

precise control over fuel injection. This type of engine puts the injector into the cylinder and allows for multiple injection events to control when combustion is happening. The engine is compressing air until the last minute. The design of the engine is somewhat different than a conventional engine, in that the pistons and the cylinder head are more of a requirement to help with complete combustion within the cylinder (**FIGURE 2-28**). The design of the piston head creates turbulence, which causes the fuel to atomize as it hits the machined piston head, resulting in a more efficient combustion process. This process allows for a more complete combustion, which lowers emissions, improves performance, and increases the longevity of the engine.

Introduction of Gasoline Direct Injection Engines

The introduction of GDI for use in the production automobile has marked the next evolution of the gasoline engine. Increasing the power by increasing the compression within the engine helps decrease emissions and increase fuel economy (**FIGURE 2-29**). To gain these features, the fuel system of the internal combustion engine had to change. The basic four-stroke principles have stayed the same, as well as the combustibility of gasoline fuel. The difference is how the fuel is introduced into the cylinder and how the cylinder reacts to the effects of that event. These type of engines go by various names, such as Volkswagen's fuel stratified injection (FSI), GM's spark-ignited direct injection (SIDI), Ford's EcoBoost engine line, and Mazda's direct-injection spark ignition (DISI), to name a few.

Description and Operation

The four-stroke Otto cycle is still one of the most widely used combustion processes in production today (**FIGURE 2-30**). Miller- and Atkinson-cycle engines use a version of either VVT or boosted intake charge but still use a form of the four-stroke Otto cycle. For most GDI purposes, conventional gasoline engine principles still apply. A GDI engine still has all four strokes of a conventional gasoline engine, but the difference is the way that the fuel is introduced to the combustion chamber. In a conventional port fuel injection (PFI) system, the fuel is sprayed at the back side of the intake valve. The fuel then stays there until the valve is opened, at which point it is pulled into the combustion chamber during the intake stroke (**FIGURE 2-31**). This system works in conjunction with the mechanical operations of the engine to sustain combustion.

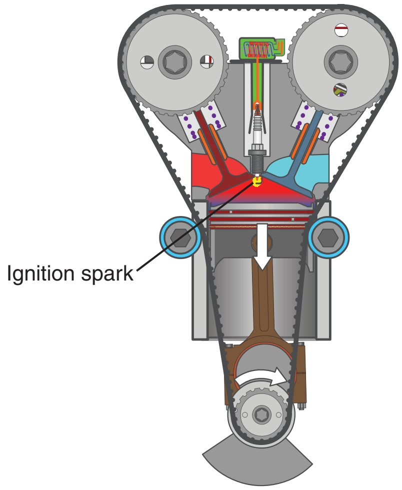

FIGURE 2-30 The Otto four-stroke cycle is used in most ICEs because of its efficiency. This does not change when an engine is using GDI. There are some variants of the Otto four-stroke cycle with the Miller and Atkinson styles of engines. Those types of engines use a different valve timing and/or forced induction to maintain the gains they provide.

The GDI engine uses the same four-stroke Otto cycle, but there are some inherent features that set it apart from a conventional fuel-injected engine. To increase the power output of an engine, the compression ratio should be increased. Some GDI engines run around

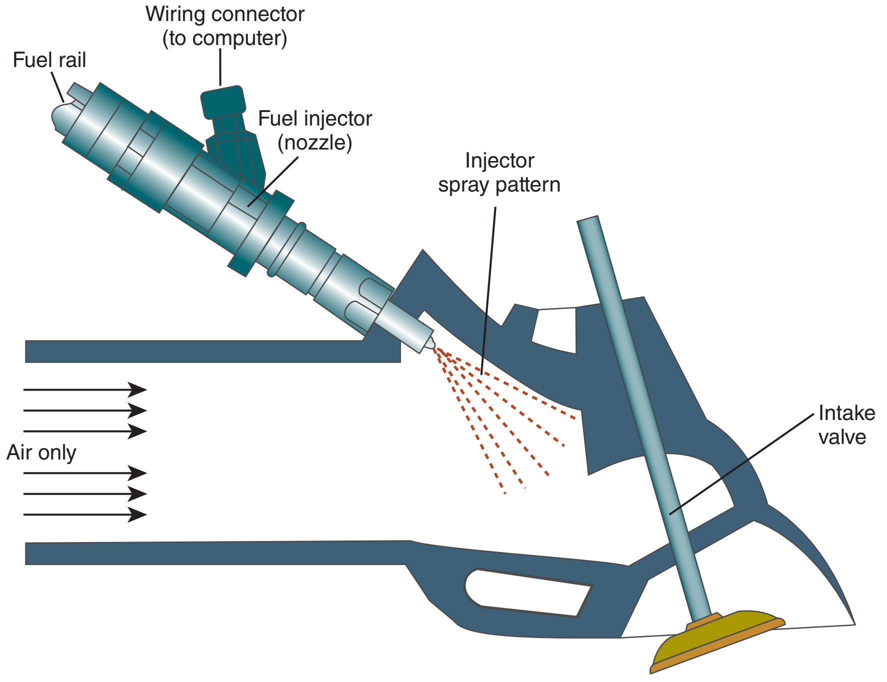

FIGURE 2-31 The port fuel injector is positioned at the back of the intake valve so that when the fuel is sprayed, it stays in the intake port. This helps clean and cool the valve. This feature is lost on a GDI engine because the fuel is sprayed in the cylinder.

11:1 to 14:1 in compression ratio. Increasing the compression ratio with fuel in the combustion chamber can lead to pre-ignition and/or detonation. As the temperature rises in the combustion chamber, the fuel that is in it can spontaneously combust before the proper time of the event. In a GDI engine, the fuel is not injected into the engine until the piston is near TDC. To achieve this feat, the fuel injector is placed inside the combustion chamber so that when fuel sprays, it sprays directly on the top of the piston (**FIGURE 2-32**). Along with this relocation, the injection pressure is increased by the **high-pressure injection pump** so that when fuel comes out of the injector, it can be sprayed in a fine mist to increase efficient combustion. This type of fuel system process is very similar to a diesel engine's common rail-injection operation, which allows the gasoline engine to increase power output with little extra fuel input. To overcome these high combustion chamber pressures, the GDI fuel-injection pump creates 500 to 3,000 psi (35–207 bar) on some models. This pressure is needed to properly inject, atomize, and control the fuel flow into the combustion chamber. Fuel is supplied to the high-pressure pump by a low-pressure pump, which is usually mounted in the fuel tank. In some applications, the high-pressure pump acts as the lower pressure pump by using suction to move fuel from the tank to the high-pressure pump. The PCM must monitor the inlet pressure and the outlet pressure so that the engine is operating correctly to maximize performance. Along with the changes in fuel systems, the engine's pistons must be

