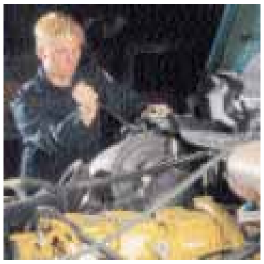
Study Unit

Diesel Engine Computer Systems



Computers control many aspects of engine operation. Controlled systems range from more-obvious applications such as fuel injection systems to less-likely ones like engine cooling fans. The precise nature of computer control systems is largely responsible for the increased fuel efficiency and reduced pollution emissions that characterize today's engines. This study unit explains how engine-controlling computers interface with other engine systems. Since this interface occurs through the use of input and output devices, which are more-general terms used to describe sensors and actuators, much of this study unit identifies common devices, explains how they work, and then describes their specific role in one or more engine systems.

When you complete this study unit, you'll be able to

- Identify the functional components that make up an engine-controlling computer system and describe the role of each
- Explain the difference between analog and digital signals as they relate to an ECM system
- Describe the operating principles and common engine-control applications for various types of temperature, pressure, position, and speed sensors
- Describe the operating principles and common engine-control applications for various types of output devices including relays, solenoids, stepper motors, and piezo actuators
- Understand the operating principles of various ECM-controlled engine systems including the fuel injection, engine braking, emissions control, and fault indication systems

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COMPUTER SYSTEM BASICS

Like anything unfamiliar, an engine's computer system may seem strange and confusing at first. Yet, vehicle-computer systems can be easier to troubleshoot and repair than engine or electrical-system failures.

Today's computers use state-of-the-art technology to control a vehicle's fuel, ignition, emission, transmission, engine brake, and service braking systems. Also, computers are used to control diagnostic, climate control, and many other systems with which drivers interface.

Basic Computer Operation

Unlike human beings, computers have no true intelligence. A computer is only an electronic device that processes information very swiftly. For any given task, a computer requires much more instruction than a person does. For example, getting a glass of water is a very simple task for most people. In contrast, a computer-controlled robot would require millions of instructions to get the same glass of water.

A computer is, however, a marvel in the speed at which it can process information and instructions. Most computers can process millions of instructions every minute. The speed with which it processes information is what makes a computer ideal for controlling a vehicle's operation. The functions of the computers found in our vehicles can be broken down into three categories:

- Receiving data
- Processing data and/or storing

- Outputting signals

The computer in Figure 1 controls a very basic system. Here, an input device called a *sensor* sends a value to the computer. This value, in electronic terms, can be a voltage or digital number. This input value tells the computer the condition of the monitored system. The computer compares the value received against a preprogrammed value in the computer's memory and makes a decision. The computer then converts this decision into an output signal that either controls an output device or reports information to a dashboard gauge, warning light, or other diagnostic system.

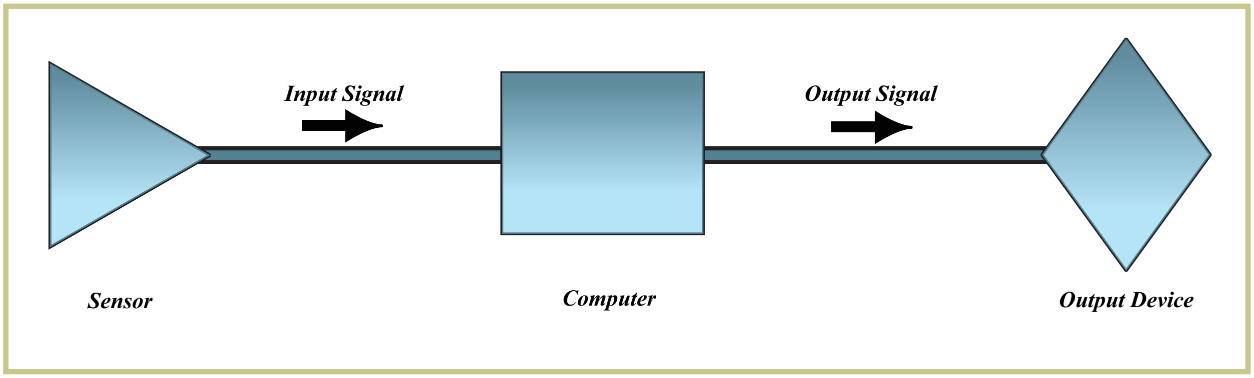


FIGURE 1—A computer system receives inputs from sensors and other devices, evaluates and otherwise processes the input, then sends a signal to an output device.

