# Introduction to Engine Performance – Study Guide



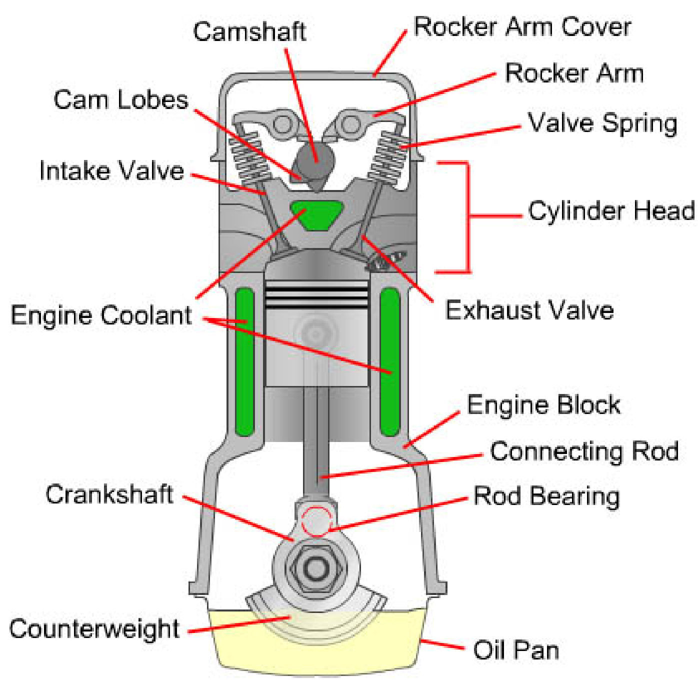
## Introduction

The engine is the power plant of a vehicle. Automotive engines have gone through tremendous changes since the automobile was first introduced in the 1880s, but all combustion engines still have three requirements that must be met to do their job of providing power – air, fuel, and ignition. The mixture of air and fuel must be compressed inside the engine in order to make it highly combustible and get the most out of the energy contained in the fuel mixture. Since the mixture is ignited within the engine, automobile power plants are called **internal combustion** engines. Most can be further classified as **reciprocating piston** engines, since pistons move up and down within cylinders to provide power. This up-and-down motion is converted into turning motion by the crankshaft.

This course will provide an introduction to automotive engines and engine performance. Subjects covered will include:

- Major engine components
- Engine classifications
- The four stroke cycle and other engine design operations
- Engine construction
- Air-fuel systems
- Ignition systems
- Cooling and lubrication systems
- Exhaust systems, computer systems, and emissions
- Engine performance and diagnostic strategies
- Engine diagnostic tools
- Basic diagnostic testing

***Some of the main engine components***




## Course Objectives

Upon completion of this course, technicians should understand and be able to apply and demonstrate their knowledge of:

- Engine classifications and components
- Engine operations and construction
- Engine systems including cooling, lubrication, computer, and fuel and ignition systems
- Exhaust and emissions systems
- Engine performance and diagnostic strategies
- Basic engine diagnostic testing and test equipment

### Using the Job Sheets

As you proceed through this module, on some pages you will find links to job sheets. Each link will open a window with a printable procedure or job sheet that contains hands-on lab activities based on the NATEF standards related to the content you are studying. When you come upon a procedure or job sheet link, you can click on it to access the material and print the job sheet for completion in the shop. See your instructor for guidance in completing the job sheets. Some jobs sheets will require supplemental materials such as a vehicle service manual, equipment manual, or other references. Your instructor may prefer you to print the entire set of job sheets and assign them when appropriate, or your instructor may provide you with the printed job sheets to complete. You can view and print any or all of job sheets for this course by clicking on the “Job Sheets” link.

## Basic Engine Parts and Operation

A small engine, such as one found in a lawn mower, usually contains only one cylinder and piston. Automotive engines use a number of cylinders to produce sufficient power to drive the wheels, but operate much like a small engine in many ways. Let’s look at one cylinder of an engine to see how the main parts work together.

### Engine Block

The block, highlighted here in grey, is a heavy metal casting, usually cast iron or aluminum, which holds the lower parts of the engine together and in place. The block assembly consists of the **block**, **crankshaft**, **connecting rods**, **pistons**, and other components, and is referred to as the **bottom end**. The block may also house the camshaft, oil pump, and other parts. The block is machined with passages for oil circulation called **oil galleries** (not shown) and for coolant circulation called **water jackets**.

***Engine Block***

### Cylinders

The cylinders are round holes or **bores** machined into the block for the pistons to travel up and down in.

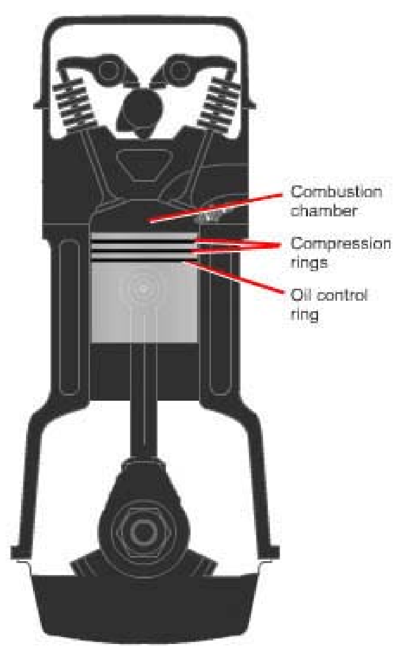
### Pistons

Combustion pressure acts upon the tops of the pistons in the cylinders, forcing them downward. Usually made of aluminum, the pistons transmit the downward force to the connecting rods. The top of the piston’s travel is called Top Dead Center (TDC) and the bottom of a piston’s travel is called Bottom Dead Center (BDC).

### Piston Rings

Rings are installed in grooves around the pistons to form a seal between the piston and the cylinder wall. Two types of rings are used: **compression rings**, which prevent combustion pressure from entering the crankcase, and **oil control rings**, which prevent engine oil from entering the **combustion chamber** above the piston. Oil rings scrape excess oil from the cylinder walls for return to the crankcase.

***Cylinder***



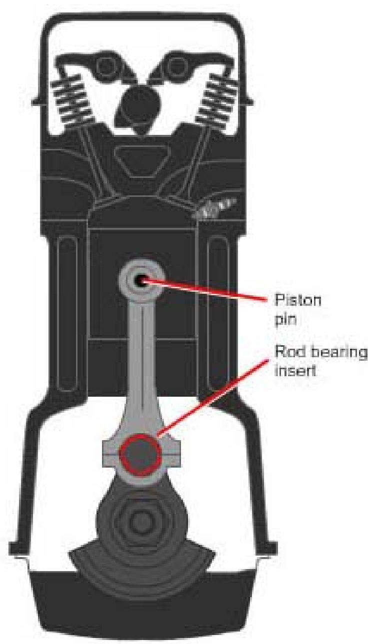

***Piston***

### Connecting Rods

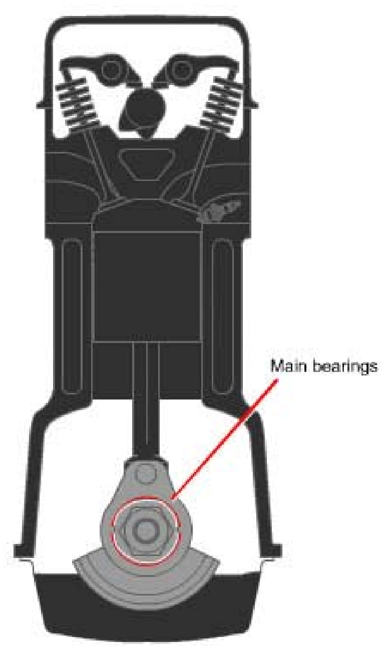
A rod connects each piston to the crankshaft. The small, upper end of the rod commonly has a bushing pressed into it. A **piston pin**, or **wrist pin**, attaches the piston to the rod through this bushing, which allows the rod to pivot as needed. The larger, lower end of the rod is attached to the crankshaft through **rod bearing inserts** that are stationary relative to the rod and allow the crankshaft to turn within the rod on a film of oil.

### Crankshaft

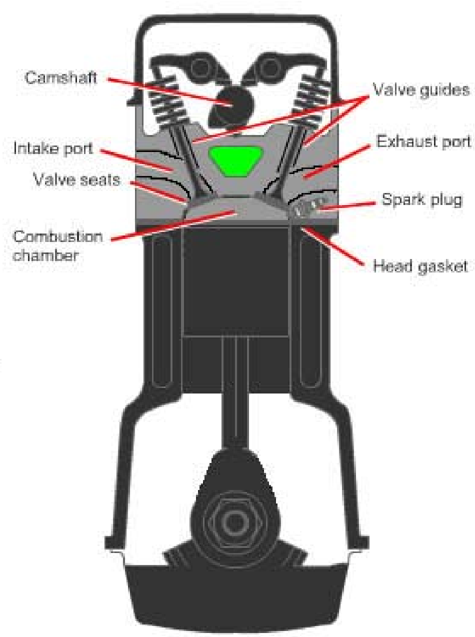
The crankshaft is a strong, alloyed iron or steel shaft that converts the up-and-down motion of the pistons into a turning motion that can be transmitted to the drive train. The crankshaft is supported by the block in several places along its length. The crankshaft rides in **main bearings**, which are inserts similar to the rod bearings at these supports. Where the crankshaft is connected to the rods and where it is supported by the block are called **journals**. The crank is finely machined and polished at these places. The crankshaft is also drilled with a network of oil passages to deliver oil under pressure to these places from the oil galleries. At the front of the crankshaft, outside the engine front cover, a heavy wheel containing a rubber vibration damper is installed. Also called a **harmonic balancer**, it often incorporates the crank drive belt pulley, which powers belt-driven accessories. At the rear of the crankshaft, a large **flywheel** is mounted. The flywheel can serve several purposes: a ring gear is mounted to its circumference to provide a means to start the engine. It also connects the engine to the transmission. Finally, on vehicles with manual transmissions, the flywheel is made very heavy to help smooth out power pulses from the engine (this is accomplished by the torque converter on vehicles equipped with automatic transmissions).




***Connecting Rod***




***Crankshaft***




***Cylinder Head***

### Cylinder Head

The head bolts to the top of the block, covering and enclosing the tops of the cylinders. The head forms small pockets over the tops of the pistons called **combustion chambers**. The **spark plugs** are threaded into holes in the head and protrude into the combustion chambers (gasoline engines). **Intake ports** and **exhaust ports** are cast into the head, and small holes called **valve guides** are machined into it to position the valves. The valves close against machined, press-fitted inserts in the combustion chamber ports called **valve seats**. On overhead cam engines like the one pictured here, the head also houses the **camshaft**. The assembly, together with other valve train components and the intake and exhaust manifolds, is referred to as the **top end**. Between the head and the block, a **head gasket** seals the combustion chambers, and water and oil passages.

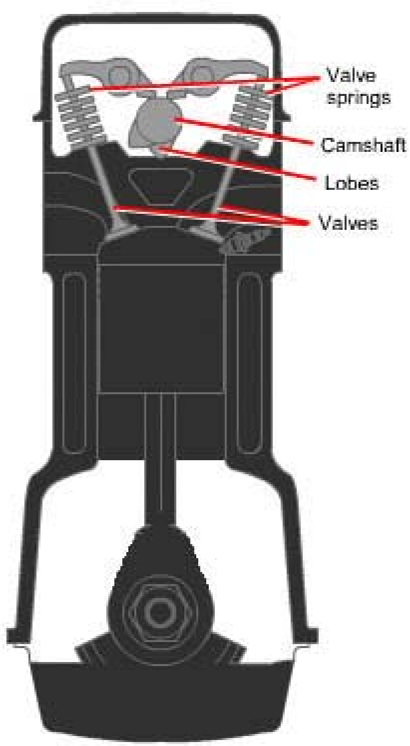
## Valve Train

The valve train consists of the **valves**, **camshaft**, and other associated parts. The valves control the flow of the incoming air-fuel mixture and the outgoing exhaust gasses. The **intake valves** are larger than the **exhaust valves**, and many engines today have two intake and two exhaust valves per cylinder to improve efficiency and performance.

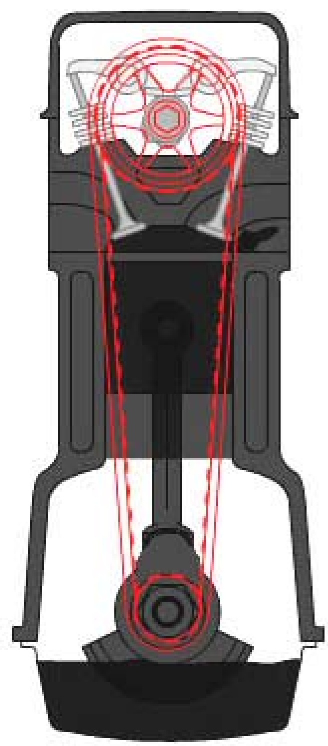
Like the crankshaft, the camshaft rides on a film of oil as it rotates on journals. Rotation of the camshaft opens the valves, and **valve springs** close them. The camshaft has carefully machined high spots called **lobes** that act upon the valves (or other parts) to open each valve at precisely the right time. As the lobe moves away, the spring closes the valve. Some engines have *dual overhead cams* (DOHC), with a cam for the intake valves and one for the exhaust valves. The engine shown here uses a *single overhead cam* (SOHC).

Engines with the camshaft in the block are called **pushrod engines**, because long pushrods are used to transmit the camshaft's movement up to the **rocker arms**, which rock to open the valves. On these engines, the cam acts on a valve lifter, which in turn acts on a pushrod to move the rocker arm and open the valve. We will examine this arrangement later. Overhead cam engines may have a set of parts called valve followers, which operate like lifters. Some engines have a gear on the camshaft to drive the ignition distributor and oil pump, and some diesel engines and older gasoline engines have a rounded lobe on the camshaft to drive a mechanical fuel pump.

The engine top end and bottom end must be timed together so that the valves will open and close at the proper times for the positions of the pistons, and this is accomplished through the camshaft drive. The camshaft is driven by a sprocket gear mounted on the front of the crankshaft. The sprocket either meshes with a sprocket on the front of the camshaft, or, more often, the two sprockets are linked by a belt or a chain. In the engine shown here, **timing gears** and a **timing belt** are used. Both sprockets must be installed with their timing marks aligned in the proper positions in order to time the engine.




***Valve Train***



***Timing Gears and Belt***

## The Four-Stroke Cycle (Otto Cycle)

A **stroke** is one movement of the piston from TDC to BDC. The term “stroke” also refers to the distance from TDC to BDC. One stroke of the piston moves the crankshaft through one-half of a revolution. Almost all engines on the road today operate on a cycle of four piston strokes. The strokes are the **intake stroke**, **compression stroke**, **power stroke**, and the **exhaust stroke**. This cycle turns the crankshaft through two revolutions and then the process begins again.

### Intake Stroke

The process begins with the intake stroke. The piston moves down from top dead center (TDC) to bottom dead center (BDC). The movement of the piston creates a partial vacuum, drawing air and fuel into the cylinder through the open intake valve. The ideal air-fuel mixture for performance, economy and emission control is 14.7 parts air to 1 part fuel. On Throttle Body fuel Injection (TBI) systems and old carbureted systems, fuel is carried in the air stream through an intake manifold and into the intake port. On Multiport Fuel Injection (MFI) systems, each cylinder has its own injector, which allows fuel to be injected into the port with more precision and uniformity than possible with Throttle Body systems. During this stroke, the exhaust valve remains closed.