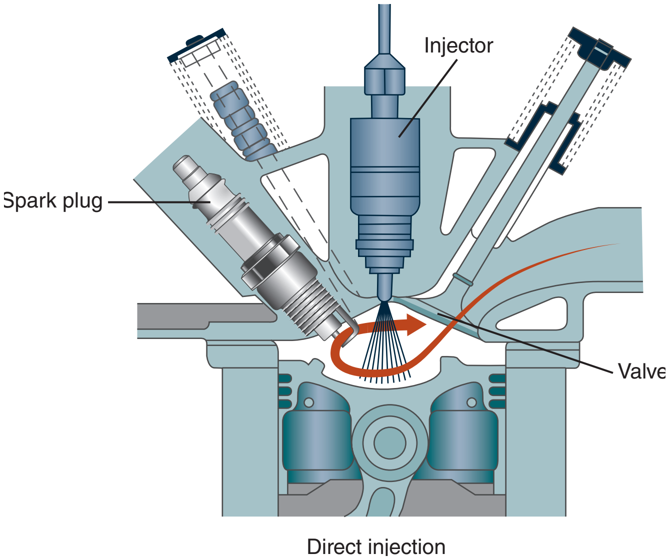

FIGURE 2-32 The GDI injector sprays directly into the cylinder like a direct-injection diesel engine. This allows for more precise control of when the fuel hits the top of the piston, and the PCM can electronically adjust this control.

designed to help with fuel dispersion once it is injected into the cylinder (**FIGURE 2-33**). A conventional piston is usually concerned with piston-to-valve interference, not with how the fuel is atomized within the cylinder. With GDI, the piston design plays an integral part of how the fuel is atomized within the cylinder, so it must be designed to maximize the fuel injection.

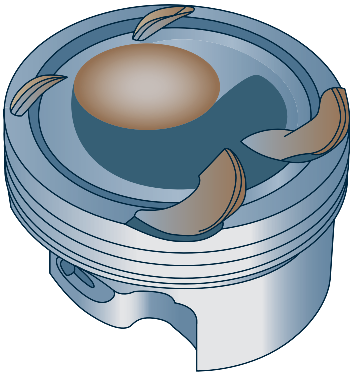

FIGURE 2-33 The design of a GDI piston helps disperse the fuel once it has been injected into the cylinder. When the fuel hits the piston, it atomizes to mix more with the air in the combustion chamber. This provides a more complete and powerful combustion event, which leads to more power and less emissions.

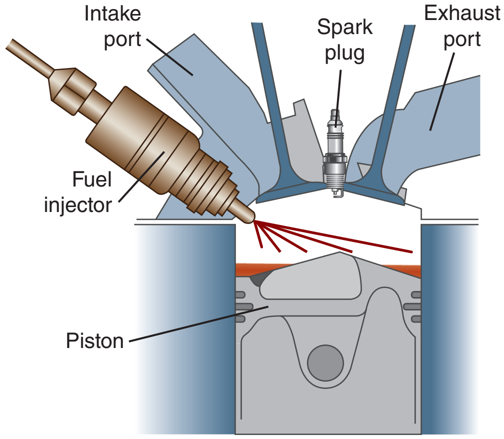

FIGURE 2-35 The GDI piston head helps direct fuel toward the spark plug so that it is able to be efficiently combusted to create the greatest possible power.

FIGURE 2-34 The GDI piston is designed differently from a conventional piston: It plays a role in directing fuel toward the spark plug for more efficient combustion.

FIGURE 2-36 The port fuel injector is smaller than the GDI injector because it only has to reach the intake port to fill up the back side of the valve with fuel. The GDI injector has to reach all the way into the combustion chamber.

Gasoline Direct Injection Engine Components

Piston Designs

A comparison of the piston design of a conventional port fuel-injected engine and that of a GDI engine reveals that the pistons in a GDI engine are designed to direct the fuel that is injected into the cylinder toward the spark plug. By directing the fuel up and toward the spark plug, the air-fuel ratio can get as high as 30:1. This lean condition allows for a highly efficient engine. The downside of running an engine this lean is that it runs very hot, which can lead to the production of NOx. This is remedied by introducing EGR into the cylinder to cool the combustion chamber temperatures.

The design of a GDI piston is contingent on the location of the injector in the combustion chamber. The purpose of the design is to push the fuel injected into the cylinder toward the spark plug (**FIGURE 2-34**). The interchangeability of pistons within this type of engine is not possible because depending on the location of the piston in the engine, it may affect the fuel direction when it hits the piston (**FIGURE 2-35**). The atomization of fuel within the cylinder is one of the features of the pistons; another is the higher compression ratio. By increasing the compression ratio within the engine, the efficiency and the power output increase. Because of the increased pressures within the cylinder, the pistons in a GDI engine must be much stronger than those in a conventional engine. As these pressures increase, the use of forged pistons in GDI applications is becoming the acceptable practice by manufacturers of these types of engines.

Injectors

A GDI engine, like a conventional combustion engine, uses a fuel injector to introduce fuel into the combustion chamber (**FIGURE 2-36**). The location of the injector is different, though, because the GDI injector is located within the