A *sensor* measures a physical property (such as temperature) and converts that measurement to an electrical signal. The voltage level of the signal emitted by the sensor corresponds with the measured value. For instance, one type of temperature sensor represents the temperature to which it's exposed by emitting a small voltage (several millivolts) that's proportional to the measured temperature. A type of pressure sensor measures fluid pressure, such as the pressure of oil inside the crankcase, then converts that measurement into a voltage level it supplies to the computer. The computer uses this voltage to generate the pressure reading displayed on the dashboard, illuminate a warning light when the level is too low, and control output devices. Most vehicle sensors employ either a change in voltage or resistance to "report" to the computer what they observe while monitoring an engine system. You'll learn much more about how various types of sensors function later in this study unit.

Of course, a real-world engine- or vehicle-control computer is much more complex than the one shown in Figure 1. An engine-control computer, often referred to as an *electronic control module (ECM)* or by a similar name, receives data from and outputs signals related to many engine systems including:

- *Common rail fuel injection systems*—These very common ECM-controlled fuel injection systems include a crank-shaft-driven fuel pump that provides pressurized fuel to a storage component known as the *rail* (Figure 2). Distribution lines transmit fuel from the rail to injectors serving each cylinder. The ECM turns on fuel flow from each nozzle, either as part of the regular injection process or, in some engines, to support the diesel-particulate filter washdown process. Very high fuel pressure in the rail is key to the successful operation of these systems. However, since the rail supplies fuel to all cylinders at a rate that varies dramatically with operating conditions, and the incoming fuel supply comes from a pump that's not electronically controlled, the ECM constantly monitors data from a rail pressure sensor to determine when rail fuel pressure drops below or rises above the target value. When pressure exceeds the acceptable limit, the ECM adjusts a metering valve that increases the flow of fuel from the rail into a drain line until the pressure sensor data indicates rail pressure has fallen into the acceptable measurement range. Similarly, if pressure in the rail is too low, the ECM adjusts the metering valve to allow less fuel to flow from the rail into the drain line. When a controller, like the ECM, adjusts a controlled device like a metering valve based on the input from a sensor that's monitoring the effect of the adjustment, the control system is referred to as a *closed-loop system.*