### Compression Stroke

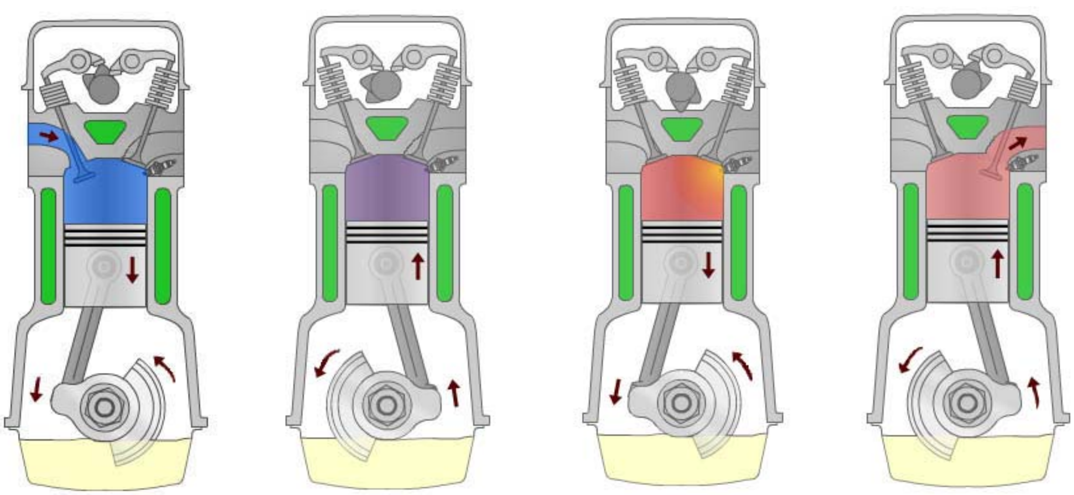
After the piston passes BDC, the compression stroke begins. The intake valve closes and the mixture in the cylinder is compressed by the piston as it moves upward again to TDC. The intake and exhaust valves are both closed during this stroke, so the pressure and temperature of the air-fuel mixture rises. A typical compression ratio for a gasoline engine might be 9:1. The compression ratio is the volume of the cylinder, including the combustion chamber, with the piston at BDC compared to the volume with the piston at TDC. The crankshaft has now made one revolution.

### Power Stroke

This is what it’s all about! As the piston nears TDC with both valves closed, the compressed air-fuel mixture is ignited. Combustion occurs, resulting in a tremendous pressure increase that pushes the piston back down the cylinder. This is the power or “working” stroke. The intake and exhaust valves remain closed. In an idling engine, this happens in each cylinder about five times a second and running at 4,000 RPM it happens over 30 times a second!

### Exhaust Stroke

Now, the spent gasses must be removed from the cylinder to make room for the next air-fuel charge. The exhaust stroke begins as the piston nears BDC. The exhaust valve opens and the piston moves upward again, pushing the burned exhaust gases out of the cylinder. The intake valve remains closed until the piston has almost reached TDC again. At this point, the engine has completed one full cycle, and the crankshaft has rotated twice. The entire process then repeats.

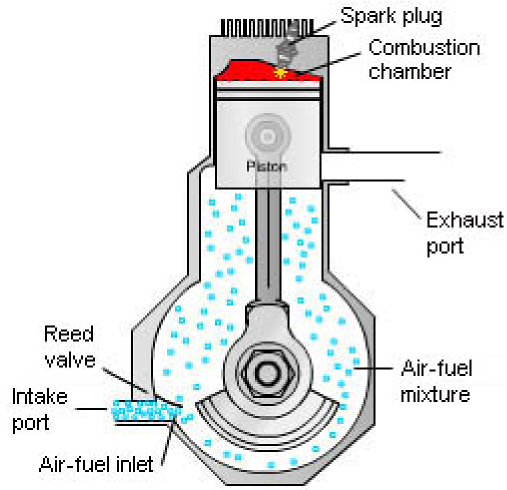


***Intake*** ***Compression*** ***Power*** ***Exhaust***

**Other Engine Designs**
While the vast majority of automobile engines are gasoline-powered, four-stroke reciprocating piston engines, other engine designs have been developed and used in automobiles, some quite successfully. Additionally, changing economic, environmental, and political conditions have created a demand to modify or retire this proven workhorse with new or re-worked designs. As materials and technologies improve and evolve, some of these contenders may come into common use in automobiles.

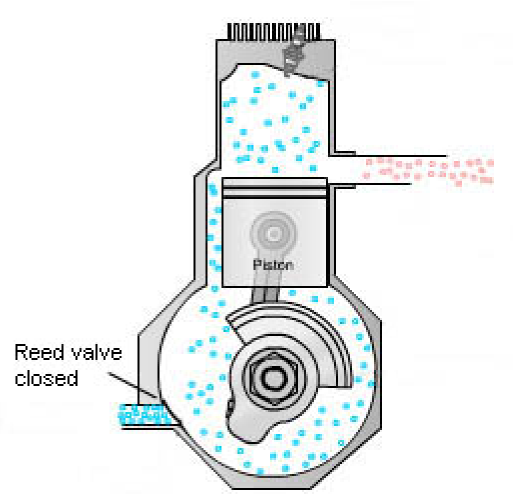
**Two-Stroke Cycle Engines**
A two-stroke cycle engine is another reciprocating piston design. Every downstroke delivers power in this design, and it has no valve train. Instead, in a conventional two-stroke gasoline engine, the air-fuel and exhaust gas are managed by the piston as it covers and uncovers intake and exhaust ports in the side of the cylinder. It also has no oil sump or pressurized oil delivery system, because the crankcase is part of the fuel delivery system. Instead, the crankcase is lubricated by mixing a small amount of oil with the fuel. Being able to deliver power with every down stroke and not having a heavy valve train means the two-stroke engine can provide a lot of power for its size and weight. Two-stroke engines have been used for many years in small engine applications such as outboard boat engines, motorcycles, ultralight aircraft, chainsaws and lawn equipment, etc. Some two-stroke engine automobiles have been imported to the U.S., and many medium and heavy duty diesel applications are currently equipped with two-stroke engines.

Unfortunately, the light weight and simplicity come at a price. Conventional two-stroke gasoline engines produce higher exhaust emissions and yield lower fuel economy than a comparable four-stroke engine. This is largely due to the burning of the oil in the combustion chamber and leakage of unburned fuel inherent in the engine's design. The causes of this will be clearer when we examine the operation of the engine. Nevertheless, the two-stroke engine has received renewed interest in recent years, as innovations and advancements in fuel injection, materials, and engine management systems develop. These engines have a pressurized lubrication system, fuel injectors, and superchargers that compress the intake air, similar to a two-stroke diesel engine.




***End of up stroke***

**The Two-Stroke Cycle**
We'll begin the explanation of the two-stroke cycle with the firing of the spark plug, which occurs before every downstroke. As the piston moves down, delivering power, the intake and exhaust ports are both covered. At the same time, the downward movement of the piston is pressurizing the crankcase with the next air-fuel charge, which was drawn into the crankcase through the air-fuel inlet and around the reed valve. This pressure forces the reed valve to close. As the piston continues downward, it uncovers the exhaust port. Remaining combustion pressure begins to blow the spent gas out the port. Further downward movement uncovers the intake port as well, and both ports are open for an instant, as the pressurized air-fuel charge from the crankcase enters the cylinder. The incoming air-fuel purges the remaining exhaust gas from the cylinder. As the piston travels upward again, it covers the intake and exhaust ports so compression can begin. At the same time, the piston's movement creates a vacuum in the crankcase, opening the reed valve again and drawing in the next air-fuel charge.




***Near end of down stroke***

### Diesel Engines

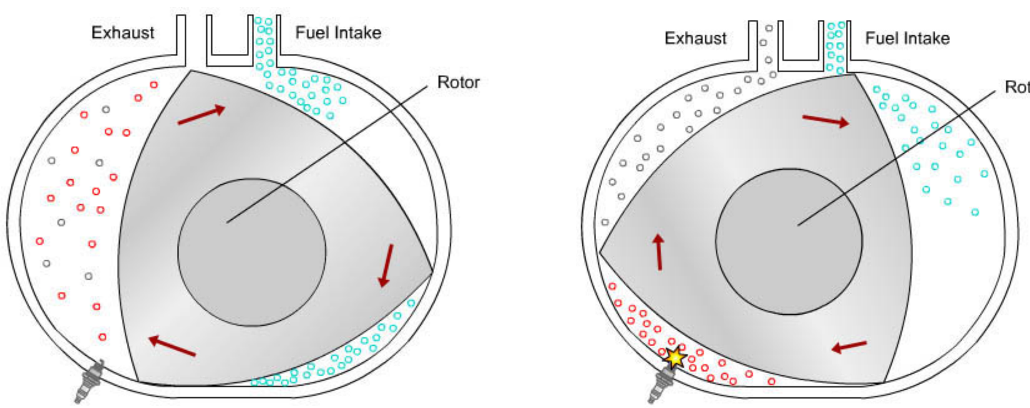
The diesel engine is another reciprocating piston design. Diesel engines in passenger cars and light trucks operate on the four-stroke cycle, but they have important differences from the gasoline engines we have discussed. The most significant difference is the way in which diesel engines ignite the fuel. Rather than using a spark to start the combustion, a diesel engine uses the heat produced by compression of the air in the cylinder. Diesel engines must compress the air much more than a gasoline engine does – about twice as much – in order to produce enough heat to ignite the fuel. **Compression ignition** engines such as diesels must be designed heavier and stronger than **spark ignition** engines to withstand the compression and combustion produced in the cylinders. These engines have steel sleeves pressed into their cylinder bores.

All diesel engines use fuel injectors to deliver the fuel to the combustion chambers at just the right time. If the fuel were delivered along with the air, as in a gasoline engine, the fuel would ignite prematurely. The fuel pressure at the injectors must be very high to overcome the pressure in the combustion chambers created during the compression stroke. Keep in mind that with the port fuel injection systems on gasoline engines, the fuel is injected outside the combustion chamber near the intake port and drawn into the cylinder on the intake stroke.

Other significant differences between gasoline and diesel powered engines are the result of differences in the fuels they burn. Diesel fuel is an oil, and as such, it is thicker, heavier, and less volatile than gasoline. However, there is more energy contained in a gallon of diesel fuel than in a gallon of gasoline. While a gasoline engine can produce more power by weight than a diesel engine, the diesel engine runs much leaner and provides better fuel efficiency by about one-third. This has made diesel engines attractive to automobile manufacturers at times, but these engines have other drawbacks that have prevented them from taking over in passenger cars. High exhaust emissions of particulates (soot) and oxides of nitrogen ($NO_X$) due to the high combustion temperatures are an obstacle. Difficulty in starting diesel engines in cold weather, sluggish acceleration, smell, and noise are other factors that have prevented diesels from being widely used in automobiles, but this may change again in the future.

### Rotary Engines

The rotary engine is one of the few mass-produced automobile engines that is not a reciprocating piston design. Instead, combustion directly causes the rotation of rotors within a chamber. This design can produce a very powerful, smooth-running engine with fewer moving parts than a piston engine, and it can operate at higher RPM. Mazda introduced this engine in the late 1960s and produced it until 1995. Sealing the combustion chambers of the rotary engine has been an engineering challenge, and the tightening of emission standards required complicated emission control systems that rendered the engine impractical for a time. Improvements in materials and design have permitted a return of the rotary engine, and it was re-introduced in 2003.




***Rotary Engine -*** *Movement of the rotor produces a low pressure area at the intake, drawing in the air-fuel mixture. Further rotor movement compresses the mixture and it is ignited. The resulting power pulse pushes on the rotor. The rotor continues turning to expel the exhaust gas. Three power pulses are produced for every revolution of the rotor.*

**Electric vehicles** have been under development for years. Battery powered electric vehicles have been developed by most car manufacturers, but they have some drawbacks. One is the limited range of travel on a battery-charge and the time required for a recharge. Another drawback is the size and weight of the large battery pack, which contains acid that could be a hazard in the event of an accident. While battery powered vehicles are quiet, smooth in operation, and produce no exhaust emissions, the electricity required to recharge them must come from somewhere. They may reduce dependence on petroleum, but if the energy to recharge them comes from a stationary coal-fired electric power plant, the reliance has merely shifted from one fossil fuel to another, and an emissions problem could remain.

An interesting aspect of electric vehicle technology is **regenerative braking**, which uses the inertia of the vehicle to charge the batteries when decelerating. During acceleration, the motor drives the wheels; during deceleration, the wheels are driving the motor. The motor becomes a generator and charges the batteries as it helps to slow the vehicle. Interest continues in electric vehicle technology because it is believed to be an integral part of other alternative power plants for vehicles.

A **hybrid vehicle** is one that combines two or more sources of power, such as a small gasoline engine and an electric motor. In some designs, the engine and the electric motor can drive the vehicle together, and in other designs, the engine only drives a generator, which either charges the batteries or powers the electric motor. Hybrid power plants are not a new idea. For example, most locomotives are diesel-electric and use diesel engines to generate electricity to power electric motors that drive the wheels. Hybrid automobiles are designed to improve fuel economy and reduce emissions.

**Fuel cell electric vehicles** are a type of hybrid. These vehicles use an electrochemical device to produce electricity to power a motor. Unlike a battery (which is also an electrochemical device), a fuel cell does not “run down” or wear out. It uses hydrogen for fuel and draws oxygen from the air for oxidation in the cell. The chemical reactions from hundreds of fuel cells in a vehicle produce electricity and the only byproducts are water, heat, and some nitrogen compounds. Fuel cell technology presents challenges because of the nature of hydrogen. Besides being a bulky and highly explosive gas, it must be refrigerated to -425 degrees F to be stored and handled as a liquid. It also requires more energy to produce hydrogen than the hydrogen will provide when it is consumed. These challenges will have to be met before fuel cell technology will be practical for use in automobiles.

From this point on, this course will deal with gasoline powered four-stroke piston engines.

## Engine Classifications

Engines can be classified in many different ways, according to their design characteristics and operation. These differences can affect the methods of maintenance and repair. Some ways engines can be classified are:

- **Operational design** (four-stroke, two-stroke, rotary, etc.)
- **Number of cylinders** (four, five, six, eight, 12, etc.)
- **Arrangement of cylinders** (V-type, inline, etc.)
- **Displacement** (3.8 liter, 3800 cubic centimeters, 5.0 liter, etc.)
- **Number of valves and valve train type** (overhead cam, pushrod, 24-valve, etc.)
- **Ignition type** (spark or compression, spark distribution system, etc.)
- **Cooling system** (air or liquid)
- **Fuel type** (gasoline, diesel, propane, etc.)

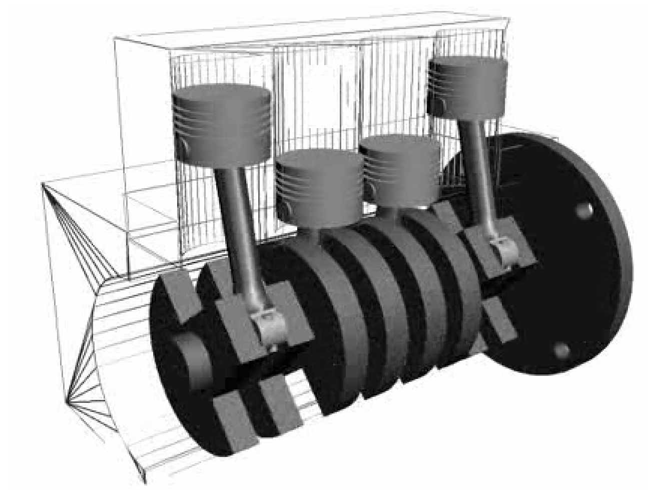
We have already discussed operational design, but the other classifications may need explanation.

### Number and Arrangement of Cylinders

Automobile engines can have three, four, five, six, eight, 10, or 12 cylinders. More cylinders mean more power strokes per revolution of the crankshaft, which provides more power and smoother running. The cylinders can be arranged in a number of ways. The three most common cylinder configurations are **inline**, **V-type**, and **opposed**.

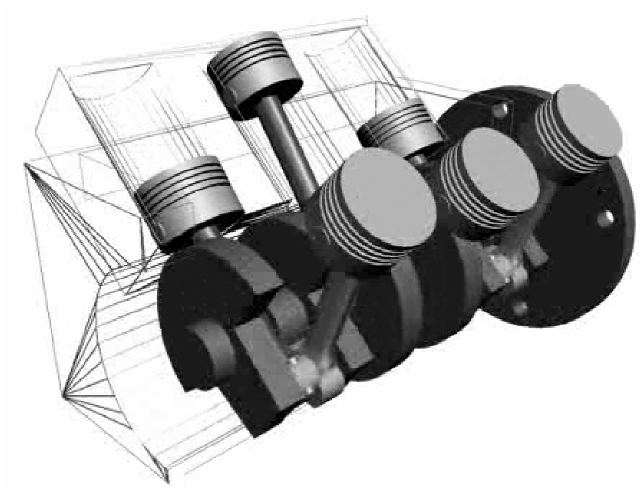
Engines with even numbers of cylinders have pairs of **companion cylinders**, in which the pistons move up and down together. When one of the pistons is on its power stroke, the other one will be on its intake stroke. Likewise, when one piston is on its exhaust stroke, its running mate will be on its compression stroke.