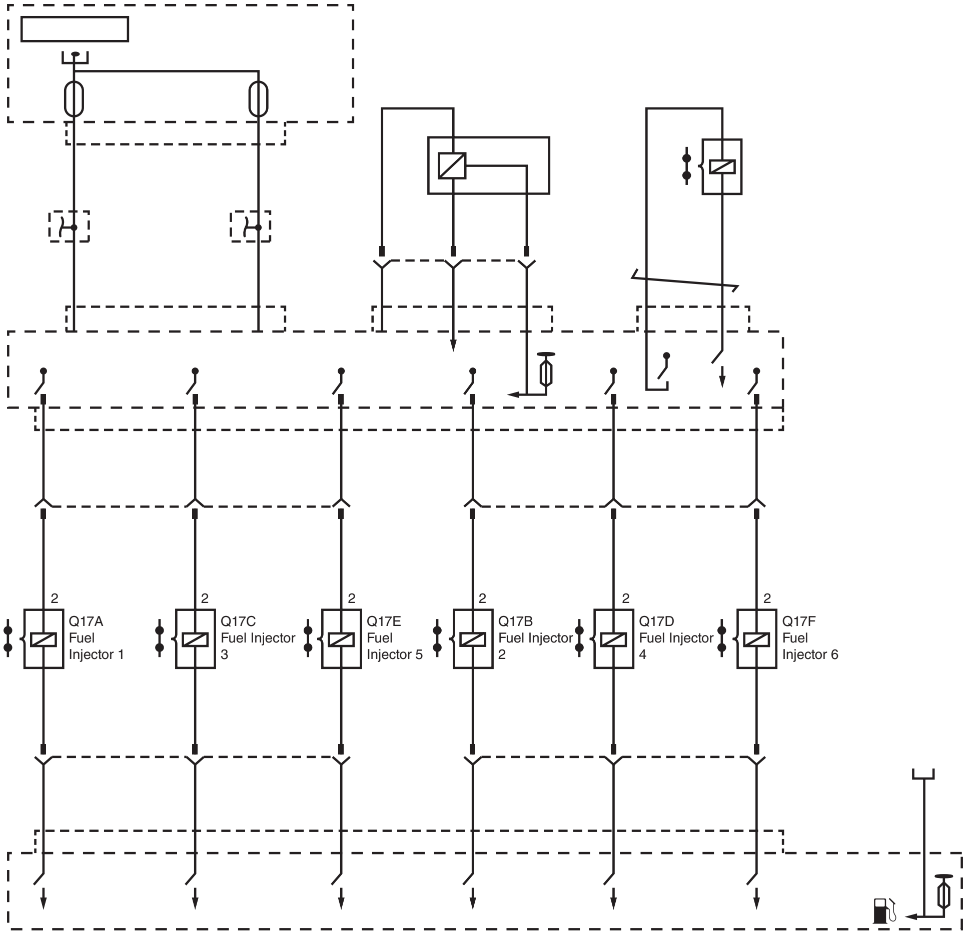

FIGURE 2-37 The GDI injectors use step-up transformers to induce a higher voltage, overcoming the increased pressures in which the injector operates. The injector is trying to overcome both the combustion and increased fuel pressures.

combustion chamber. The ability of the injector to directly inject fuel into the combustion chamber allows the PCM to precisely control how much fuel enters the cylinder and at what point. The port fuel-injection system sprays fuel at the back side of the intake valve, hoping that all of it will be delivered into the cylinder. To make the injection event happen at the correct time, the PCM uses CMP and crankshaft position (CKP) sensors to coordinate the opening of the injector. This allows for having multiple injection events to better fill the cylinder before the ignition event happens.

Due to the extreme pressures that the GDI injectors are subjected to, vehicle battery voltage is not sufficient enough to open the injector's pintle. Because of this increased pressure, the injector must first be opened with a higher voltage, around 65 volts. This is used to overcome the increased pressure; once the injector is open, the voltage returns to 12 volts to maintain the position of the injector pintle. The injection control voltages above the normal battery voltage are created within the PCM, using step-up transformers so that it can induce the needed voltage to overcome the increased pressures (**FIGURE 2-37**). In order to introduce the fuel into the combustion chamber in the correct location, the tip of the injector has precision machined holes in specific locations to direct the fuel toward the machined surface of the piston head (**FIGURE 2-38**). The injector has a slender tip so that it can protrude through the cylinder head, and it allows the cooling jacket around the injector to help cool the head of the injector in the combustion chamber (**FIGURE 2-39**). To help control emissions and carbon inside the engine, manufacturers are trying different styles of injectors to increase longevity and decrease maintenance.

Regulator

The regulator is integrated into the low-pressure side of the GDI fuel system so that when the fuel in the line expands, it has a place to exhaust (**FIGURE 2-40**). When the vehicle sits for a period of time and hot soaks, the regulator allows for the expansion of the fuel in the fuel line. When the fuel expands, the regulator allows the increased pressure to be returned to the fuel tank from the line to prevent component damage. For normal operation, the regulator should not be needed, because the PCM is constantly getting a fuel pressure reading from the **high-pressure fuel sensor** on the fuel rail or injection pump. This sensor allows the PCM to use PWM on the high-pressure fuel pump so that

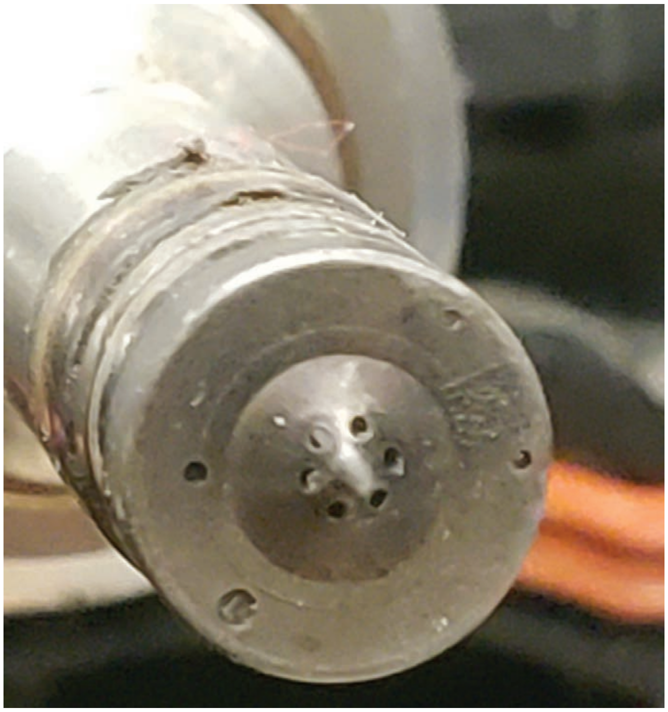

FIGURE 2-38 The machined holes in the tip of the injector help atomize and direct the fuel flow toward the correct location on the piston head. The pressure and direction allow for the piston head to control the splash and direct it toward the spark plug for a more complete combustion event.