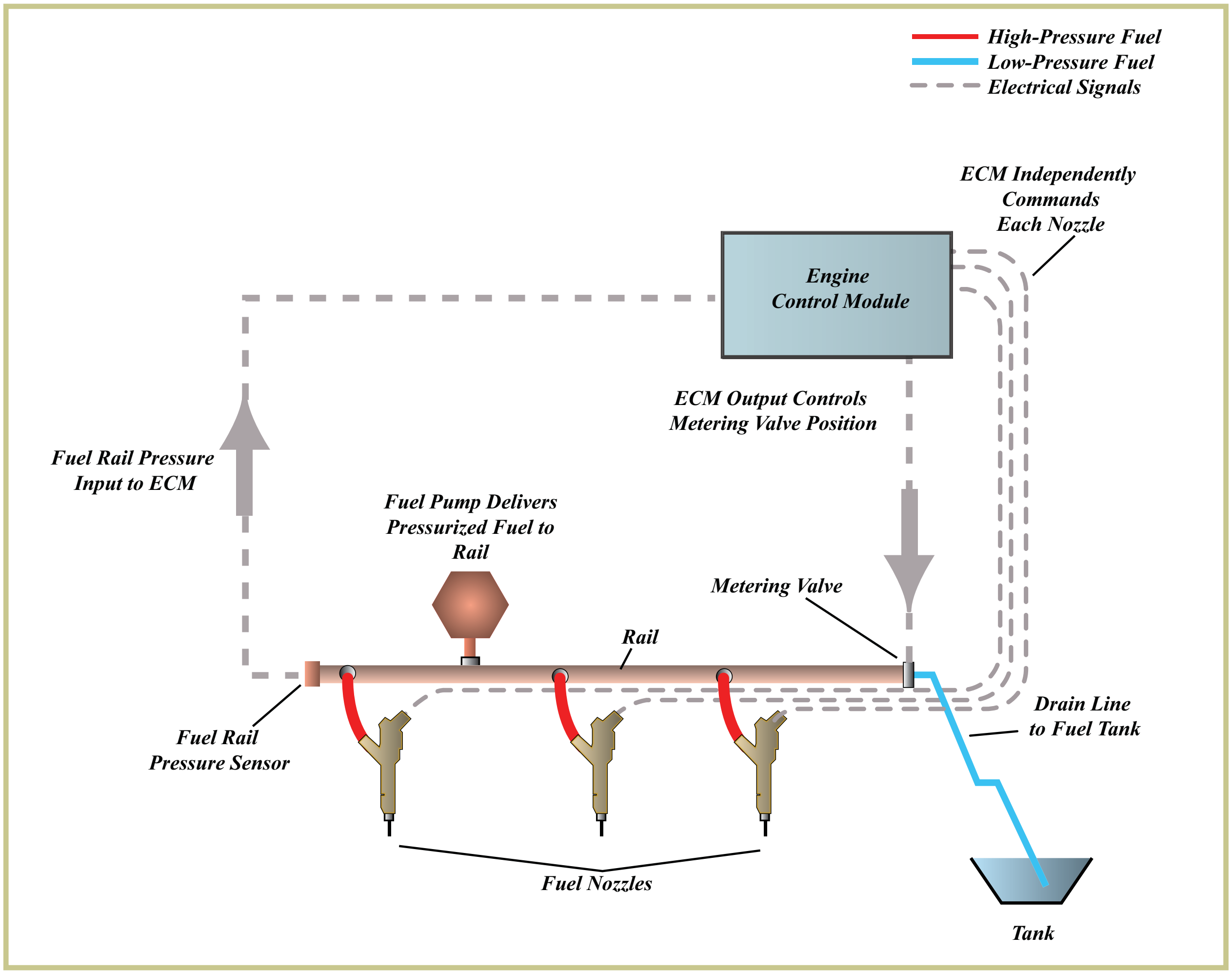


FIGURE 2—Much of an ECM's computing power focuses on the supply of fuel for the combustion process. This common rail fuel injection system is an example of a computer-controlled engine system you'll often encounter.

Shortly in this program you'll learn much more about the engine systems that are briefly described here as well as the components they include. Your studies will focus on input devices, known as sensors, computer-controlled valves as well as other output devices, and the important role played by a feedback circuit in closed-loop control system operation.

- *Electronic unit fuel injection (EUI) systems*—Relying on data the OEM loaded into the ECM, throttle position, engine and outdoor temperature, and even altitude, the computer system energizes and de-energizes the solenoids that control the injector's spill and needle-control valves. This process precisely controls the pressure at which fuel is injected and the exact timing (start point) and duration of the injection process.

- *Hydraulically actuated unit injector (HEUI) systems*—The ECM controls HEUI unit injector operation in a way that's similar to the EUI described above. However, in these systems the extremely high fuel pressures achieved prior to injection are accomplished through the use of a hydraulic pumping element. The pumping element's pressurization of engine oil, monitored by the *injection control pressure (ICP) sensor,* is electronically controlled by an *injection pressure regulator (IPR)* whose spool is positioned by the ECM. Throughout this process, the ECM receives and processes pressure-measurement data from the ICP sensor, which it uses to determine whether or not to change the injection pressure.

- *Engine braking systems*—Often referred to as *jake brakes,* these systems help reduce vehicle speed without the use of wheel brakes. As you'll shortly read in more detail, this is accomplished by adjusting the valve opening and fuel-injection behavior of one or more cylinders (Figure 3). The intention of these adjustments is to use power from the drive wheels to turn the cylinder(s) into a compressor. The ECM is responsible for halting fuel injection to the cylinder(s) involved in the engine braking process, and for changing the position of the cylinder valves to facilitate the power-absorbing compression process.