**Inline** engines have all their cylinders in a straight row. This is a common arrangement for four-cylinder engines and inline six-cylinder engines are still produced. Many years ago, inline eight-cylinder engines were produced, but there are several problems associated with an engine of that length.



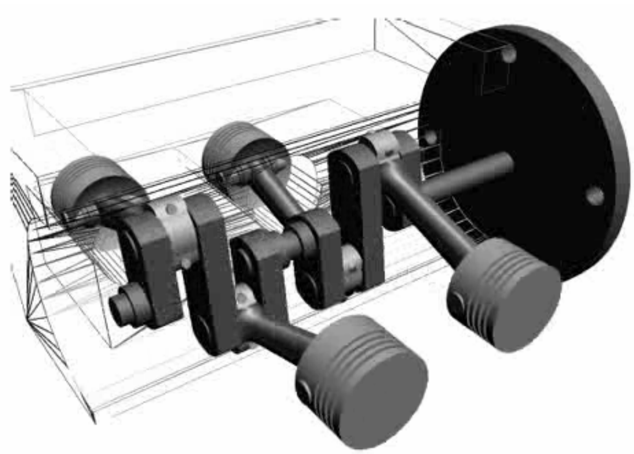
***An Inline Four-cylinder Engine***

**V-type** engines have two cylinder banks, a left bank and a right bank, at an angle to one another such that when viewed from the front or rear, the block forms the shape of a "V". As with all matters of automotive service, left and right are referenced from the vantage point of someone sitting in the vehicle. V-6 and V-8 engines are common, while a few V-10 and V-12 engines are produced. The V-6 has several advantages over inline-6 engines. The V-type is more space- and weight-efficient. Two connecting rods from opposing banks share one crank pin (rod journal).



***A V-6 Engine***

**Opposed** engines have cylinders that face each other from opposite sides of the crankshaft. This arrangement is sometimes called a boxer or pancake engine, because the cylinders lay flat, giving the engine a low profile. This makes it suitable for rear- and mid-engine applications, and this type of engine has been used in Porsches, Volkswagens (air-cooled), and Subarus.



***An Opposed Four-cylinder Engine***

A **slant** arrangement has also been used. This arrangement is a variation on the inline design, and some manufacturers have used it to lower the hood line. It sets in the engine compartment at a slant, and may resemble "half" of a V-type engine. A few high-end automakers have produced engines with 16 cylinders in a "W" arrangement, but with a price of around one million dollars for the vehicle, you are unlikely to see one in a typical shop.

The cylinders are assigned numbers by the manufacturer for reference. The numbering system varies by manufacturer. Sometimes the numbers are stamped into the intake manifold. The **firing order** is the sequence in which the spark plugs fire, and is usually different from the order of the cylinder numbers. The firing order may also be stamped on the intake manifold, but both sets of numbers are available in the service information for the vehicle. The firing order will vary among manufacturers or divisions.

**Displacement**

Commonly called "engine size," the displacement of an engine is the volume of all the cylinders added together. In the U.S., engine displacement was expressed in cubic inches for many years. In modern vehicles, displacement is usually given in liters (L) or cubic centimeters (cc).

The diameter of the cylinder is called the **bore**. If the bore and the length of the piston stroke are known, the volume of a cylinder can be calculated. The simplest formula for calculating the volume of a cylinder is:

$$\text{Bore}^2 \times \text{Stroke} \times 0.7854 = \text{cylinder volume}$$

This result is multiplied by the number of cylinders to arrive at the displacement of the engine. The value of 0.7854 is pi /4. Using the formula to determine the displacement of a six-cylinder engine with a bore of 10cm and a stroke of 8cm, we find:

$$100 \times 8 \times 0.7854 \times 6 = 3{,}769.92$$

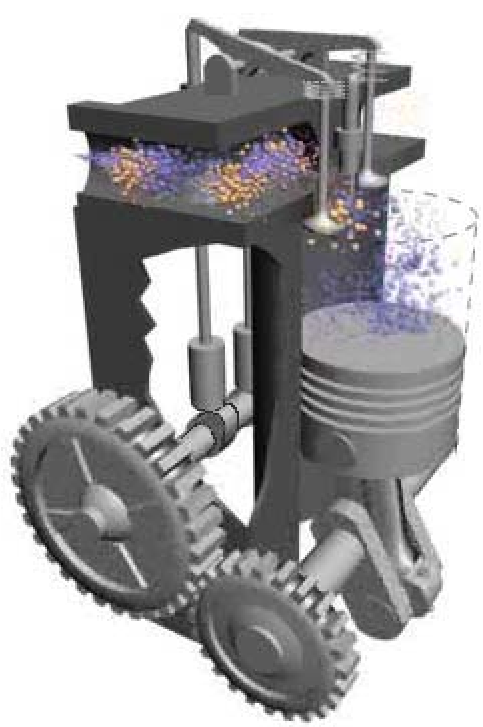
This would be expressed as 3770cc, or approximately 3.8L.

**Number of Valves and Valve Train Type**

In an earlier section, we saw the operation of an engine with a single overhead cam. We noted that a dual overhead cam (DOHC) engine has a cam for the intake valves and one for the exhaust valves. A V-type DOHC engine has four camshafts – two for each bank. Dual overhead cams are frequently used on engines that have more than two valves per cylinder. Four-cylinder engines typically have eight, 12, or 16 valves. A six-cylinder may have 12, 18, 24, or 30 valves, and a V-8 may have 16, 24, 32, or some other number of valves.

Pushrod engines (those with the cam in the block) are sometimes referred to as "overhead valve" engines to differentiate them from overhead cam engines, but all modern automobile engines use overhead valves. The term was originally used to distinguish the pushrod valve arrangement from engines that have the valves in the block, a design now found only in antique cars and some small engines.

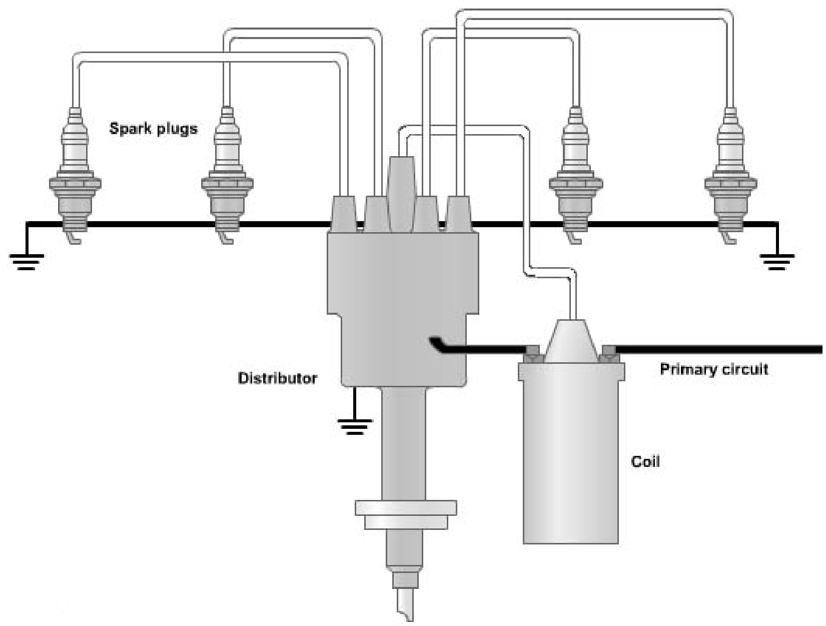
In pushrod engines, the cam acts on a valve lifter, which in turn acts on a pushrod to move the rocker arm and open the valve.



***Pushrod Engine***

**Ignition Type**
In our discussion of engine designs, we noted that there are two methods of igniting the fuel: **spark** and **compression**. Gasoline engines use a spark to ignite the fuel, while diesel engines have no spark plugs and use the heat of compression to ignite the fuel.

A further distinction can be made regarding spark ignitions systems, and that is whether they use a mechanical ignition distributor or not. Until 1984, all gas engines used a distributor driven by the camshaft to send a spark on its way to each cylinder at the proper time. These systems are now called **Distributor Ignition (DI)** systems. Today, most engines produced are distributorless and rely on engine sensors and electronic components to accomplish this task. These systems are called **Electronic Ignition (EI)** systems. Note that for a time, these were referred to as Distributorless Ignition Systems (DIS). Note also that distributor systems since the mid-1970s have used electronic components and were once referred to as "electronic ignition." Ignition systems will be discussed in a later section.




***Distributor Ignition***

**Cooling System Type**
Engines are either **air-cooled** or **liquid-cooled**. Nearly all automobiles currently in production have liquid-cooled engines. Air-cooled engines can be found in motorcycles, lawn mowers, and some automobiles. Cooling fins cast on the outside of engine parts, especially the cylinders and heads, increase surface area and help dissipate heat into the air flowing around them. Air-cooled engines run at higher temperatures than liquid-cooled engines under some conditions, and they can't maintain as constant a temperature. This causes an exhaust emissions problem (especially oxides of nitrogen) that has limited their production in recent years.

In liquid-cooled engines (often called "water-cooled"), a pump circulates coolant though cavities and passages called water jackets around the cylinders and combustion chambers. A thermostat keeps the engine at the optimum operating temperature by controlling the coolant flow between the engine and the radiator, where the heat is given off to the air passing through it. The coolant is normally a mixture of 50% water and 50% antifreeze. The antifreeze provides protection against freezing, boiling, and rust and corrosion, and provides lubrication and seal conditioning. We will examine the liquid cooling system in another section.

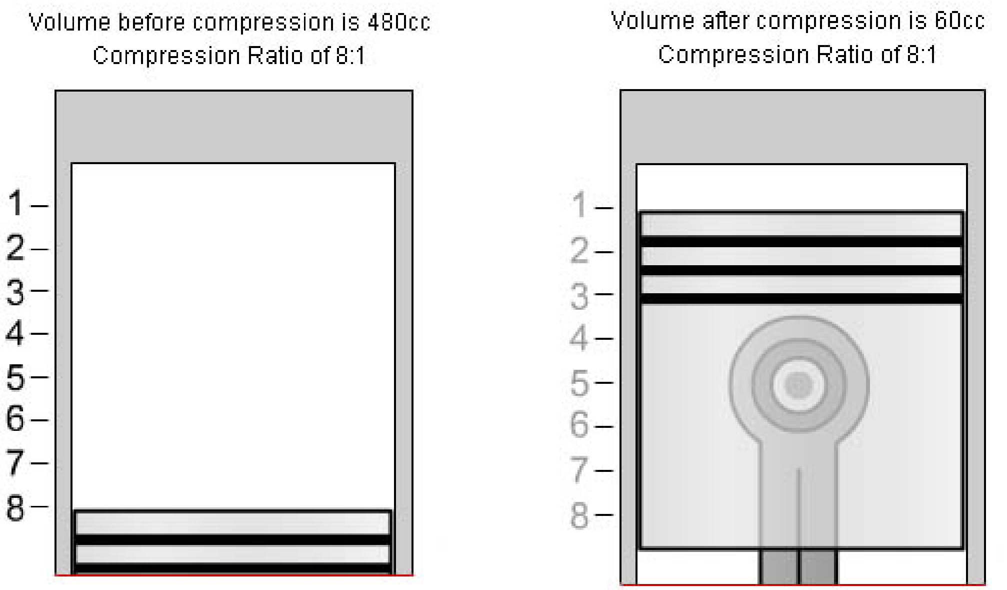
**Fuel Type**
By far the most common fuels are gasoline and diesel fuel; however, some fleet vehicles burn alternative fuels such as natural gas, propane, or liquefied petroleum gas (LPG). These engines are usually converted gasoline or diesel engines.

## Characteristics of Combustion
The combustion chamber is the area over the piston when it is at TDC. It is formed by the top of the piston, the bottom of the cylinder head, and the cylinder wall in between (if there is any cylinder wall

exposed at TDC). Many things, such as the design and shape of the combustion chamber, compression ratio, fuel properties, engine temperature, and other factors can affect combustion in an engine.

**Compression Ratio**

In an earlier section, we said that the compression ratio is the volume of the cylinder, including the combustion chamber, with the piston at BDC compared to the volume at TDC. Below, you can see that the volume of the cylinder at BDC is eight times as large as its volume at TDC, for a compression ratio of 8:1.




A higher compression ratio can increase the power and fuel economy of an engine, but it also increases exhaust emissions and the temperature in the combustion chambers. Higher compression engines require a fuel with a higher **octane rating** (anti-knock rating).

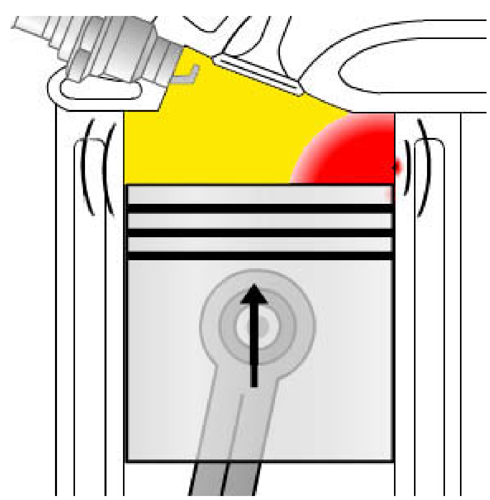
**Abnormal Combustion**

Sometimes, conditions that cause abnormal combustion occur. The result is a loss of power, engine noise, and possibly engine damage. Abnormal combustion typically takes one of two general forms: pre-ignition or spark knock.

**Pre-ignition**

Pre-ignition occurs when the air-fuel mixture self-ignites during the compression stroke before the spark plug fires. This condition has the effect of trying to force the piston back down the cylinder before it reaches TDC. Pre-ignition is the result of a hot spot in the combustion chamber that prematurely ignites the mixture. The early combustion creates abnormally high cylinder pressures and temperatures that the engine cannot withstand.

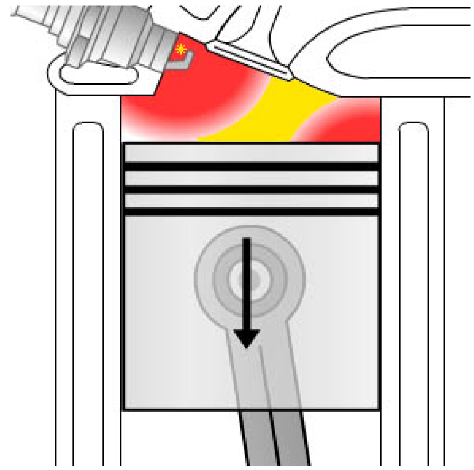
Causes of pre-ignition include "hot" spark plugs (incorrect heat range), excessive accumulation of "glowing" carbon deposits in the combustion chamber, overheated exhaust valves, and cooling system malfunctions. Pre-ignition is more prevalent during high speed and load conditions. Engine damage resulting from pre-ignition can include melted spark plug electrodes, melted/scuffed pistons, ring damage, and distorted valve heads.



***Pre-ignition***

## Spark Knock (Pinging)

Spark knock, or "pinging," is caused when the flame front initiated by the spark plug collides with an undesired flame front. The undesired flame front starts when part of the unburned air-fuel mixture is compressed to a pressure and temperature that exceeds the "self ignition" limit, causing it to spontaneously ignite. The fuel explodes too quickly, rather than burning smoothly. This condition is also referred to as "detonation."



***Spark Knock***

Spark knock makes a "pinging" noise and occurs mostly under high load and low to medium speed conditions.

Common causes of spark knock include low octane fuel, carbon deposits in the combustion chamber, high compression ratios, and high cylinder temperatures. Spark knock causes a rapid rise in pressure and temperature that can damage spark plug electrodes, pistons, rings, valves and valve seats. While spark knock is not as damaging as pre-ignition, the high combustion temperatures of prolonged knocking may lead to pre-ignition in severe cases.