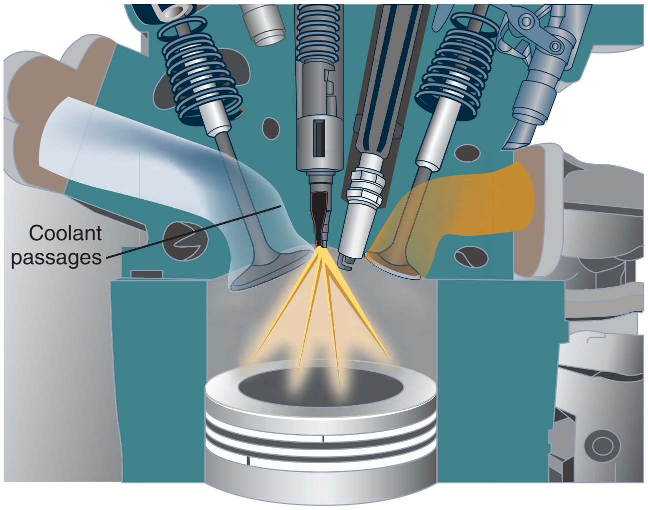

FIGURE 2-39 The GDI engine must be cooled to help with keeping the fuel in the injector in a liquid form so that it can be injected properly. If the injector were not cooled, the fuel would vaporize, and the injector may overheat and not operate correctly.

excess pressure will not be built up in the high-pressure fuel system. Knowing the pressure on the high-pressure side of the fuel system will indicate the amount of pressure needed from the low-pressure side of the system to fulfill the needs of the engine. Fuel pump modulation increases the life of the fuel pump and prevents the need for an active fuel pressure regulator.

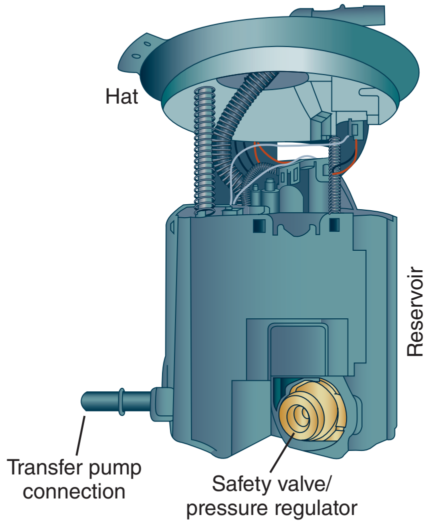

FIGURE 2-40 The regulator for the GDI engine is located on the low-pressure side of the fuel system in the fuel tank so that the expansion of the fuel can be handled before it causes component failures.

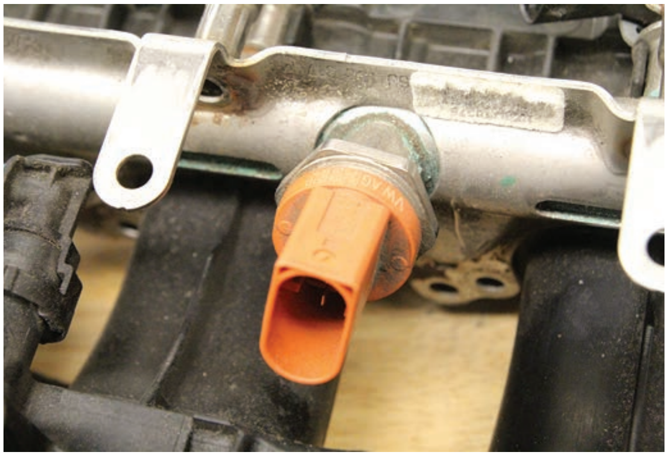

FIGURE 2-41 The high-pressure fuel sensor is used to monitor the fuel pressure on the high side of the fuel-injection system. This pressure is used by the PCM to change output of the pump to match the needs of the engine.

High-Pressure Fuel Sensor

To help the PCM regulate the on time of the low-pressure fuel pump and the high pressure, the GDI fuel system employs a high-pressure fuel sensor that monitors the high-pressure injection pump's output (FIGURE 2-41). This sensor is basically an electrical transducer that takes a mechanical pressure and turns it into an electrical signal that can be used to determine how the fuel system is operating. The electrical transducer has a very simple layout for operation: a one-wire 5-volt reference signal and ground (FIGURE 2-42). This sensor is essential to the operation of the fuel system on a GDI engine. Without the input from the high-pressure fuel sensor, the PCM would not know what the fuel system was doing or the needs of the engine.

FIGURE 2-42 The high-pressure fuel sensor is a very simple transducer that gives feedback to the PCM so that it understands the amount of pressure that is present in the high-pressure side of the fuel system.

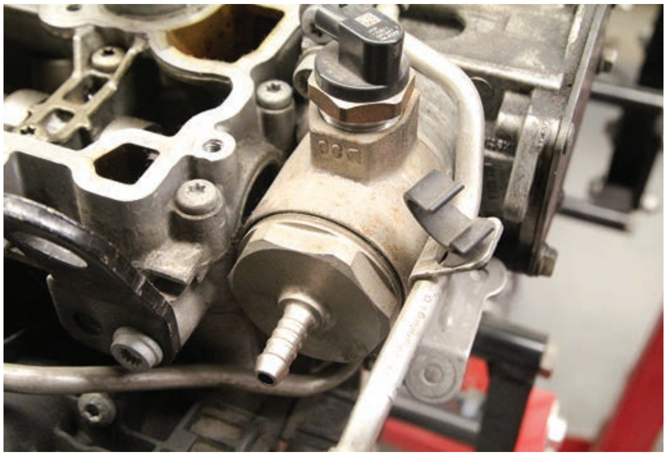

FIGURE 2-43 The high-pressure injection pump is used to create the pressure necessary to overcome the combustion chamber pressures in order to create a combustion event.

High-Pressure Injection Pump

The heart of the high-pressure fuel system is the high-pressure injection pump (**FIGURE 2-43**). The high-pressure pump consists of a three- or four-lobe design, located on the camshaft, that allows it to create the pressure needed to overcome the combustion chamber pressures. By using the camshaft to actuate the fuel pump, the pump will operate as long as the camshaft is turning. When the camshaft stops, pressure development stops. The camshaft lobe pushes a single-piston barrel pump that the PCM controls by monitoring the fuel pressure sensor located on or near the pump. Using a control valve in the fuel pump, the PCM changes the amount of pressure that the injection pump is creating. The fuel pumps on a GDI-equipped vehicle have an infinite number of combinations for controlling each fuel pump so that the injectors receive the correct amount of fuel pressure.