- *Exhaust gas recirculation (EGR) systems*—One of several computer-controlled systems whose purpose is limiting pollution levels. In this case, the pollutant is known as *NO_x (oxides of nitrogen).* The EGR system includes an ECM-controlled valve, which routes some of the exhaust gas to mix with intake air, reducing the amount of oxygen available for combustion. As you'll learn in this study unit, ever-expanding computer control capabilities have played a tremendous role in reducing vehicle emissions.

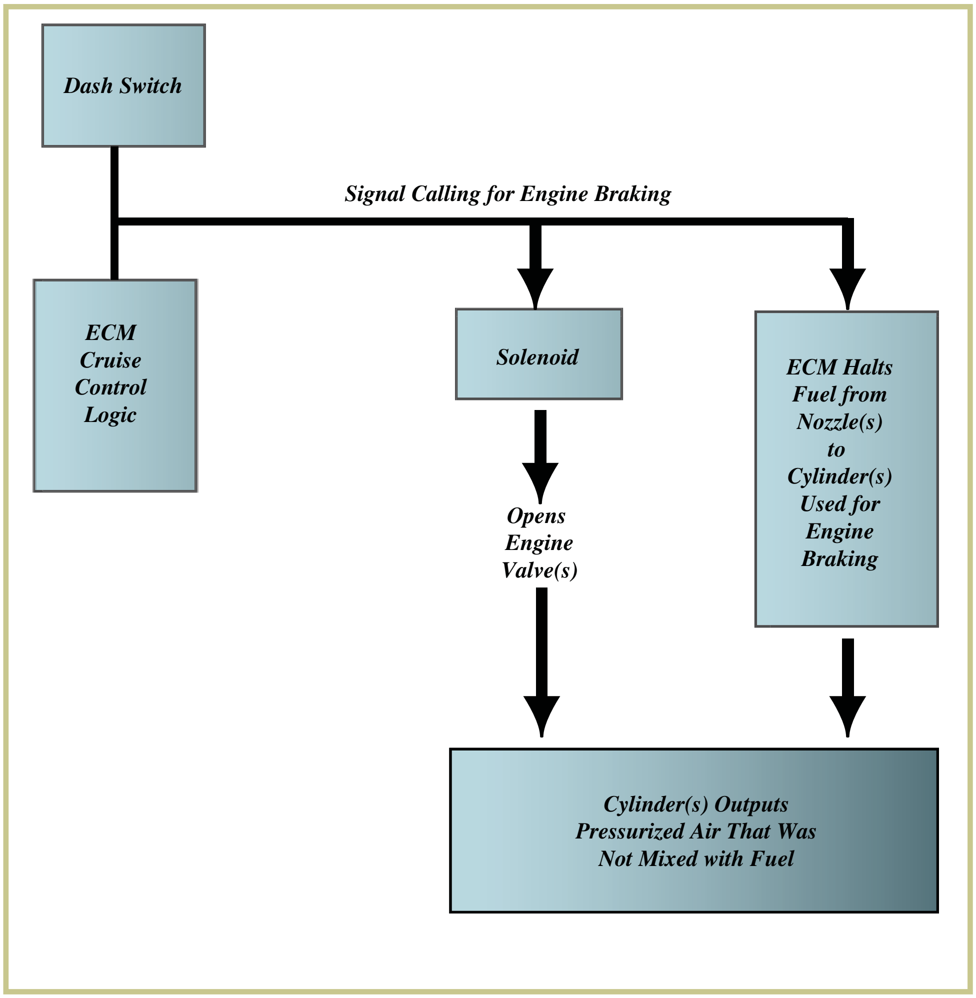


FIGURE 3—Modern engine braking systems rely on the ECM to stop fuel flow to one or more cylinders while altering engine-valve opening points as a way to temporarily transform the cylinder(s) into an air compressor.

Depending on the OEM, the engine's main control computer might be called something other than its ECM. *Electronic control unit, engine control unit (ECU),* and *electronic engine control (EEC)* are three such alternative names, as is *power train control module (PCM).* It's also likely that you'll encounter engines with multiple controllers, such as one devoted to fuel injection or an *aftertreatment module,* which manages portions of the emissions-control system, rather than a single engine-control computer. For simplicity, in this study unit, we'll refer to a computer that controls engine functions as an ECM.