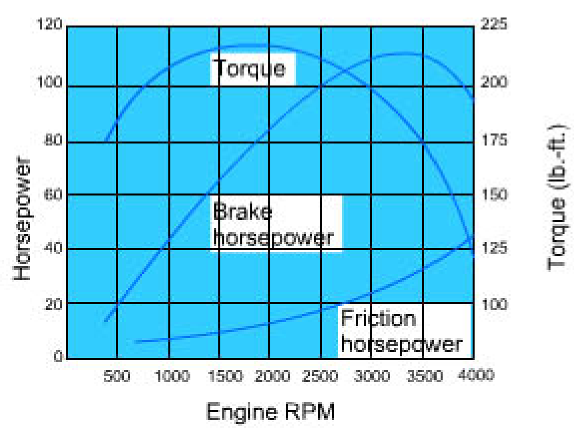
## Spark Timing and Advance

Spark timing must change to account for different operating conditions such as engine speed and load. The time required for combustion remains fairly constant, so this means that as engine speed is increased, the spark, which would normally occur just before the power stroke begins, must happen earlier in the compression stroke. Ignition timing is referenced in **degrees**, and earlier timing is said to be advanced, while later timing is said to be retarded. On many DI systems, the initial timing, or **base timing** is adjustable and must be set to a specification. The vehicle's computer, or **powertrain control module (PCM)**, or other mechanisms automatically handle the necessary changes in timing to match the operating conditions. The base timing specification is usually several degrees before TDC. Engines with EI systems have no base timing adjustment.

Incorrect spark timing can cause abnormal combustion, and excessive timing advance can cause spark knock or pre-ignition. Most late model vehicles are equipped with a PCM controlled **Knock Sensor (KS)** system. Engine mounted knock sensors are used to detect vibrations caused by knock. When a knock is detected, the PCM retards spark timing to eliminate the knock.

## Torque and Horsepower

Torque is turning or twisting force. The power developed in an engine's cylinders is converted into a turning force by the crankshaft, which delivers this torque to the drive train where it is transmitted to the wheels. Torque is measured in **pounds-feet (lb-ft)**, although it is often casually expressed as "foot-pounds," which is actually a measure of work. In the metric system, torque is given in Newton-meters (Nm) or kilogram-meters (kg-m).




Horsepower is the rate at which torque is produced. One horsepower was designated many years ago as the amount of work required to lift 550 pounds one foot in one second.

The torque and horsepower an engine can deliver vary with engine speed. In the example of a typical performance graph shown here, note that maximum torque is developed at low to moderate RPM, while brake horsepower (the power available at the end of the crankshaft) continues to rise into the high RPM range. At higher RPM, the torque and horsepower curves begin to drop, due to difficulties in the engine's breathing at the higher speeds. The line on the graph for friction horsepower represents the horsepower used to overcome the internal resistance in the engine.

## Engine Systems

Engines are complex machines that rely on several systems for their operation. These systems include **air-fuel delivery**, **ignition**, **cooling**, **lubrication**, **exhaust**, **emission controls**, and the **computer system**. It is important to understand the systems when diagnosing performance problems. These systems all work together to provide efficient operation.

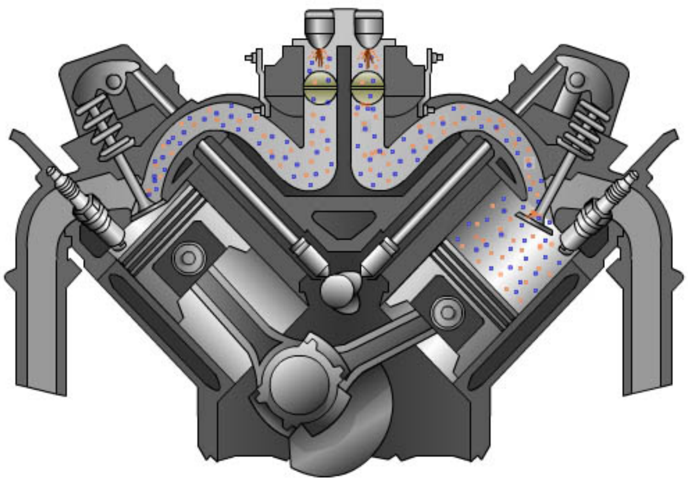
### Air-fuel Delivery Systems

Air is provided to the cylinders through various methods of induction. Induction systems are matched, or tuned, to a particular application. The air filter surface area, throttle body bore diameter, and even the tubing from the air cleaner assembly to the throttle body control the air charge volume to the engine.

The **intake manifold** plays an important but different role in the air intake systems for Throttle Body Injection and Multiport Fuel Injection systems. All new automobiles sold in the U.S. since 1990 use fuel injection systems.

On engines equipped with TBI, the intake manifold must carry both air and atomized fuel to the cylinder head intake ports. Therefore, intake manifolds for TBI systems, like those for carbureted systems, are designed with compromises to meet both objectives. "Wet" manifolds, as they are known, must maintain proper velocity throughout the desired engine operating range to hold fuel in suspension while providing sufficient air capacity to obtain peak horsepower.

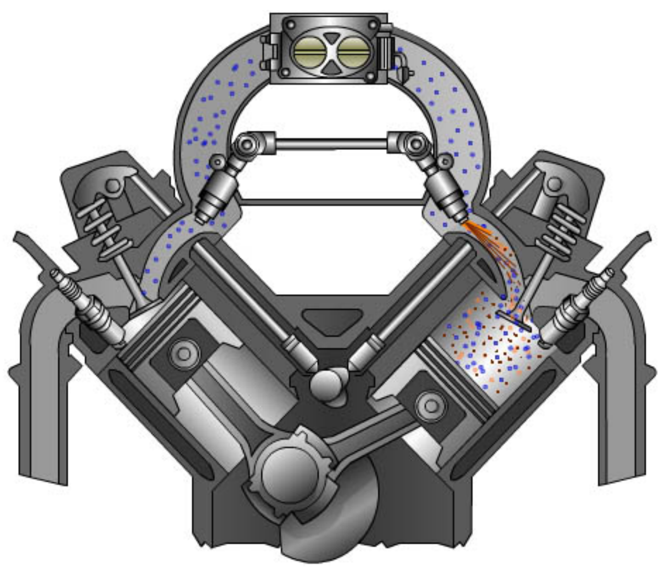
In the illustration of a TBI system shown at right, the cylinder on the right is on its intake stroke. You can see the air-fuel mixture in both sides of the manifold and air-fuel entering the right cylinder around the open intake valve.



***TBI Air-fuel Intake***

The intake manifold for an MFI system does not carry fuel, and can be tuned for either maximum torque or horsepower. Since it carries only air, it is referred to as a "**plenum**." Long air passages, called runners, that provide for increased low-end and mid-range torque, are possible without the concern of fuel condensing on the manifold walls.

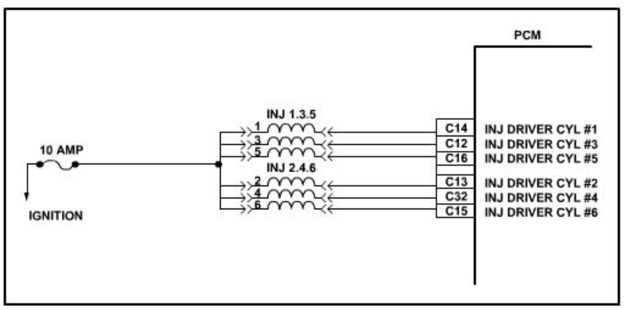
In the illustration of an MFI system shown here, the cylinder on the right is on its intake stroke. You can see the **fuel injector** spraying a pulse of fuel and the air-fuel entering the right cylinder around the open intake valve. The plenum carries only air.



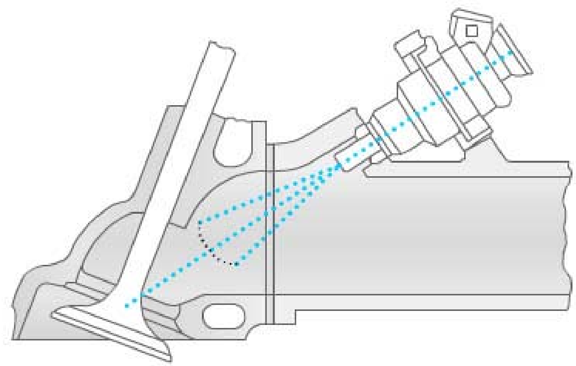
***MFI Air-fuel Intake***

Fuel is delivered either above the throttle plate (TBI), or in the intake port nearer the intake valves (MFI). The fuel injector(s) are controlled by the PCM. Many designs of fuel injectors are used, but all have the same primary function. When the injector nozzle opens and the pressurized fuel is injected, an atomized air-fuel mixture is provided to the engine. The fuel further atomizes as it enters the combustion chamber.

Fuel injectors are provided a continuous supply of pressurized fuel from the electric **fuel pump**. An injector is a solenoid that energizes when grounded by the PCM to deliver pressurized fuel into the intake manifold or intake port. The PCM controls fuel flow by **pulse width modulation** of the injector "ON" time. The duration of this "ON" time is called the **pulse width**. When fuel requirements increase, the injector "ON" time increases, producing a richer air-fuel mixture. When fuel requirements decrease, the injector "ON" time decreases, producing a leaner mixture.

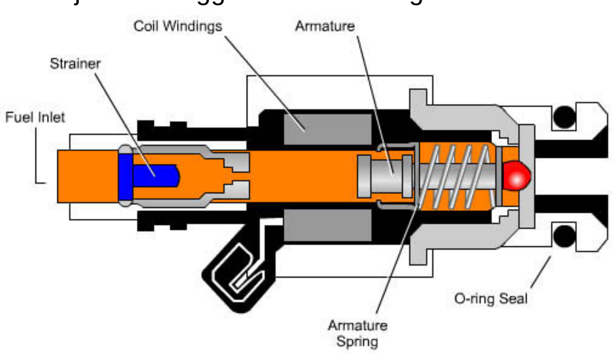



***Typical Fuel Injector Circuit***

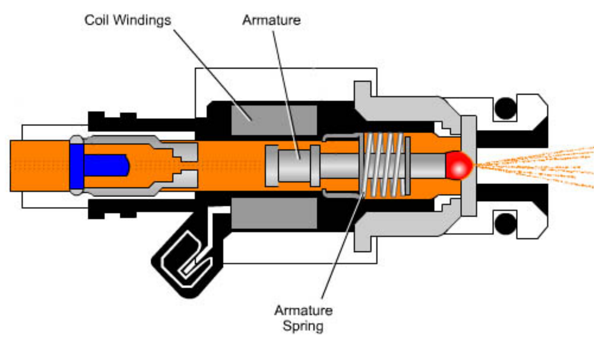


***Fuel Injector Spray Pattern***

A fuel injector is an electromagnetic device. The precision mechanical components are controlled by means of the solenoid in the injector, and the solenoid is energized through an injector driver in the PCM. The injector is triggered based on ignition reference pulses.



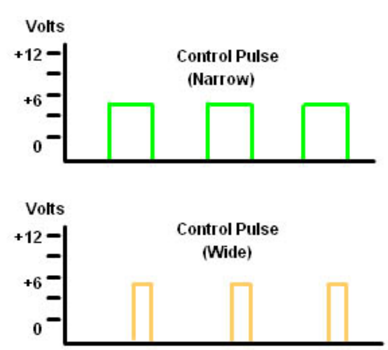

***Fuel injector off***




***Fuel injector energized***

Although engine RPM determines when an injector opens, the PCM determines how long to leave the injector open based on its readings of coolant temperature, engine load, throttle position and **oxygen sensor (O2)** voltage. The PCM driver circuit controls the "ON" time of the solenoid by providing a ground. When the injector driver opens the circuit to the solenoid (turns it off), return spring tension pushes the ball or pintle onto its seat and shuts off fuel flow.

Because of the wide variety of air-fuel systems on vehicles, it is imperative to consult the service information for the vehicle on which you are working before you attempt diagnosis and repairs.




***Pulse Width Modulation***

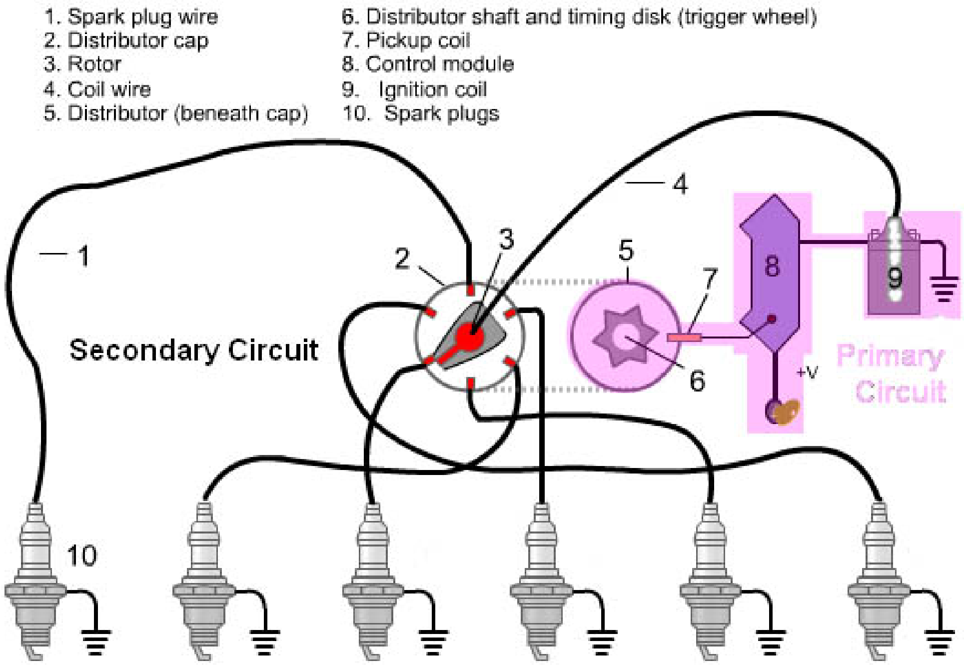
- ***Always follow all safety precautions and keep fuels away from sparks or flames.***

**Ignition Systems**

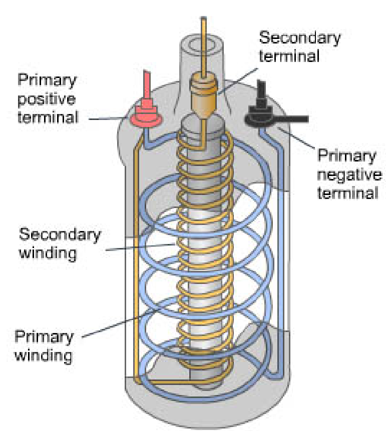
The ignition system must take the vehicle's system voltage of about 12 volts and transform it to a high voltage of up to 60,000 volts to create sparks that jump the gap between the electrodes in each spark plug. It must do this hundreds of times a second and at precisely the right time for each cylinder under all operating conditions. We know that the ignition system provides the spark to ignite the air-fuel mixture, but how does it do it?

First, let's divide the ignition system into its two main sections, the primary and secondary circuits. The **primary ignition circuit** consists of the **battery**, the **ignition switch**, another **switching device**, and any other parts of the system that operate at or near vehicle system voltage (normally from about 12.6 volts to about 14.2 volts). In fact, all of the vehicle's electrical system that operates at this voltage can be referred to as the "primary electrical system."

The **secondary ignition circuit** is the high-voltage section, and consists of the **distributor cap** and **rotor** (DI systems), **spark plug wires**, and **spark plugs**. Both the primary and secondary circuits must include a return path to ground.




*Ignition System (DI)*



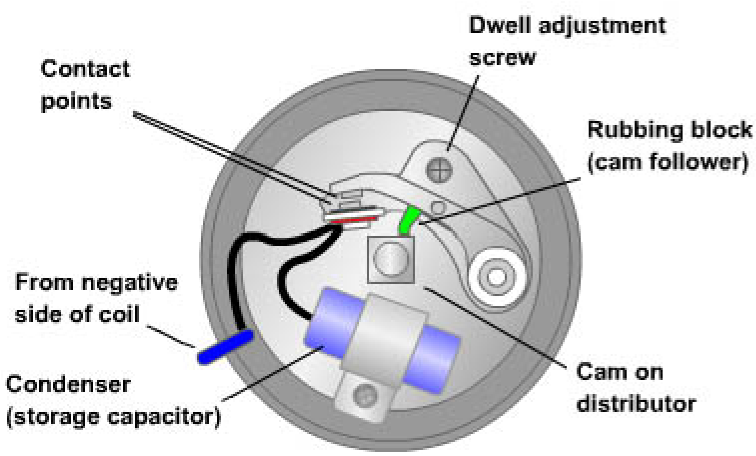

*Ignition Coil*

Another very important component in the ignition system is the **ignition coil**. The coil (or coils) is part of both the primary and secondary circuits. The high voltage is produced here.