Modes and Applications

Electronic Control Modes of Operation

When GDI is in operation, the PCM determines which mode is best for the engine's current situation. The ability of the PCM to change the way that it introduces fuel into the combustion chamber allows it to maintain the optimal mixture for the engine's situation. The first mode is called the **stratified charge mode**. This is an ultra-lean burn mode that is used for low-load conditions or when the engine is reducing speed. The fuel is injected in the final stages of the compression stroke, which reduces the amount of fuel needed to create a combustion event. This results in a very lean condition and allows the fuel to mix with only a smaller portion of the intake air in the cylinder. This increases fuel economy, and the extra air in the cylinder can be used for a cooling effect on the combustion event.

The **homogenous operation mode** is used for acceleration, full load, or high-engine speeds. This mode injects the fuel during the intake stroke, which allows the fuel to fully mix with the intake air. This condition creates a condition that is closer to the correct stoichiometric mixture, which decreases the emissions from the engine. To achieve this, the mixture is slightly rich when it is injected into the engine, causing the power to increase. The transition from homogeneous to stratified mode is called homogeneous-stratified mode. This mode uses a double injection event: once on the intake stroke and then again at the end of the compression stroke. This is done in two events to reduce the soot produced by the combustion process. Double injection can also be used to heat the catalyst in stratification mode.

Dual Injection Fuel Systems

Direct injection does have some issues with operation because of the increased heat and carbon buildup. When using direct injection, the major mechanical components that are constantly exposed to high temperatures do not have the ability to cool themselves efficiently. When a PFI system was used on an ICE, the fuel was used to clean the engine, as well as to help transfer some of the heat to different areas of the engine, which increased component life. The engine has the ability to use the cooling and cleaning properties of port fuel and gains the increased performance of direct injection by combining both types of injection (port and direct).

The port fuel injector is used to help cool the airflow as it enters the cylinder. Spraying the fuel onto the back side of the intake valve helps clean the valve and decrease the possibility of engine drivability issues (**FIGURE 2-44**). PFI systems work better at lower rpm to decrease the particulate matter (PM) produced by a very lean, hot

FIGURE 2-44 Using dual fuel systems helps minimize the maintenance needed on the fuel system. This also helps the engine meet tightening emission standards across the world.

FIGURE 2-45 The noise-absorbing material is used to stop the fuel system noises from escaping the engine compartment.

combination. The port fuel injectors also do not make the noise that GDI injection does, so this combination will take the load off the GDI components, which can potentially lower the noise created from engine operation. The PCM has complete control of both of the systems, so it can use both when it is possible to increase power and decrease maintenance on the system. Toyota has been using its D-4S system since the early 2000s to meet the efficiency and pollution guidelines for acceptable levels of miles per gallon (liters per 100 km) and parts per million (ppm) of pollution. This technology has been refined to work out any issues with using both systems simultaneously. Combining the systems can lead to an engine that can meet emission standards and also create a better experience for the driver.

Noise and Maintenance Issues

The increased pressures in the fuel system, the increased voltage used to open the injectors, and the design of the combustion process all affect the increased noise in the engine. The GDI "rattle" is more apparent on early engine models because the acoustics had not been worked out yet. To verify that this is normal operation, find a similar known-good engine and verify that it makes the same type of noise. OEMs have tried to minimize the noise heard by the human ear by pairing the fuel system with noise-absorbing material (**FIGURE 2-45**). If the results of the comparison with another vehicle are inconclusive, the next step is to check technical service bulletins (TSBs) to determine whether there are updated components and/or a software update that may help with reducing the noise.

Another issue apparent in many GDI applications is carbon buildup on the injector and the intake valves. Because the injector is in the combustion chamber, it can get very hot, which can create an environment

FIGURE 2-46 The buildup of carbon on the tip of an injector can cause the spray pattern to not match what is needed to promote proper combustion.

conducive to the buildup of carbon on the tip of the injector (**FIGURE 2-46**). This can restrict the flow of fuel from the injector into the cylinder, which can cause drivability or fuel economy issues.

Another area of concern are intake valves, because they are exposed to the same temperatures as the injector, but they are also susceptible to carbon buildup. In earlier PFI engines, the fuel from the injector would constantly wash the back side of the intake valve, which cleaned and cooled it. Now that the fuel is injected directly into the cylinder, the valve has no other way than the cylinder head water jackets to cool itself. As the carbon builds up on the intake valve, it eventually does not allow the intake valve to seal on the seat, which then can cause a leakage of combustion pressures. That leakage can cause a misfire, which can lead to a drivability problem (**FIGURE 2-47**). Cleaning the intake valves requires a carbon deposit fuel system cleaner. In some applications, it may be necessary to clean the valves with a brush to break up the carbon deposits. This can be done by removing the intake manifold if the valves can be accessed

FIGURE 2-47 Carbon can keep valves from sealing correctly and cause a drivability issue. To fix this issue, the cylinder head may need to be removed in order to remove the valve and clean it.

FIGURE 2-48 GDI ICE applications within an HEV drivetrain help lower emissions and increase power output for vehicle operation. This increase in power (out of the same input of fuel) will further increase the range of an HEV.
Used with permission from Hyundai Motor America.

through the intake ports. If the ports are not accessible, then the cylinder head must be removed to access the valves.

Hybrid Electric Applications

HEV operation requires an ICE to generate power for the high-voltage system. Decreasing emissions and increasing the power output is the goal of the OEMs when designing an HEV. Highly efficient operation is the key to increasing HEV range and decreasing the effect on the environment from ICE emissions. Employing a GDI engine in an HEV application can further minimize the harmful NOx and carbon monoxide emissions from the chemical conversion of petroleum products to mechanical motion (**FIGURE 2-48**). This creates a vehicle that mimics a conventional gasoline-powered vehicle while introducing the operator to an electric propulsion system characteristics. When looking at these HEV applications, making the engine operate as efficiently as possible and keeping the maintenance requirements at a minimum is crucial to having a successful application. A unique application is Toyota's synergy drive, which is powered by a GDI engine with a D-4S fuel injection system (**FIGURE 2-49**). Along with this fuel injection system, Toyota integrates the Atkinson cycle in this type of application to further increase the fuel mileage within the HEV. Combining these types of technologies creates an application that has the benefits of both a port fuel engine and the increase efficiency of a GDI engine.

FIGURE 2-49 The Toyota D-4S system utilizes both a port fuel injector, along with a GDI high-pressure injector. When the vehicle is in cleaning mode, the PCM utilizes the port fuel injectors to clean the intake valve when engine operation dictates cleaning is required.
Courtesy of Cllackr/Wikimedia.