Similarly, *body control modules (BCM), bulkhead modules (BHM),* and *instrument cluster units (ICU)* are computers that monitor and issue output signals related to other vehicle systems like the cruise control, climate control equipment, and the instrument panel. Throughout this study unit you'll learn more about how sensors, computers, and output devices work together to optimize engine and vehicle performance.

Data Received by the Computer

It's best to think of data as information. This information can be as simple to understand as the position of a switch, such as whether or not the cruise-control switch is in the on or off position. More often, the data received by the computer arrives in the form of an electronic signal from a sensor.

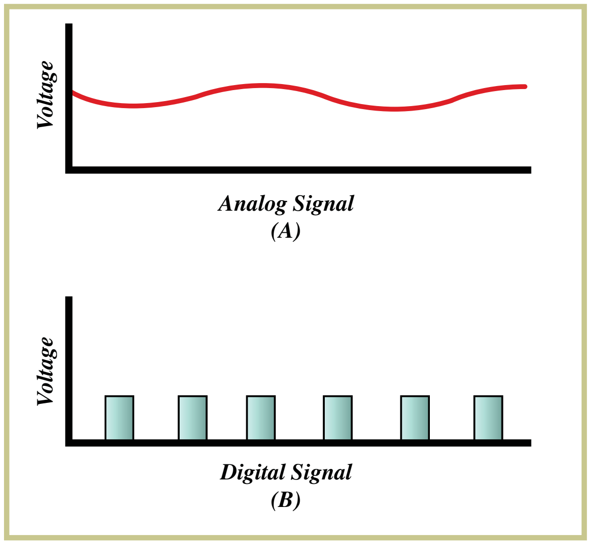
The data received by the computer can be grouped into one of two categories, analog and digital.

A *digital signal* is one that varies between one of two states, such as the positions of a switch that's either on or off. In the technical terms applied to computers, digital signals are identified as being either a 0 or a 1. Modern computers perform their operations on digital data.

An *analog signal* is one that varies within an acceptable range. For instance, a sensor's evaluation of oil temperature may be reported as a voltage level that falls somewhere between 0 and 5 volts. In this case, the lowest expected temperature might be represented by the temperature sensor with an analog signal equal to 0 volts. Meanwhile, a 5-volt signal would indicate the temperature sensor is experiencing the highest temperature it's designed to evaluate. In an analog sensor, each voltage level between these two extremes corresponds to a different temperature level. Analog data sent to a computer is converted to digital data before the computer attempts to evaluate it.

In Figure 4, you can see examples of analog and digital signals. In Figure 4A, the voltage of an analog signal varies with time. This varying signal might represent a changing temperature or pressure level. In Figure 4B, the voltage level of a digital signal, which varies between two predefined unique or *discrete* values, appears as pulses of voltage. These pulses might represent the position of an on/off solenoid (which is

FIGURE 4—The voltage level of the analog signal in A varies continuously while the digital signal in B is made of pulses that simply switch on and off.



either energized or de-energized). These pulses can also represent temperature, such as the voltage emitted by an analog sensor. In this case, the analog signal goes through an analog-to-digital conversion process in the computer's input module. The result of this conversion process is that the analog signal is converted into a digital number that can be evaluated by the computer.

Data Is Processed by the Computer

Once the computer receives data, which once again can be thought of as information, it goes to work evaluating it. This evaluation may involve simply comparing the received data (such as a specific pressure level) with a predefined minimum acceptable value or it may involve very complex calculations involving dozens of measured values and mathematical formulas. Whether relatively simple or extremely complex, these evaluating tasks are carried out in the computer's *central processing unit,* or *CPU.*

While a computer's CPU can be thought of as its brain, it can't control a system on its own. First of all, it relies on a set of instructions to tell it what to do with the data it receives. Often, these instructions (which are commonly referred to as *software* or as a *computer program*) tell the CPU to compare the incoming data with predetermined acceptable limits, such as a minimum and maximum acceptable engine coolant temperature, which are stored in memory. The CPU relies on other computer components to store data, instructions, and even these predetermined limits. You can think of a computer's data-storage features as belonging to two groups: storage locations that can be written over and altered and locations that remain either permanently unchanged or at least are unchanged until significant actions are taken (Figure 5). You'll hear the type of memory that's quickly overwritten or modified referred to as *volatile memory*. In most cases, the contents of volatile memory are erased each time the truck's key is turned off.