The coil is a step-up transformer that produces high-voltage pulses. Aptly named, it contains two coils of wire that are insulated from each other: a primary winding and a secondary winding. The outer, primary winding contains hundreds of wraps of relatively large wire, while the inner, secondary winding contains thousands of wraps of much smaller wire. The wires are insulated from each other, so that current must flow through all of each coil. The start of the secondary winding is connected to one end of the primary winding. The primary winding receives vehicle system voltage (or near to it), and the secondary winding produces high-voltage pulses that exit the center **high tension** terminal of the coil on their way to the spark plugs. The high-voltage pulses are created through **electromagnetic induction**, and this is where the switching device comes into play.

Current flowing through the primary winding creates a strong magnetic field around the coil. When the switching device interrupts the current flowing through the primary winding, the magnetic field collapses across the secondary winding. This induces a pulse of high voltage in the secondary. Since the secondary winding has many more turns of smaller wire than the primary winding, the moderate amount of current that was flowing through the primary induces the pulse of high voltage at a very low current in the secondary. Little current is needed; it is high voltage that's required to create a spark capable of jumping the spark plug gap and igniting the air-fuel mixture.

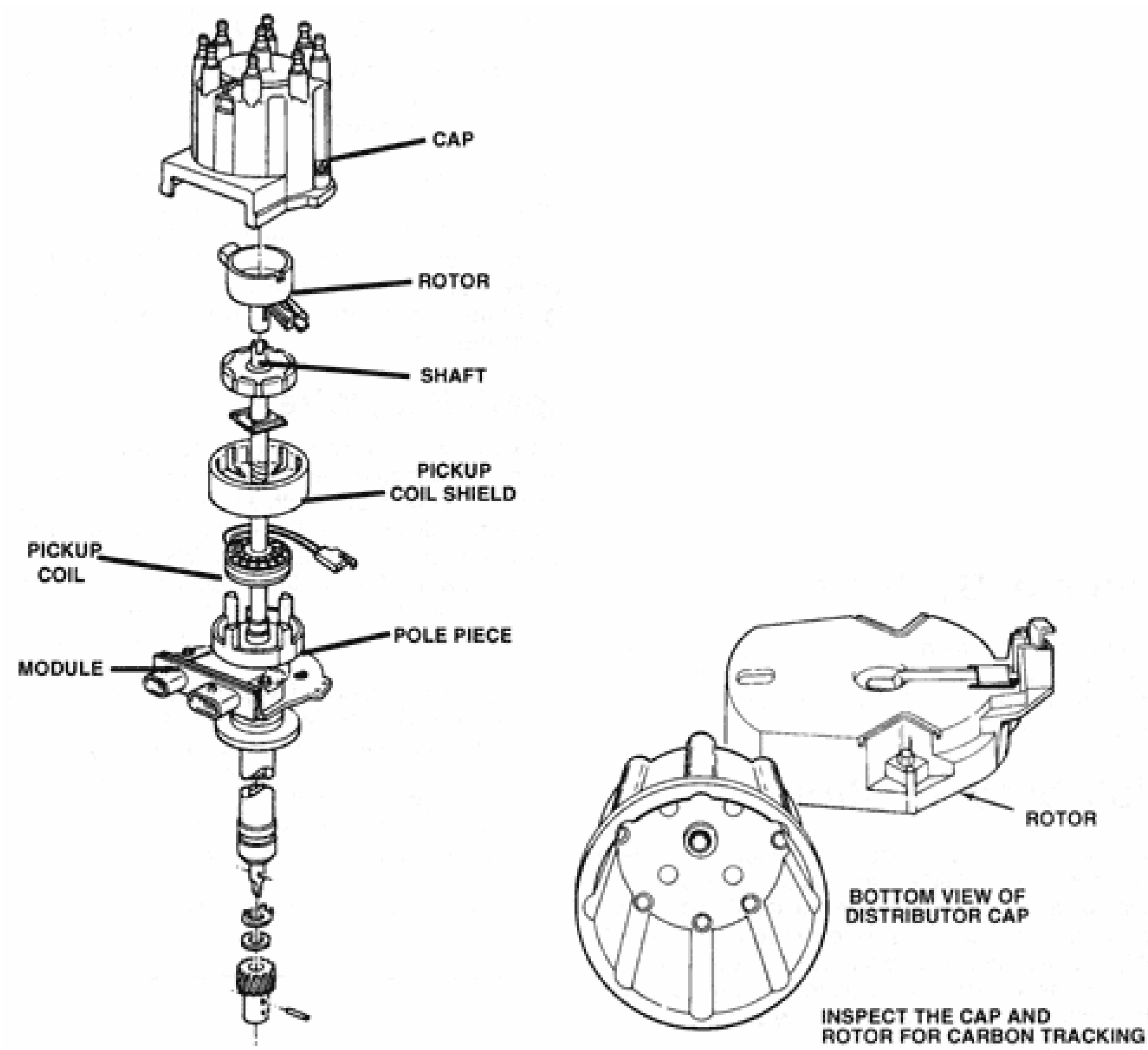
The switching device must turn on and off very rapidly, since it must interrupt the circuit to produce each spark. In years past, electromechanical **contact points** (breaker points) located in the distributor were used for this. The points opened to trigger the firing of the coil. It's helpful in understanding later ignition systems to examine how these early systems work, and as of 2004, the ASE Engine Performance certification test still makes reference to contact point ignition systems. As the distributor shaft rotates, cam lobes on it open the points to interrupt the circuit, and spring tension closes them to energize the primary winding again (called **dwell time**). A capacitor called a **condenser** is used to minimize arcing across the points. Contact point systems require periodic adjustment and replacement, and have performance shortcomings by today's standards, but they work. These systems were used for over 60 years, but by 1975, most vehicles produced used electronic switching to fire the coil. Contact points can still be found in electromechanical relays and solenoids.




***Contact Point Ignition System***

Solid state, electronic triggering and switching devices are now used in all automobiles produced, but the principle is the same. These systems are much more accurate and provide better emissions, fuel economy, and performance than contact point systems could. They can produce higher voltages and are more reliable with little or no maintenance needed. Different manufacturers have used several different designs of electronic triggering and switching. These systems use some type of signal generator on the distributor or crankshaft, such as a **timing disc** (i.e., trigger wheel) and **pickup coil** in the distributor, or a **Hall-effect pickup** on the distributor or crankshaft. On these systems, movement of the timing disc generates a voltage signal in the pickup coil, which is sent to a transistor in the control module or PCM to control switching. Other engine sensor inputs may also be used.

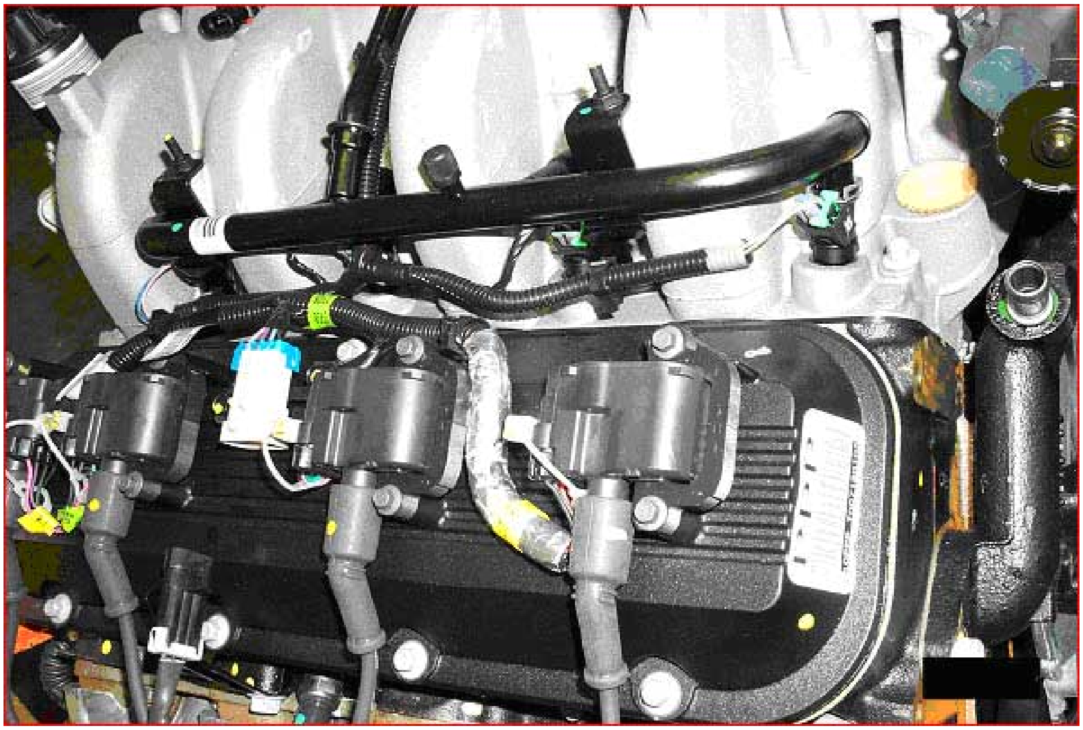
In DI systems, the high-voltage pulses from the coil are sent to the rotor at the top of the distributor shaft. As the rotor turns, the pulses are sent to the proper spark plug wires through the distributor cap. Old distributor systems used weights on the distributor plate called a **centrifugal advance** to advance the timing for faster RPM, and a **vacuum advance** mechanism to retard the timing under lighter loads. These adjustments are made by the PCM on today's cars. Refer to the diagram of a DI system with electronic triggering and switching on page 16.




***Distributor assembly from a High Energy Ignition (HEI) system***

EI systems go a step farther, eliminating the need for a distributor, cap, rotor, and sometimes spark plug wires. Like some later DI systems, these systems use input from a **crankshaft sensor (CKP)** and often a **camshaft sensor (CMP)** and other engine sensors for trigger timing. Ignition is controlled by an **electronic control module (IC)** and/or the PCM.

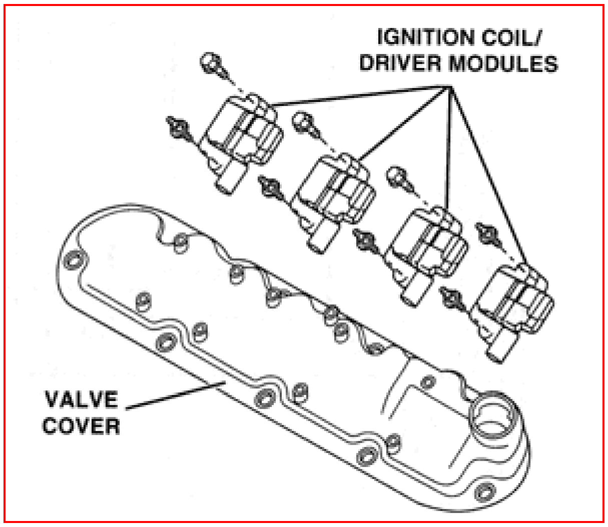
In EI systems, multiple coils are used. Some systems use one coil per spark plug, while others use one coil per pair of spark plugs. Systems that use one coil for two spark plugs have pairs connected in series and both spark plugs fire at the same time. One cylinder will be ending its compression stroke, while the other will be ending its exhaust stroke, and this method is called a **waste spark** system, as the spark on the exhaust stroke does nothing.



***On this one-coil-per-plug system, the coils are mounted on the valve covers. Note the fuel rail located above the valve cover.***

Because of the wide variety of ignition systems on vehicles, it is imperative to consult the service information for the vehicle on which you are working before you attempt diagnosis and repairs.

- Use care working with the secondary circuit with the engine running. While getting a shock from the high voltage is not normally injurious ***to healthy persons***, it is not pleasant. Far more common are injuries caused by the involuntary reflex reaction to being shocked (banged head, lacerated hand, or worse).



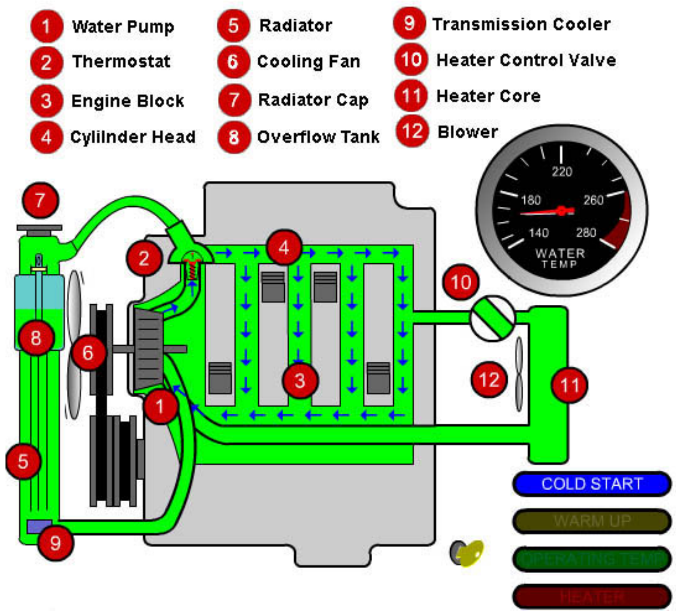
**Cooling System**

With combustion temperatures as high as 4,500 degrees F (2,468 °C) and consistently over 2,000 degrees F (1,080 °C), an engine would be destroyed in minutes without the cooling system. An engine burns cleanest and with the least wear when at its normal operating temperature of around 200 degrees F (93° C). The cooling system is designed to allow fast warm up and then maintain this optimum temperature. This is accomplished with a thermostat that controls coolant circulation in the system. Temperature-controlled electric radiator fans and other fan controls such as fan clutches (belt-driven fans) also assist with temperature control and conserve engine power. Many cooling systems must also cool the automatic transmission fluid. A transmission pump sends the fluid through lines from the transmission to the radiator, which has cooling lines built into it. The cooled fluid is then returned to the transmission.

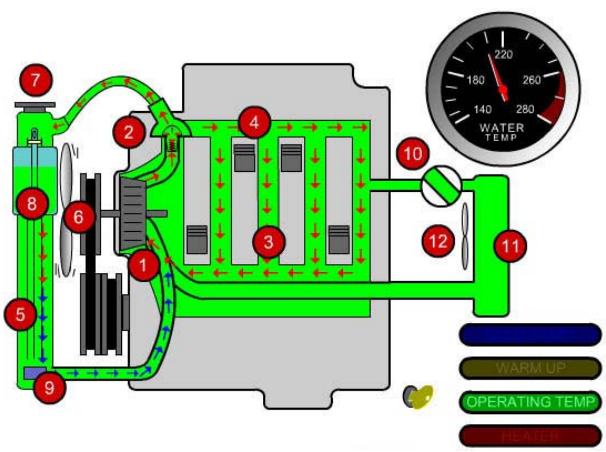
Coolant is pumped through the engine, where it absorbs the heat of combustion, to the radiator, where this heat is transferred to the atmosphere. The radiator is a **heat exchanger**. Hot coolant flows through tubes that are folded back and forth many times. The tubes have many fins attached to provide more surface area with which to dissipate heat. Air flowing around the tubes carries away the excess heat, and then the coolant returns to the engine to continue the process.

Let's begin at the **water pump** and follow the coolant flow through a typical system. The pump sends the fluid to the **engine block**, where it flows through passages around the cylinders. The coolant then flows through the **cylinder head** and to the **thermostat**, where it is directed back to the pump (cold/closed) or to the radiator (hot/open).

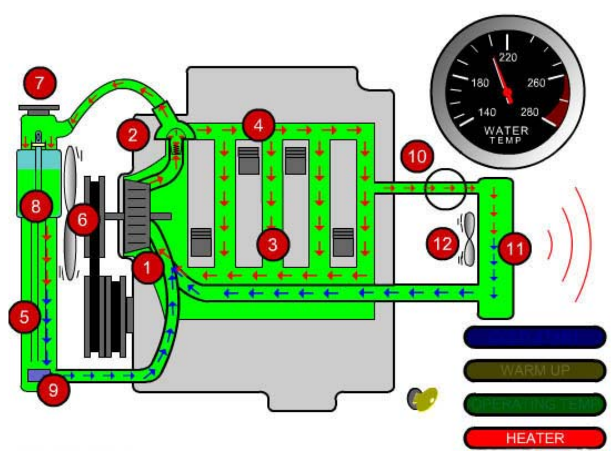
To heat the passenger compartment, another circuit is added to the cooling system. This circuit pumps hot coolant from the cylinder head through a **heater core** in the dash, and then back to the pump. In this way, heat can be obtained whether the thermostat is open or closed. The heater core is another heat exchanger, like a small radiator. A **blower** (fan) blows air through the heater core and into the passenger compartment. A heater **control valve** controls coolant flow through the heater core, according to the temperature selected by the operator.