Compression Ignition Engines

LO 2-5

Examine applications of homogeneous charge compression ignition engine technologies.

A CI engine is very similar to an SI engine, apart from the fuel and a spark plugs. Most CI engines use a lower-grade petroleum product that is less likely to spontaneously combust than gasoline. With a fuel that is more tolerant to high temperatures and pressures, the engine can have a higher compression ratio that increases the power output from the chemical input. This process is still a four-stroke Otto cycle, but without the aid of an ignition system. Lacking this system minimizes the number of pieces that could fail (**FIGURE 2-50**).

FIGURE 2-50 CI engines can come in all sizes and are designed to work for the needs of the application they will be used in.
Used with permission from Volkswagen AG.

All of this increased power comes at a cost of increased emissions from higher temperatures in the combustion chamber, increased noise from the combustion process, and soot from unburnt particulate matter. Emissions and noise have been the weaknesses of CI engines: The noise has been a customer concern, and the emissions have been a governmental one. The efficiencies that CI are known for are the reasons that it is heavily used in the heavy trucking/equipment industries. Moving big equipment reliably and cost effectively is the goal of any company, which means CI engines are the answer. The passenger vehicle market has recently seen a new resurgence of light-duty diesel engines whose noise, emissions, and stigmas have changed, so they are now more appealing to the customer.

The newer CI engines behave like their SI counterparts in noise, emissions, and availability. What they excel in is the increased power that comes from their design. This increased power comes from a heterogeneous burn, which creates power at lower speeds than an SI engine. Unfortunately, as technology advances and vehicles are engineered more to behave like the consumer wants, the higher the cost becomes, which is why most of these types of applications are more expensive than their SI competition. As energy changes within a CI engine from a chemical fuel to a mechanical motion, the efficiency of the conversion event increases to higher than that in an SI engine, which is where the benefits come from.

Thermal Efficiency of a Compression Ignition Engine

The thermal efficiency of a CI engine is where the engine creates its higher output per input. A CI engine is 30 to 35% efficient in the way it uses the potential heat input to create an output. This lean burn type of combustion process, coupled with a higher compression ratio than an SI engine, is the main reason why it is the chosen type of engine for industry. The main driver of thermal efficiency in any engine is the ability to use a higher compression ratio to increase the complete burn and output power based on input. The higher the compression ratio and complete organic burn of the fuel, the more efficient the engine is considered.

FIGURE 2-51 Increasing the fuel efficiency and combustion process of the ICE occurs through homogeneous combustion.
© Koki Nagahama/Getty Images AsiaPac/Getty Images.

Homogeneous Charge Compression Ignition Engine

The **homogeneous charge compression ignition (HCCI) engine** is a new technology that uses the CI engine's efficient combustion with the ease of operation of an SI engine. Instead of using a lower-grade fuel oil such as diesel fuel, HCCI engines use gasoline, which is known to have better pollution and operational features (**FIGURE 2-51**). The use of gasoline instead of a diesel fuel decreases the temperature that is required to have a combustion event, which lowers the NOx present after the combustion process. Operating under the Otto four-stroke process, fuel is introduced into the cylinder from an injector that is mounted in the cylinder head. As the piston completes its intake stroke, sucking in air and combining that air with fuel, the compression stroke starts at BDC. The piston is traveling back up the cylinder, building pressure as it does so, to the point where the piston reaches before top dead center (BTDC). The pressures that have built up cause the fuel to spontaneously combust, starting the combustion process. This process produces a lean condition that maximizes the air-fuel ratio, which promotes complete combustion with far less emissions.

The biggest issue is controlling the timing event for the combustion process. With conventional SI engines, simply controlling injection and ignition timing could be done by the PCM. In the HCCI engine, the combustion event is not directly controlled by the PCM; it is more of a molecularly controlled event. When the combustion occurs with no spark, complete combustion happens, which limits the thermal loss from the event, thus helping to more quickly prime the cylinder for the next event. The temperature up within the cylinder can be maintained by varying valve events and introducing EGR into the cylinder.

FIGURE 2-52 Mazda uses a hybrid type of homogeneous charge compression ignition (HCCI) engine that uses SI and CI types of technologies to increase the fuel efficiency and power of the engine.
Used with permission from Mazda Motors Corp.

Mazda Spark Controlled Compression Ignition Engine

Mazda's spark controlled compression ignition (SPCCI) engine version uses a spark plug to help with ignition when the conditions are not optimal for HCCI combustion (**FIGURE 2-52**). The types of situations would be cold start, when ambient temperature is not high enough to promote combustion, and high-load situations, where the HCCI is not as reliable. When the spark plug does operate, it will work to change the compression ratio to a lower one that would work better with SI. To allow for the change from HCCI to SI, the engine will change its timing through the PCM and valve timing to allow it to operate simultaneously on both types of systems. Mazda is using the spark plug to start the combustion event—to increase combustion chamber pressures to the point that the fuel around the spark event will spontaneously combust, thus starting the HCCI event. This change from one to the other is where concerns could arise, so technicians must understand this process when they diagnose the potential concerns with this type of system.

WRAP UP

Ready for Review

- In most HEV applications, the ICE is primarily used for power generation for the EV drivetrain.
- To help with increasing ICE operational mileage, regenerative braking helps recapture expended energy and recharge the battery pack.
- The HEV is an intermediate step between a conventional ICE powered vehicle and a pure EV.
- The PHEV is an HEV that allows the operator to recharge the battery pack from home power to extend its range before it runs the ICE to recharge the vehicle.
- Maintaining the battery SOC is crucial in maintaining propulsion system operation at optimal speeds.
- An FCEV combines hydrogen with oxygen to generate electricity.
- FCEVs still utilize electric drive propulsion motors to propel the vehicle.
- The only by-product of FCEV operation is H_2O.
- Spark ignition (SI) is an engine used today that has a spark plug to ignite the fuel-air mixture in the cylinder.
- The basic four-stroke cycle for a petroleum-based engine is intake, compression, power, and exhaust.
- An internal combustion engine (ICE) is just an energy conversion device.
- Thermal efficiency of a SI engine is approximately 20 to 30%; a CI engine is approaching 40%.
- The Atkinson-cycle engine uses a modified Otto cycle that decreases load on the piston, thus increasing power efficiency.
- The Miller-cycle engine is similar to the Atkinson cycle except a supercharger is required to maintain the Miller cycle's efficiency, along with a delayed intake valve closure.