***Coolant Flow - Warm-up***



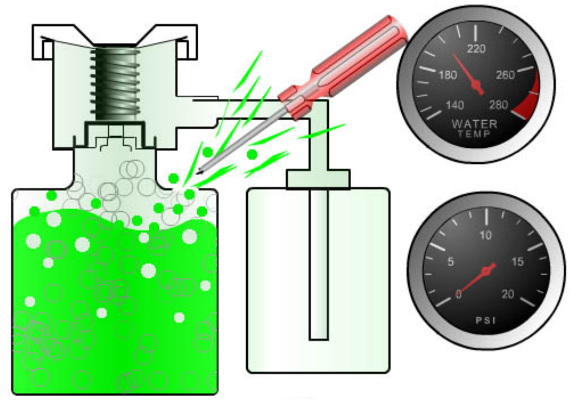

***Operating Temperature***




***Heater Circuit***

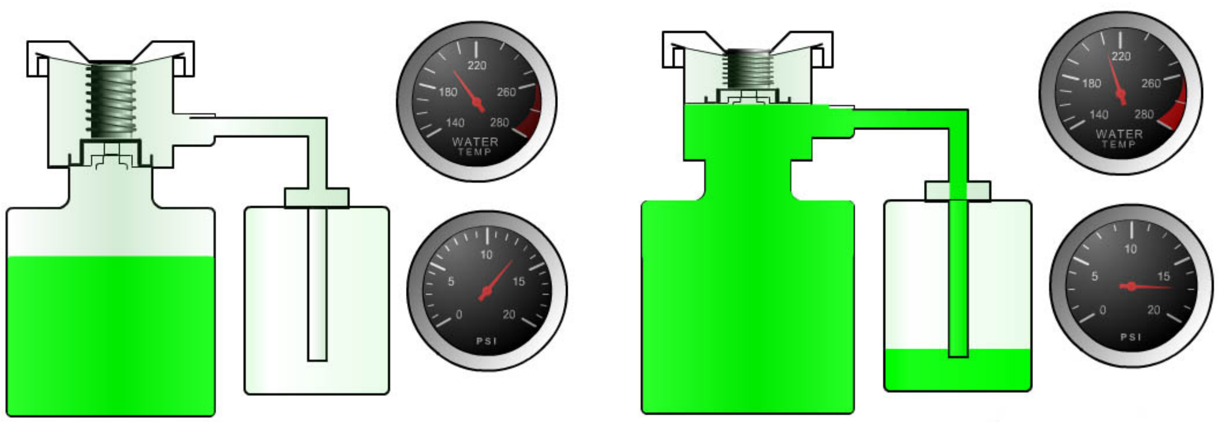
To cover all possible vehicle conditions, the **coolant** must have a low freezing point, a high boiling point, and the ability to hold a lot of heat. Water is an effective heat carrier, but its freezing and boiling points must be enhanced to make it a suitable coolant. A mixture of water and antifreeze (ethylene glycol) is used for this. A 50/50 mix yields protection against freezing to -35 degrees F (-37° C) and raises the boiling point to 223 degrees F (106° C). Antifreeze also contains an additive package to inhibit corrosion and lubricate the water pump.

The coolant must not boil because when a fluid boils, it cannot absorb any more heat. Its temperature will remain the same, even though the temperature of the surrounding metal may continue to rise. Since coolant temperature can sometimes rise as high as 275 degrees F (135° C), more must be done to raise the coolant's boiling point. The boiling point is further raised by pressurizing the system, typically to about 15 pounds per square inch (psi). This will raise the boiling point another 45 degrees F (25° C). The relationships between heat, pressure, and changes of state (liquid to gas and back) are examined in detail in the Today's Class.com course ***HVAC***, in the *Refrigeration Systems Overview* section.




***Pressure Failure***

As the coolant in the system heats up, pressure is created. The **pressure cap** on the radiator provides a pressure relief valve. If the pressure exceeds the cap's rating, it will push the calibrated, spring-loaded valve off its seat, releasing coolant into the overflow reservoir tank. When the radiator cools down, the reduced volume of coolant creates a vacuum in the radiator, pulling open another valve that allows coolant from the reservoir tank to flow back into the radiator.

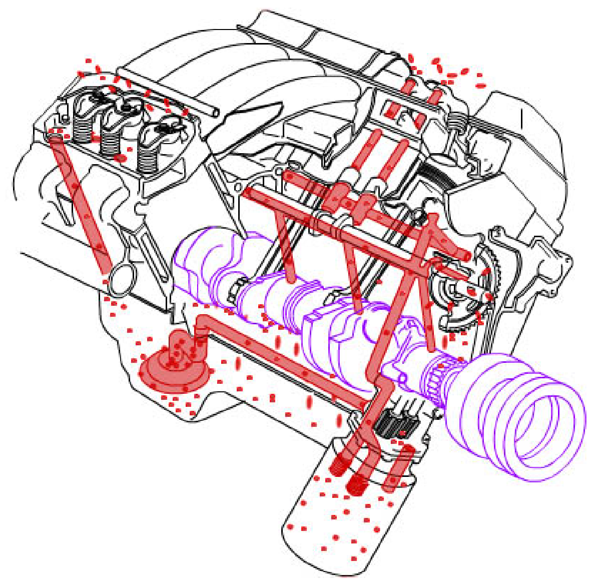



***Pressure Relief – Note the temperature and pressure gauge readings in the illustrations.***

If an engine runs very far outside its optimum temperature range, either too hot or too cold for very long, drivability and emissions problems can occur, in addition to severe engine or other system damage. If a vehicle's temperature warning light should illuminate, or the gauge rises into the red or "hot" zone, ***turn the engine off at once!*** Note also that it is possible for an engine to overheat without illuminating the warning light. Excessive engine pinging, very hard or swollen hoses, boiling in the overflow reservoir or escaping coolant, or steaming from the system are indications of overheating.

- ***Never attempt to remove the radiator cap with a warm engine, with the engine at operating temperature, or higher! Severe burns can result! Ensure there is no pressure on the system before opening the radiator cap. See your instructor for tips on determining system pressure and temperature.***
- ***Antifreeze is poisonous and especially toxic to animals.***

**Lubrication System**
Like the cooling system, the engine lubrication system is crucial to engine operation. Oil in the lubrication system reduces friction and wear between moving parts, and helps carry away heat. If oil is not delivered under pressure to the vital engine parts such as rod and main bearing journals, the engine will seize in minutes. The parts will melt and fuse together, destroying the engine. Pressurized oil is supplied to the main and rod bearings, cam bearings, lifters and rocker arm assemblies (pushrod engines), and other critical areas. Piston pins are usually lubricated with a stream of oil sprayed or thrown from rod journals beneath, which also serves to cool the piston head. Other, less heavily loaded parts are lubricated by splashing or runoff, such as the cylinder walls, piston rings, timing chain, and many other parts.



***Oil Flow***

A reservoir of oil is maintained in the **oil sump** at the bottom of the **oil pan**. Submerged in this oil is a **pickup tube**, covered with a **screen**. The pickup tube leads to the **oil pump**, which is driven by the cam or crankshaft. From the oil pump, oil is usually first delivered to the **oil filter**, and then to the **main oil galleries** for distribution to the moving parts. The crankshaft bearings receive oil from the main galleries and then the oil flows through passages in the crankshaft to lubricate the rod bearings. After the oil reaches its destinations, it sprays, oozes or drips away from the parts. On top of the cylinder head and in other places, the oil flows into **drain holes** that collect it and return it to the crankcase.

The oil pump must provide pressure at idle as well as at high speeds. The faster the oil pump turns, the more oil is pumped, and so a **pressure relief valve** is used to divert excess pressure at high speeds. Also, a **bypass valve** near the oil filter opens in the event of a clogged filter to prevent oil starvation. The pickup tube screen usually has a bypass hole for the same purpose.

Correct bearing clearance is critical to maintaining oil pressure. As bearings wear, the clearance between the bearings and the shafts increases. This allows too much oil to bleed off, reducing the pressure to parts of the engine that are farther from the pump, starving them for oil. This can cause the valve train to become noisy and wear rapidly. When the clearances are large enough, the protective oil film can no longer be maintained at the bearings and engine failure is imminent. The engine will begin to knock.

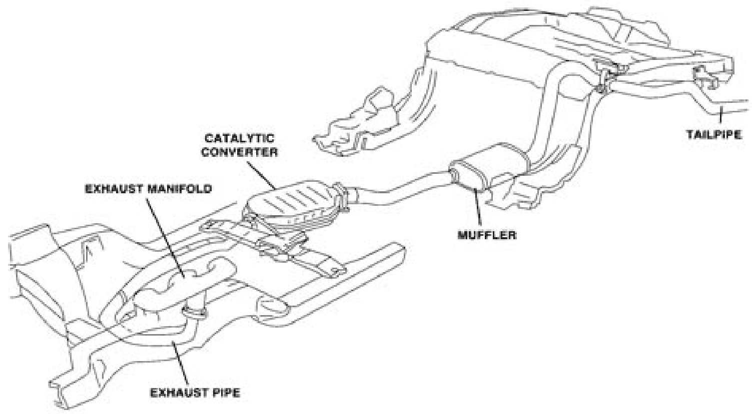
- ***Used motor oil contains contaminants from the combustion process and is considered a hazardous waste.***

**Exhaust System**
The exhaust system must collect the spent gas from each cylinder and route it to the rear of the vehicle for discharge to the air. The major components of the exhaust system include:

- Exhaust manifold(s)
- Exhaust pipes and seals
- Catalytic converter(s)
- Muffler(s)
- Tailpipe(s)
- Heat shields
- Hangers, clamps, and hardware

Exhaust systems have a major affect on airflow through engines**. Exhaust pipe** diameters must be sufficient to allow the engine to expel exhaust gases at the proper rate, with minimum **backpressure**. If exhaust gases are not expelled effectively, the air-fuel charge to the cylinder will be diluted and engine performance will suffer. If the diameter is too large, the engine could run cooler, increasing emissions levels.

Although exhaust system operation is simple, the design is often more complex. **Exhaust manifolds** must fit in cramped engine compartments without sharp bends that would restrict gas flow, while still leaving access for serviceability. High-pressure pulses produced when the exhaust valves open and close must also be muffled to reduce exhaust noise. Baffles in mufflers minimize exhaust noise, and catalytic converters contribute to noise reduction.




***Exhaust System***

A major component in the exhaust system is the **catalytic converter**, whose primary purpose is to control exhaust emissions. However, a deterioration of the materials inside the converter, possibly due to a prolonged misfire condition, can cause an exhaust restriction that may have a significant effect on engine performance.

If an exhaust restriction occurs, the complaint might be "lack of power." To determine if there is a restriction, check exhaust system backpressure using service manual procedures.

- ***Don't forget that exhaust system components get very hot after the engine has been running. Catalytic converters get especially hot and have been known to start dry grass fires.***
- ***Ensure proper ventilation to avoid asphyxiation when running an engine to check for exhaust leaks.***

**Emission Controls**

When the Industrial Revolution began in the 19th century, the practices of industries and a growing population soon began to have a significant damaging effect on the environment. Pollution of the air and water became a serious problem, and eventually, regulations were enacted to curb the releasing of harmful pollutants into the environment. As the number of motor vehicles on the road steadily increased during the 20th century, it became evident that vehicle emissions were a significant part of the problem that would have to be addressed. California led the way by passing state laws to reduce vehicle emissions. Its dense population centers and climate conditions had caused a severe smog problem in the Los Angeles Basin. By the mid-1960s, the first emission control systems were being installed on all new cars sold in the U.S., and in 1967, the **Clean Air Act** was amended to include standards for automotive emissions. The **Environmental Protection Agency (EPA)** develops and enforces environmental regulations. Within a few years, fuel economy standards were introduced as well, in the **Corporate Average Fuel Economy (CAFE)** standards. With increasingly stringent emissions regulations that began in 1993, much has been done to reduce vehicle emissions, and emissions from an average vehicle today are less than 5% of a 1960 model. However, the increase in the number of vehicles on the road causes emissions to continue to be a concern.

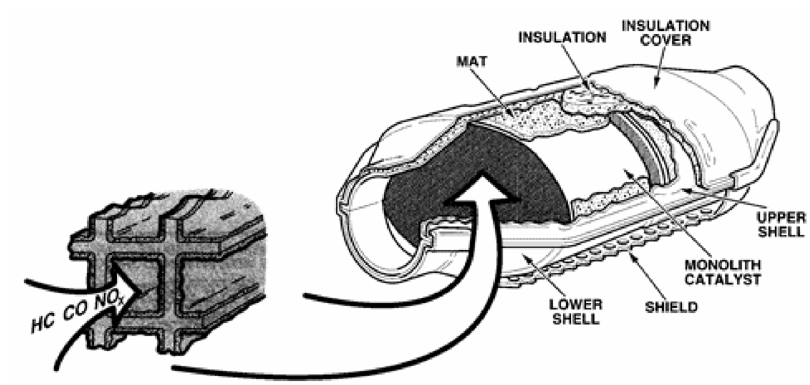
Emissions from the exhaust, crankcase, and fuel evaporation are controlled. Standards are set primarily with regard to three emissions: **hydrocarbons (HC)**, **carbon monoxide (CO)** and various **oxides of nitrogen ($NO_X$)**.

**Hydrocarbons** are simply unburned fuel. During combustion, hydrogen and carbon are converted in combination with oxygen, but not all of the molecules are converted. Some pass through the combustion chamber and come out of the engine as unburned fuel known as hydrocarbons. High levels of hydrocarbons are often related to problems in the ignition system. Some causes of high HC are misfire, improper timing, low compression, vacuum leaks, or incorrect air-fuel ratio.

**Carbon monoxide** is partially burned fuel, and the product of incomplete combustion. As previously stated, carbon is one of the elements that make up the fuel burned in the engine, together with oxygen. If the combustion were complete, carbon emissions would come out of the engine in the form of carbon dioxide, or $CO_2$, which is harmless to humans. Carbon monoxide, on the other hand, is a potentially lethal gas that is also odorless and colorless. High carbon monoxide emissions can be caused by an excessively rich fuel mixture, low idle speed, a restricted air filter, faulty PCV system, or a faulty fuel delivery system.

Nitrogen makes up about 78% of the air going into an engine. Under extremely high temperatures, it combines with oxygen to form **oxides of nitrogen ($NO_X$)**. $NO_X$, when exposed to sunlight and combined with unburned hydrocarbons, creates the visible air pollutant known as smog. Smog is a problem in many heavily populated areas of the world. Oxides of nitrogen can also combine with other molecules in the atmosphere to form compounds contained in “acid rain.” $NO_X$ is created when combustion chamber temperatures are too high (above approximately 2500°F). Common causes of excessive $NO_X$ include inoperative EGR, cooling system malfunction, lean air-fuel ratios, etc.