- VVT allows for varying valve opening events to increase engine efficiency and power.
- AFM is a GM cylinder deactivation program that takes one of their V8 engines and, under light load, disables four cylinders to improve fuel mileage. This is done by stopping oil flow to the lifters on that cylinder, thus not allowing the valves to open.
- MDS is a FCA cylinder deactivation system that takes their V8 engine and, under the right conditions, disables four of its cylinders, which will increase fuel mileage.
- VVL changes the amount of valve lift when actuated independent of the camshaft.
- Fiat's MultiAir® system changes the actuation of the valves to vary the valve events, increasing power or economy.
- Nissan's VC engine can change the compression of the cylinder, based on engine load.
- The HEV consists of an ICE and an EV drivetrain that allows for extended range after the initial battery charge is depleted.
- To help with ICE efficiency, GDI was developed for the ICE.
- Similar to a diesel engine, the GDI engine only compresses air until the last second before TDC when the injector sprays fuel into the cylinder.
- To help with atomization, the design of the piston head creates turbulence within the cylinder when the fuel is sprayed in.
- The Otto four-stroke cycle is a piston cycle strategy with an equally offset "stroke" of the crankshaft, which creates a good balance of acceleration and economy in a conventional ICE application.
- The use of injectors located in the combustion chamber allows for a higher compression ratio and almost instantaneous combustion when the fuel is injected.
- To overcome the high-compression pressures in the combustion chamber, the fuel injected into the cylinder must be done in a high-pressure format. This is done through the high-pressure injection pump.
- GDI injectors operate on a higher voltage than the port fuel type of injector that is on a conventional ICE.
- The high-pressure fuel sensor controls the operation of the high-pressure fuel injection pump to maximize fuel pressure within the system at all times.
- The stratified charge mode is utilized for a lean burn situation.
- The homogeneous operation mode is utilized for acceleration.
- Some applications have both type of fuel injectors to help smooth out emissions and increase smooth operation.
- On most GDI applications, the lack of spraying fuel on the back side of the intake valve to cool it allows for heavy carbon buildup on the valve face.
- As the carbon builds up, the valve may not close properly and may cause a misfire condition.
- Utilizing a GDI in an HEV application allows the vehicle to have the best of both worlds.
- A CI engine utilizes spontaneous combustion of a fuel on a molecular basis.
- The downside to a CI engine is increased combustion temperatures, which can increase emissions.
- Newer CI engines are just as quiet as their SI counterparts.
- The thermal efficiency of a CI engine is approaching 40%, far higher than a SI engine.
- A homogeneous charge compression ignition engine (HCCI) utilizes gasoline in a compression ignition engine application, thus lowering emissions output and increasing power.
- Mazda's SPCCI engine utilizes a spark plug to increase the combustion pressures within the cylinder to get them where the rest of the gasoline will ignite.

Key Terms

Active Fuel Management (AFM) GM's proprietary cylinder deactivation system on their V8 engines.

Atkinson cycle An engine cycle that uses a longer effective exhaust stroke than intake stroke to reduce exhaust emissions. This type of engine is widely used in hybrid electric vehicles.

battery electric vehicle (BEV) A vehicle powered by battery only.

Fiat's MultiAir® system FCA's variable valve lift system that allows the PCM to determine the best valve lift, based on the situation of the engine.

four-stroke Otto cycle An engine cycle during which the piston must travel the distance of the cylinder (a stroke) four times to complete one cycle.

fuel cell electric vehicle (FCEV) An electric vehicle that converts fuel to electricity in a direct electrochemical process, with more energy extracted from the fuel source than in traditional internal combustion engines.

gasoline direct injection (GDI) A fuel injection system in which fuel is sprayed directly into the combustion chamber.

high-pressure fuel sensor Monitors the fuel rail pressure on a GDI engine and allows the PCM to control the operation of the high-pressure injection pump.

high-pressure injection pump A pump that is mechanically driven that takes a low-pressure fuel and increases pressure to allow for proper GDI injector operation.

homogeneous charge compression ignition (HCCI) engine A gasoline-fueled engine that utilizes compression ignition strategies to combust the liquid gasoline fuel in the cylinder without the aid of a spark plug.

homogeneous operation mode Used for acceleration, full load, or high-engine speeds on an GDI-equipped engine.

Miller-cycle engine An engine cycle that uses a longer exhaust stroke than intake stroke through delayed closing of the intake valve. This engine uses a supercharger to pressurize air into the cylinder when needed.

Multiple Displacement System (MDS) FCA's proprietary cylinder deactivation system that is utilized on the hemispherical equipped pushrod engines.

Nissan's Variable Compression (VC) A Nissan proprietary system that allows for the changing of the cylinders compression ratio by rotating a pivot shaft in the crankcase.

plug-in hybrid electric vehicle (PHEV) A hybrid electric vehicle in which only one power source, the battery, is used to propel the vehicle for a certain distance, limited by the storage capacity of the battery and the efficiency of the motor.

spark ignition (SI) engine An engine that relies on an electrical spark to ignite the air and fuel mixture.

state of charge (SOC) The amount of electrical potential present in a battery cell or battery pack.

stratified charge mode This is an ultra-lean burn mode used on a GDI engine that is used for low-load conditions or when the engine is reducing speed.

top dead center (TDC) The very top of the stroke of the piston in a cylinder, where the piston cannot move any higher.

variable valve lift (VVL) A system that can change the lift of any valve independently of camshaft operation.

variable valve timing (VVT) The advancement or retarding of individual camshafts to increase engine performance.