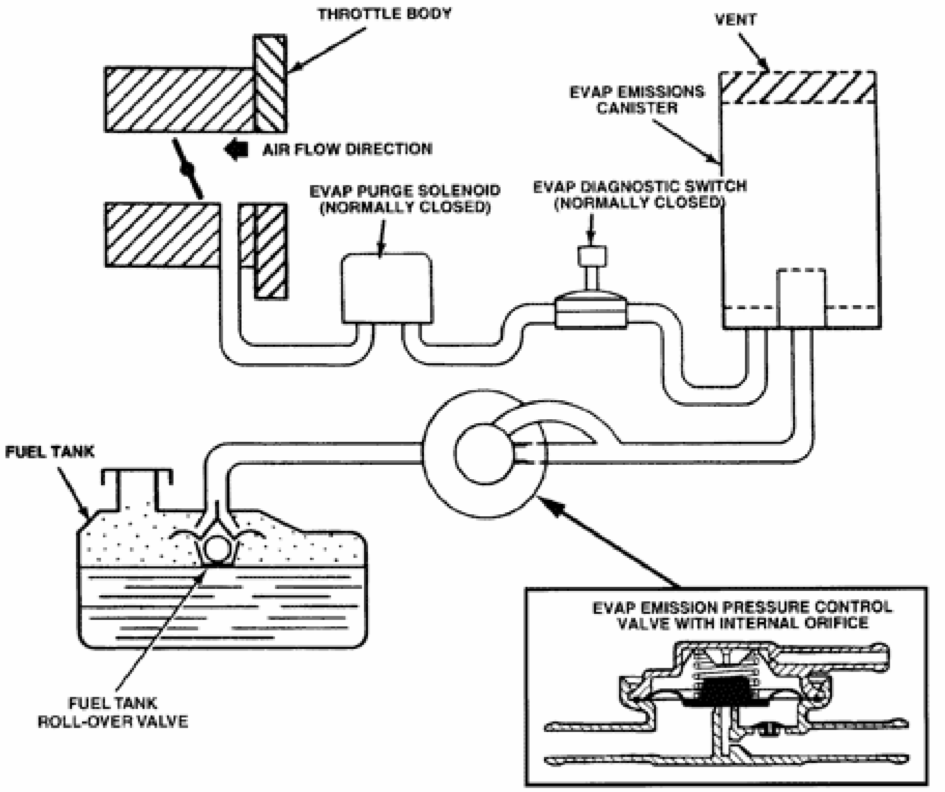
The **catalytic converter** reduces all three exhaust emissions. Converters contain small amounts of rhodium, palladium and platinum. When heated, these elements act as catalysts and convert the exhaust gases -- the HC, CO and $NO_X$ into the harmless substances of water ($H_2O$), carbon dioxide ($CO_2$) and nitrogen (N).




***Catalytic Converter***

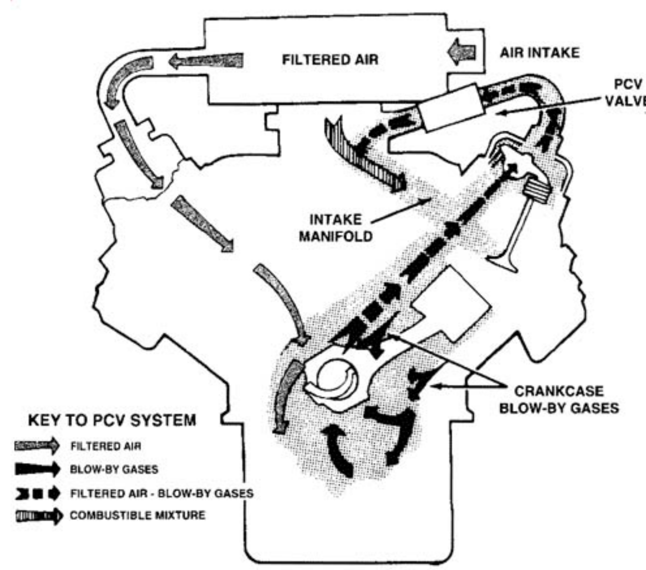
Hydrocarbons are released from fuel in vapor form. In the past, fuel tanks had vented caps, and HC was released into the atmosphere. Hydrocarbons escaped when the fuel tank was being filled, or even when the car was in operation. Hydrocarbon vapors are referred to as **evaporative emissions**. To reduce HC emissions, systems have since been developed to recover the vapors that evaporate from the fuel.

An **EVAP system** is used to collect fuel vapor from the fuel tank. These vapors are then stored in a canister filled with activated carbon. The EVAP system allows the vapors to be drawn from the canister, into the engine and burned during certain operating conditions. This is called purging, since the vapors are purged from the canister.




***An EVAP system***

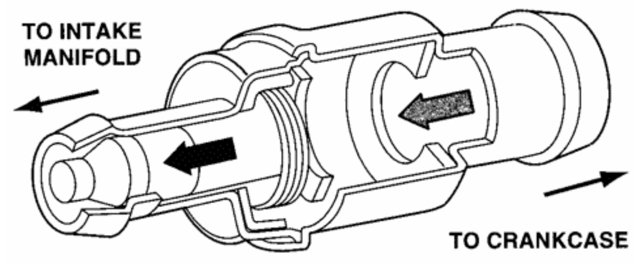
A **Positive Crankcase Ventilation (PCV) system** reduces crankcase emissions and protects the engine. During engine operation, some combustion gases leak past, or "blow by" the piston rings and into the crankcase. If the gases are not vented, moisture, sludge, and acids will build up, along with unwanted crankcase pressure. The accumulation of these harmful gases can shorten the life of the engine and cause oil leaks. These gases also contain the harmful emissions we have discussed, and are a source of air pollution.




The PCV system removes blow-by gases from the crankcase and routes them back into the combustion chamber, where they can be burned, instead of venting them to the atmosphere. The PCV system was the first emission control device used on automobiles.

In a PCV system, fresh air from the air cleaner is supplied to the crankcase where it mixes with the blow-by gases from the combustion process. The mixture of fresh air and blow-by gases passes through the PCV valve and into the intake system to be burned in the engine.

Most PCV systems use a mechanical valve to control flow rate, while others use an oil separator assembly. The PCV valve's spring tension is designed specifically for each unique engine application. The spring tension controls the flow rate of crankcase vapors into the engine, preventing pressure buildup.

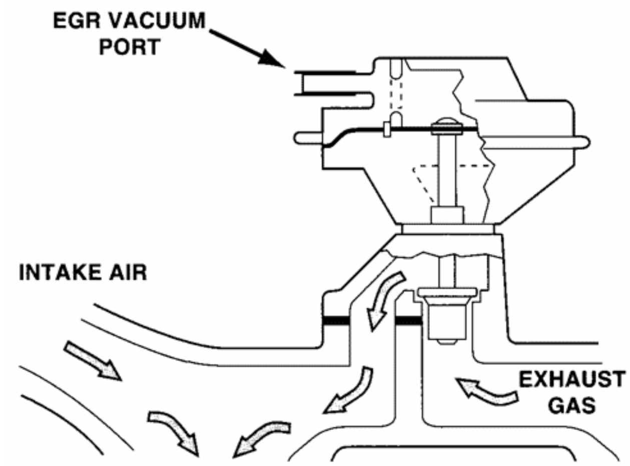



*PCV Valve*

As an engine wears, blow-by increases. A PCV valve failure, or an incorrect application may cause sludge buildup in the crankcase, incorrect crankcase pressures, or engine performance problems.

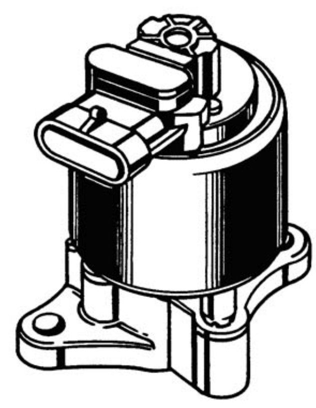
**Exhaust Gas Recirculation (EGR)** systems have been used on vehicles for many years. The primary purpose of the EGR system is to control combustion chamber temperatures, thus reducing the amount of oxides of nitrogen ($NO_X$) in the exhaust. Although EGR is necessary to control $NO_X$ emissions, it also affects volumetric efficiency. Volumetric efficiency is the ratio of the amount of air-fuel mixture that actually enters a cylinder to the amount that could enter under ideal conditions.

An EGR valve provides a link between the air intake and exhaust systems. Air flowing into the engine through the throttle body enters the intake manifold. When the EGR valve is opened, some exhaust gas is directed into the intake as well.




*EGR Valve*

As the piston moves down the cylinder on the intake stroke, the combination of air-fuel and exhaust gas enters the combustion chamber. This combination has the same volume as a pure air-fuel charge, but there is less air and fuel to burn when the mixture is ignited, due to the presence of the exhaust gas. Temperature and pressure in the cylinder are reduced, resulting in reduced $NO_X$. However, pressure in the cylinder is what pushes the piston down; therefore, engine performance can be affected by the decrease in cylinder pressure.



An EGR valve is designed to operate under engine load, when $NO_X$ is most likely to be produced as the result of high combustion chamber temperatures. If the EGR valve opens during idle or low RPM, effects on engine performance may be noticeable. One benefit of the EGR system is that cooler combustion temperatures help the exhaust valves stay cooler.

Some engines do not use an EGR valve. In such applications, low $NO_X$ levels are achieved through a combination of engine design and computer calibrations of fuel control and timing. With the appropriate valve overlap, cylinder temperatures are controlled, and emissions reduced.

These are some of the major subsystems of emission controls. Some vehicles may have other systems.

An **exhaust gas analyzer** can be used to measure the percentages of different gasses in the exhaust stream. Most machines measure the three main pollutants, along with the amount of oxygen ($O_2$) and carbon dioxide ($CO_2$) for reference. The makeup of the exhaust gas can also be a useful tool in diagnosing the causes of excessive emissions as well as drivability issues.

- ***It is against federal law for an automotive technician to remove or defeat emission control systems. It is also illegal to manipulate data or falsify records in order to issue a pass on a vehicle emissions inspection in states where they are required.***

**Computer System**
On late model vehicles, the **Powertrain Control Module (PCM)**, or in some cases, the **Vehicle Control Module (VCM)** operates the entire engine management system. A PCM is a computer that controls the engine and transmission and stores **Diagnostic Trouble Codes (DTC)** for these systems. A VCM also controls and stores codes for other systems, such as the antilock brake system.

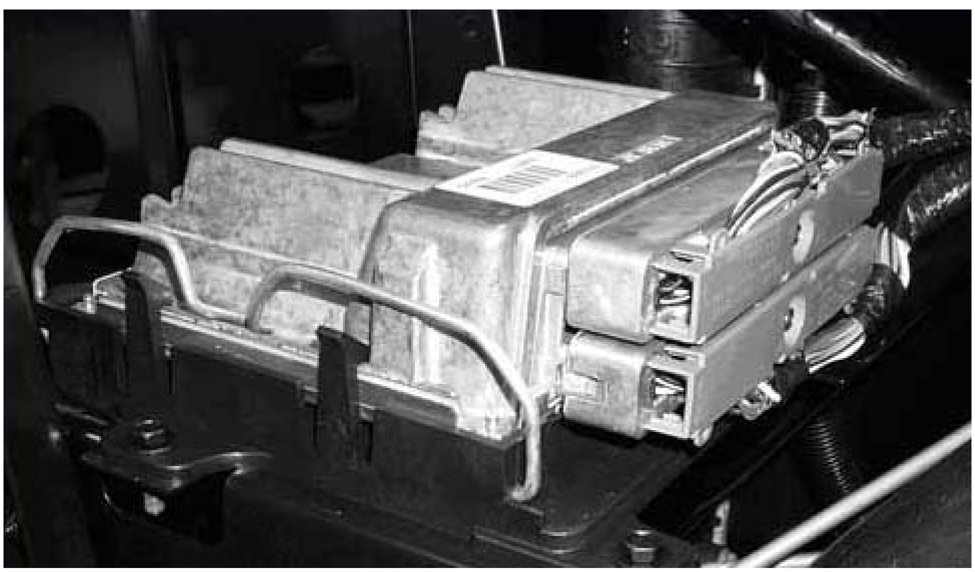
“Computer” is a broad term. A computer is any device that can take input information and perform a set of instructions, then generate a specific output. For example, a computer may receive input from a keyboard (such as typing numbers), calculate a formula with those numbers, and then output a result on a screen. The computer also may activate a motor, turn on a switch, or perform just about any kind of engine management task.

The computers in vehicles are no different. They receive input data from various devices, such as switches and sensors that provide information regarding conditions such as:

- Engine load
- Engine temperature
- Gear range
- Speed

The computer also performs specific output functions, such as:

- Metering fuel
- EGR operation
- Adjusting timing, etc.
- Control transmission shifting

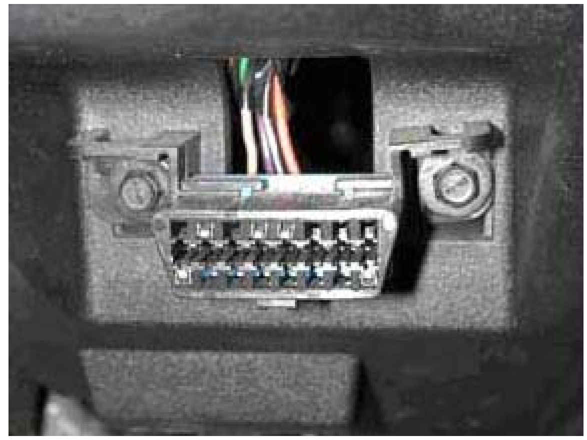


***Typical PCM***

Computers use voltage signals from the inputs and send signals to output devices. Two types of signals are involved: **analog** and **digital**. Incoming analog signals must be converted to digital format for the computer to use the data. Output digital signals may be modulated by **frequency** or **pulse width**.

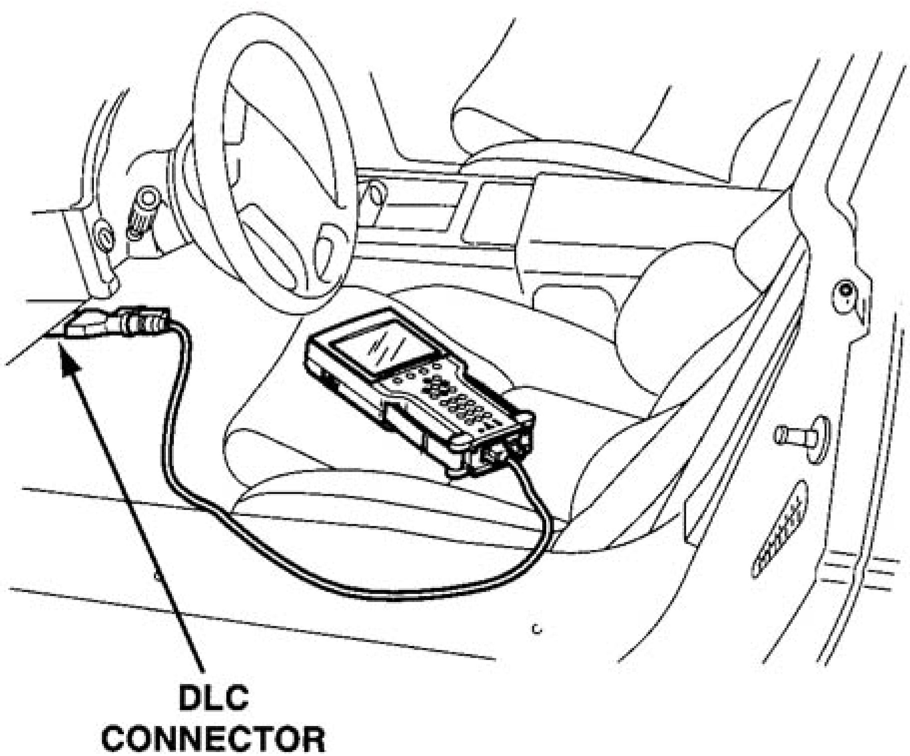
One of the bigger chips is the **Microprocessor Unit (MPU)**, which may also be called the **Central Processing Unit (CPU)**. Service on some of the newer models may involve reprogramming or changing the calibration in the PCM. It is necessary to refer to the vehicle service information for these procedures.

Various computers in an electronic system communicate by means of a **serial data stream**. Serial data is a string of information transmitted in sequence, one item at a time, making up the data stream. In electrical terms, serial data consists of voltage signals changing between high and low, or ON and OFF. Each individual signal, either a “1” or a “0,” is known as a “bit.” A “1” is ON, and a “0” is OFF. A series of 8 bits makes up a “byte,” also called a “word.”



***DLC***

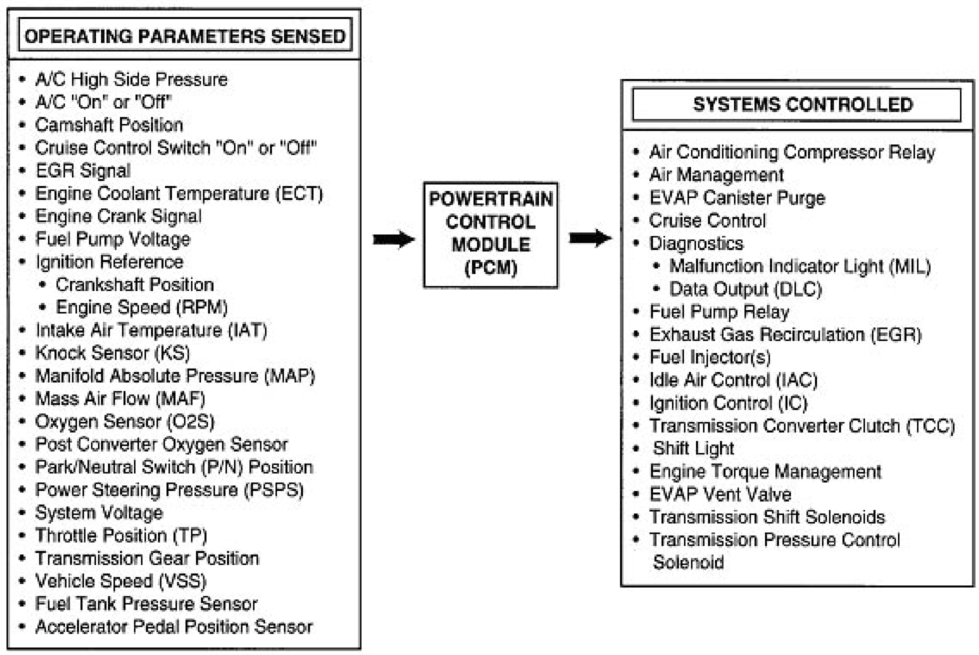
The wire(s) that carry the serial data messages are called the **data bus**. Besides allowing control modules to communicate with each other, the data bus also allows the technician to tap into the data stream to run system diagnostics by connecting an electronic **scan tool** to the **Data Link Connector (DLC)**.




Since **Onboard Diagnostics II (OBDII)** was mandated in 1996 to reduce emissions (1997 for overseas imports), all vehicles sold in the U.S. have a standardized DLC connection located somewhere on the driver's side below the instrument panel. OBD-II compliant vehicles use the same standard for connections, trouble codes, and terminology. OBD-II guidelines require a vehicle system to have the ability to record a snapshot of operating conditions when a fault occurs, and the system must permit codes to be cleared with a scan tool.

The speed at which bits are transmitted in the serial data stream is called the **baud rate**, a measure of how many bits are transmitted per second. Early Engine Control Modules had a baud rate of 160. Starting with the 1986 model year, ECMs with a baud rate of 8,192 were introduced, which is clearly a much higher serial data transmission speed. A common data stream for OBD II vehicles has a baud rate of 10.4K, or 10,400 bits per second, also known as “Class 2” data stream. The next serial networks to come into wide use on vehicles will be Controller Area Networks (CAN), which can transmit data at 1Mb, or 1,000,000 bits per second.

The PCM controls many devices related to engine operation. In order to make operating decisions, the PCM depends on information from a network of sensors, switches, and other modules located throughout the vehicle. The data from these devices are considered inputs to the PCM.




**Note:** Not all sensors are used in any one system. Some, such as the TP sensor, are used in all systems. But others, such as the cruise control switch or the accelerator pedal position sensor, are used only for certain applications.

## Diagnostics

To effectively diagnose the wide range of possible engine performance problems requires more study than can be provided in this introductory course; however, some basic diagnostic information and testing methods will be provided to help you get started. Understanding some of the test methods included will also help in your understanding of how an engine works, why it works, and what happens when it doesn’t work properly.

A logical, step-by-step approach should be developed and used in diagnosing automotive systems. A systematic approach will save time and ensure that the proper repairs are made.

### Verifying the Customer’s Concern

Effective communication between the customer, service writer, and technician is essential for efficient and satisfactory repairs. To begin with, you must know the correct or normal operation of the system and verify that the customer concern is a deviation from normal operation. You need to know what, where, when, and the magnitude of the complaint.

Preliminary checks of the malfunctioning systems or components should include a **visual inspection** and confirmation. Your inspection should include listening for unusual sounds and checking for unusual odors. The vehicle service history can provide useful information as well.

**Diagnostic System Checks**
Most service manual sections have "systems checks" that verify proper operation of the system. These lead you on a organized approach to diagnostics. The "system checks" help narrow down the possible causes of a system fault.

Once you have evaluated the situation, you should have enough information to perform a bulletin search. Other service information includes videos, newsletters and troubleshooting hints in the service manual.

Using any stored DTCs, follow the designated DTC chart to make an effective diagnosis and repair. Select the symptom from the symptom tables and follow the diagnostic paths or suggestions to narrow down the possible causes and test for the root cause.

You should develop a plan for diagnostics using wiring diagrams, theory of operation, and your experience. You may need to call technical assistance for more information.

**Repair and Verification**
After a cause has been isolated, make the repairs and validate proper operation. Verify that the symptom has been corrected. This may involve performing system checks or road-testing the vehicle. Verify the correction under the conditions noted by the customer.

**Common Diagnostic Resources and Tools**
There are many resources available to the technician to help with diagnosis. Following is a list of some resources.

- **Service Bulletins** are currently available to technicians in several formats, including CD-ROM and paper.
- **Manufactures' Internet Communication Systems –** With a subscription to the manufacturer's database, you can perform a search of published bulletins via the Internet on a PC or laptop computer. After a connection to the bulletin database is established, the technician types in keywords that relate to the vehicle owners concern. The system will display any bulletins that match the keywords.
- **Service Manuals** provide information such as diagrams, specifications, diagnostic charts, and procedures for each vehicle. It contains many system checks. It is an important tool, and knowing how to find service manual information is essential to diagnosis and service of engine performance conditions. The Onboard Diagnostic System Check is a critical step in diagnosis of engine performance conditions. Locate this system check in the drivability or engine controls section of the service manual. Service manuals may be available online and in paper format.

Many diagnostic tools can be used in troubleshooting engine performance problems. Following is a list of common tools.

- **Digital Volt-Ohmmeter (DVOM)** , or multimeter is an essential automotive tool that functions as a voltmeter, ammeter, ohmmeter, and more. A high impedance unit is necessary for automotive use. Multimeter use is covered in the Today's Class.com course, ***Circuits and Meters***.
- **Scan Tool** – These will be discussed in the following section.
- **Vacuum/Pressure Gauge** – for measuring and testing engine manifold vacuum and other components. We will discuss this further in a later section.
- **Compression Tester** – for measuring cylinder compression. We will discuss this further in a later section.
- **Cylinder Leakage Tester** – for pinpointing sources of leakage in combustion chambers.
- **Dynamometer** – A large machine the vehicle is operated on that can load the engine to measure road performance characteristics.
- **Oscilloscope** – A scope provides a visual display of voltage over time on a monitor. The pattern displayed can be analyzed in various ways. Once used mainly for diagnosis of secondary ignition systems, it can be very useful in analyzing many other signals such as sensor outputs.

- **Exhaust Gas Analyzer** – Most measure the percentages of five different gasses in the exhaust stream: HC, CO, NOX, O2, and CO2. The makeup of the exhaust gas can be a useful tool in diagnosing the causes of excessive emissions as well as drivability issues.
- **Engine Analyzer** – Combines several of the above tools into one console

**Scan Tools**
A scan tool is a handheld device designed to help diagnose computer-controlled systems on vehicles. OBDII vehicles supply power to the tool through the pin connection; some older vehicles provide power through the cigarette lighter. Scan tools use an electronic storage device to store software programs, which must be updated periodically for new models and for changes to service information. The screen displays the instructions and menus, which are commanded through a keyboard or with buttons.


***Scan Tool***

Current scan tools can receive and display data, and can also send serial data messages to the PCM. This two-way communication is referred to as "bi-directional." Data the scan tool receives include DTCs that have been set by a vehicle's PCM, as well as live data from the serial stream with values for the many engine sensors and other system sensors, sometimes referred to as **parameters**. Scan tools can clear trouble codes from the PCM's active memory, and many will identify and provide information about the codes, or the codes can be looked up in the service information. Most scan tools can make a recording of a vehicle's data stream over a period of time that can then be analyzed frame by frame to help in identifying intermittent or rapidly occurring problems.

- ***Always follow the scan tool's instructions regarding initiating and terminating communications with a vehicle. Abrupt termination of communications can damage the scan tool, the vehicle PCM, or both!***

**The Importance of Mechanical Systems**
Often, diagnosing a vehicle that has a DTC is not very difficult if you use the proper tools along with the service manual. Other times, what appears to be a problem with an input device or an output may really be a problem with a related circuit. The problem could also be in a mechanical system.

Don't forget that under all the electronics, there is still a basic engine. The engine management system assumes that all of the powertrain mechanical systems are functioning properly. Several items might cause conditions that could be blamed on the engine management system. Examples include:

- Low compression
- Vacuum leaks
- Exhaust system restrictions
- Problems with fuel delivery (including fuel pump, fuel filter, fuel lines or bad fuel)
- Worn ignition system components, bad wires, fouled spark plugs, etc.
- Incorrect basic ignition timing
- Cooling system malfunctions
- Transmission/transaxle faults

**Manifold Vacuum and Testing**

The intake stroke of the pistons creates a vacuum in the manifold. Vacuum is any pressure lower than atmospheric pressure. The strength of the vacuum created affects the distribution of air and fuel to the cylinders. Higher vacuum means better distribution. An engine's ability to form and hold a vacuum is directly related to its ability to form and hold compression. When an engine loses the ability to create vacuum, performance suffers.

The amount of vacuum formed in the manifold depends on several factors. First, the cylinders must be sealed. If a cylinder has low compression or high leakage, it may not produce sufficient vacuum to draw in the air-fuel mixture. Second, the manifold must be sealed, or vacuum will be lower than normal. Gaskets, vacuum hoses, vacuum operated systems, and accessories that operate on vacuum may leak, causing lower manifold vacuum.

When the throttle plate is closed at idle, the vacuum in the manifold is greatest. When the throttle plate is open and the manifold is exposed to atmospheric pressure, vacuum is lower.

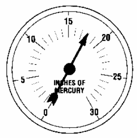
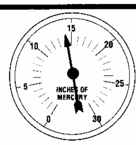
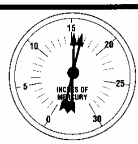
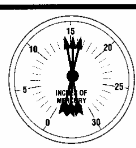
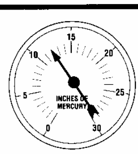
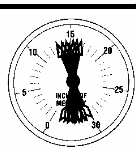
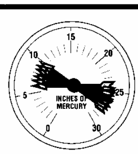
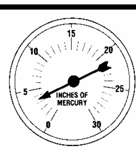
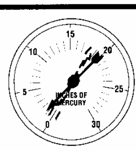
Using a **vacuum gauge** to check manifold vacuum is a quick and easy way to test an engine. It is a good indicator of the engine's ability to run efficiently. Typical engine vacuum will produce a steady reading of between 15 and 22 inches of mercury (inches Hg) with the engine at normal operating temperatures, idling, and in drive. Vacuum also changes with load, so if accessories are operated while monitoring vacuum, the readings will change. Vacuum readings will also vary between engines. One reason is differences in compression ratios. If an engine has higher compression, it will have 1 to 2 inches Hg higher vacuum. Altitude also affects vacuum. For every 1,000 feet above sea level, vacuum will be lower by 1 inch Hg. Some engines that use a high lift camshaft or have considerable valve overlap will produce a slightly lower, erratic needle reading on a vacuum gauge.

Some areas that can be diagnosed using vacuum readings include:

- Engine components (i.e., valves, valve guides and springs, piston rings)
- Manifold leaks
- Valve timing
- Restricted exhaust system.

In addition, low manifold vacuum can significantly affect the computer-controlled fuel system, in turn affecting performance. This is because the engine management system uses a **manifold absolute pressure (MAP)sensor** to influence spark timing and fuel control.

In reference to vacuum and pressure, keep in mind that a vacuum still has a certain amount of pressure. It is simply lower than atmospheric pressure. Normal atmospheric pressure at sea level is 14.7 pounds per square inch (psi), but most standard pressure gauges, such as a tire gauge, assign atmospheric pressure a value of "0." Some pressure specs are actually expressed in "psig," indicating "pounds per square inch – gauge," to distinguish them from absolute pressure. Higher air pressure will always flow into an area of lower pressure, if it is permitted.

| | Readings | Possible Cause |
|---|---|---|
|  | 1. Average, steady readings between 15–22 inches Hg (normal readings for a 60° V6 engine may be lower, i.e., 12–16 inches Hg) | 1. Normal |
|  | 2. Low but steady, between 12 and 15 inches Hg | 2. Leakage around piston rings, late ignition timing, or late valve timing |
|  | 3. Needle fluctuates or drops between 1 and 2 inches Hg at idle | 3. Burned or leaking valve or spark plug in one of the cylinders is not firing |
|  | 4. Irregular needle drop between 1 and 2 inches Hg | 4. Sticking valve, intermittent spark plug misfire, or rich or lean air/fuel mixture |
|  | 5. Normal at idle speed, but excessive vibrations at higher rpm | 5. Weak valve springs; valves sticking in guides |
|  | 6. Excessive vibrations at idle speed, but steadies at higher rpm | 6. Worn valve guides |
|  | 7. Excessive vibration at all rpm | 7. Leaky head gasket |
|  | 8. Needle oscillates slowly, or drifts, between 3 and 9 inches Hg lower than normal | 8. Intake system leak |
|  | 9. Normal at idle speed, but drops to near zero and rises to lower than normal | 9. Restriction in exhaust system |

***Manifold Vacuum Readings and Possible Indications***

**Compression Testing**

We have noted that the engine cylinders must produce good compression for proper combustion to take place. Cylinder compression can be checked using a compression tester , an inexpensive and simple tool. Compression can be tested during cranking or with the engine running. The cranking compression test is more commonly performed, but a running compression test can be useful in determining if there is an intake or exhaust restriction following a cranking compression test. The procedures are included in the job sheets, but for a cranking compression test, all spark plugs are removed, the ignition and fuel injection systems are disabled, and the end of the tester is threaded into a spark plug hole. The throttle is blocked open and the engine is then cranked through at least four compression strokes. The result is recorded and the procedure is repeated on each cylinder. On gasoline engines, compression is normally 125 to 175 psi, but the main concern is that the pressures are fairly uniform in all cylinders. Pressure should not vary more than about 15% from the highest to lowest, or around 15 psi to 20 psi. Low compression in one or two cylinders will cause a loss of power and poor running, especially at idle. A cylinder with very little or no compression will cause a “dead miss” on that cylinder at all speeds. An engine with low compression on all cylinders may lack power but run smoothly. Here are some guidelines for interpreting compression test results:

- Low compression on all cylinders can be caused by a worn or jumped timing chain or belt, or worn compression rings or cylinders. The timing chain/belt can be tested using other means.
- Low compression on two cylinders next to each other can be caused by a blown head gasket.
- Low compression with no apparent pattern among the cylinders may be caused by valve train problems such as valves being out of adjustment (not closing), broken valves or valve springs, and burned valves or seats. It can also be caused by engine damage such as a hole in a piston or cylinder wall. Broken piston rings or a cracked block or head can also cause low compression.

To determine if the problem is worn piston rings or cylinder walls, a **wet compression** test is performed. A maximum of one tablespoonful of 30W motor oil is squirted into the spark plug hole of the low cylinders and the test is run again. The oil provides a temporary seal for worn rings. If compression rises to normal, worn rings and/or cylinder walls are indicated. Note that if too much oil is used, the pressure will go up even if the rings are good. The oil will displace some of the combustion chamber volume, increasing compression.

**Intermittents**

Conditions that are not always present are considered intermittent. These may be resolved by observing history DTCs, evaluating the symptoms, and reviewing conditions described by the customer. Simulating system conditions to duplicate the intermittent and using a systematic process is important. Follow the suggestions for intermittent diagnosis in the service manual. Most professional scan tools and DVOMs have excellent data capture capabilities that can help you detect intermittent conditions.

When no trouble can be found and the vehicle seems to operate normally, it is most important to verify that the condition described by the owner is normal, compared to other vehicles. The condition may be intermittent, so verify the complaint under the conditions described by the customer before the vehicle is released.

When the problem cannot be successfully located or isolated, a re-evaluation is necessary. The problem should be verified again by repeating one or more of the initial steps.