Review Questions

1. What is the byproduct of the electrical generation process for an FCEV?
   - **a.** CO
   - **b.** CO_2
   - **c.** H_3
   - **d.** H_2O
2. When looking at a BEV, what can now happen because the ICE is removed from the vehicle's operational needs?
   - **a.** Maintenance is no longer required.
   - **b.** Components can be placed for optimal weight balancing and crash protection.
   - **c.** The vehicle will now operate longer than when it was equipped with an ICE.
   - **d.** The driver will now be able to perform basic maintenance themselves.
3. The GDI injector operates off a higher voltage than a port fuel injector because of which of the following?
   - **a.** On an HEV application, the available voltage is higher than a conventional vehicle.
   - **b.** The pintle has to overcome the higher pressures in the fuel injection systems.
   - **c.** The fuel injector operates more efficiently on a higher voltage.
   - **d.** The location of the fuel injector in the cylinder head requires a greater voltage to overcome the heat near the injector.
4. An early model of a GDI-equipped engine has a rattling sound emitting from the intake manifold area. What is the source of this noise?
   - **a.** This is a failure of a fuel injector, and the engine must be serviced to repair this issue.
   - **b.** The engine clearances are greater on a GDI-equipped engine, which increases engine noise output.
   - **c.** It is the combination of the high-pressure fuel injector operation and the combustion process.
   - **d.** When the engine is in cleaning mode, this is a common occurrence while running.
5. How much rotation of the crankshaft would complete a four-stroke cycle in an ICE, regardless of which type of operational cycle the engine runs on (e.g., Otto, Atkinson, Miller)?
   - **a.** 720 degrees
   - **b.** 360 degrees
   - **c.** 270 degrees
   - **d.** 180 degrees

6. The Atkinson cycle does which of the following to increase the efficiency within the combustion cycle?
   a. The piston within the Atkinson-equipped engine has different valve reliefs cut into it, so the compression increases within the cylinder quickly.
   b. The crankshaft on an Atkinson-cycle engine is flexible, which allows for a varying compression ratio as the engine operates.
   c. It holds the exhaust valve open longer than a conventional Otto four-stroke cycle equipped engine.
   d. It holds the intake valve open longer than a conventional Otto four-stroke cycle equipped engine.
7. In an HEV application, what will happen if the ICE is not properly maintained and cannot sustain operation?
   a. The high-voltage propulsion system will overcome the lack of ICE operation and will maintain vehicle speed.
   b. The vehicle will not move, as the ICE propels the wheels in most applications.
   c. The hybrid propulsion system will continue to operate until the battery-pack power is depleted.
   d. The high voltage controller can suspend operation of the high-voltage propulsion system if it sees an ICE related failure.
8. When evaluating a VVT failure situation, what should the technician do before replacing any components on the ICE?
   a. The PCM can pinpoint the valve train issue that is affecting the VVT, so replacing the component based on the diagnostic trouble code (DTC) is okay.
   b. The VVT components cannot be verified by the PCM, as they are all oil controlled, so diagnosing a failure requires disassembly.
   c. The oil level and condition must be verified before replacing any components, as the oil has the ability to actuate the VVT components.
   d. When evaluating the VVT system for failure, the technician must operate the engine in a non-VVT mode.
9. How does the PCM change the compression ratio of the engine in Nissan's VC technology during operation?
   a. The PCM adjusts the piston's diameter mid-stroke to change the surface area of the piston in the cylinder.
   b. Utilizing an actuator, the PCM changes the position of the piston in the bore, altering the effective compression ratio.
   c. The PCM controls the intake valve opening event to keep it open longer so that less air is compressed within the cylinder.
   d. A solenoid controls the operation of the exhaust and intake valves, minimizing the opening event of each.
10. At which of the following two sensors should the technician be looking for a correlation condition in a VVT system?
   a. TPS and CMP
   b. CKP and IAT
   c. CMP and CKP
   d. ECT and MAF

ASE Technician A/Technician B-Style Questions

1. Technician A says FCA Multi Air system changes the opening of the intake valve to increase performance independent of the camshaft. Technician B says when conducting timing chain replacement only replacement of the chain is recommended. Who is correct?
   a. Technician A
   b. Technician B
   c. Both Technician A and Technician B
   d. Neither Technician A nor Technician B
2. Technician A states that low oil level does not affect a VVT system that uses oil to operate the cam phasers. Technician B says a Chrysler MDS system controls oil flow–designated lifters, which can collapse to disable cylinders on the engine. Who is correct?
   a. Technician A
   b. Technician B
   c. Both Technician A and Technician B
   d. Neither Technician A nor Technician B

3. Technician A states that the lifter oil manifold assembly (LOMA) on an AFM engine has all the solenoids and an oil pressure sensor as part of it. Technician B says when testing for operational voltage in the system, the technician should refer to the wiring diagram. Who is correct?
   a. Technician A
   b. Technician B
   c. Both Technician A and Technician B
   d. Neither Technician A nor Technician B
4. Technician A says when oscilloscope testing the oil control valve (OCV), the waveform should be very jagged and drop out a lot. Technician B says base engine mechanical condition should be checked before condemning any other VVT components. Who is correct?
   a. Technician A
   b. Technician B
   c. Both Technician A and Technician B
   d. Neither Technician A nor Technician B
5. Technician A says magnetically actuated phasers use an oil control valve that responds to the electromagnet to control oil flow to the phaser. Technician B says increased usage of VVT/VVL systems will not happen because of the minimal gains. Who is correct?
   a. Technician A
   b. Technician B
   c. Both Technician A and Technician B
   d. Neither Technician A nor Technician B
6. Technician A says a modern GDI engine creates noise, based on the mechanical fuel pump pulses, as it creates pressure. Technician B states that homogenous injection mode injects fuel during the intake event, which allows it to mix with the air in the combustion chamber more thoroughly. Who is correct?
   a. Technician A
   b. Technician B
   c. Both Technician A and Technician B
   d. Neither Technician A nor Technician B
7. Technician A says the GDI piston design depends on where the injector is located in the cylinder head and at what direction it is pointing at the top of the piston. Technician B states that the high pressure injection pump is ran off a belt. Who is correct?
   a. Technician A
   b. Technician B
   c. Both Technician A and Technician B
   d. Neither Technician A nor Technician B
8. Technician A states that when the engine is in stratified mode, it is very lean and can create a very hot condition. Technician B says GDI injectors operate on a 12-volt power scale. Who is correct?
   a. Technician A
   b. Technician B
   c. Both Technician A and Technician B
   d. Neither Technician A nor Technician B
9. Technician A says timing the injection pump to the engine will allow for the pressure event to happen when the injector is open. Technician B states that regular maintenance of a GDI engine may require top end engine cleaning. Who is correct?
   a. Technician A
   b. Technician B
   c. Both Technician A and Technician B
   d. Neither Technician A nor Technician B
10. Technician A says the high-pressure mechanical fuel pump is operated by the camshaft on a GDI equipped engine. Technician B says the fuel injection components of a GDI engine are the same as a conventional PFI equipped engine. Who is correct?
   a. Technician A
   b. Technician B
   c. Both Technician A and Technician B
   d. Neither Technician A nor Technician B

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