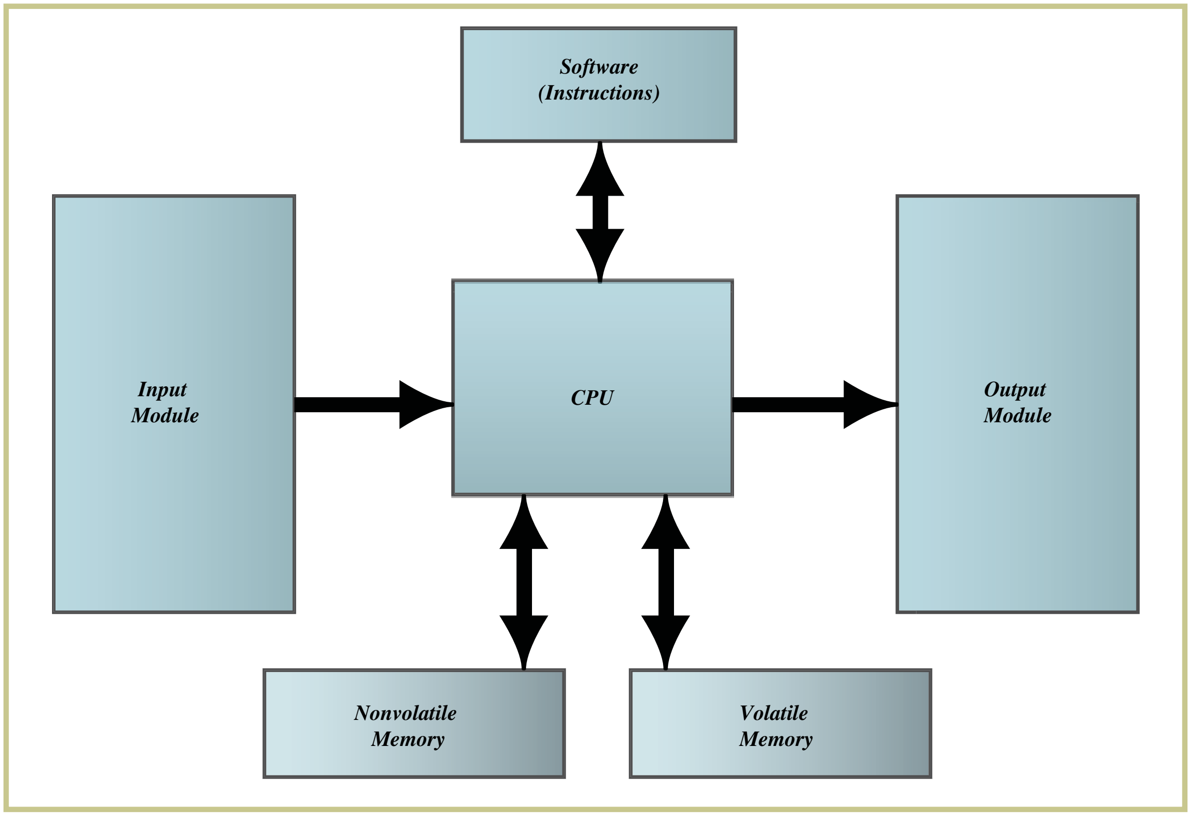


FIGURE 5—A computer can be thought of as a collection of subsystems, each performing one or more tasks.

Following is a summary of each term you're likely to encounter that relates to computer memory:

- *RAM,* or *random access memory,* is a type of volatile memory, since information stored in RAM is erased when the ignition key is switched off. RAM is where incoming information is held, updated, and evaluated as the vehicle operates. The evaluation of the information held in RAM is carried out based on instructions programmed into the computer's ROM. RAM keeps information about driver inputs, barometric pressure, temperature of the engine or air, and speed of the vehicle.

- *ROM,* or *read-only memory,* isn't intended to be overwritten. For this reason, it's known as *nonvolatile memory.* This type of memory contains the basic rules that determine the operation of various vehicle systems such as the fuel injection. It also contains OEM-determined acceptable limits for various engine parameters (like coolant temperature) above which the ECM issues a warning message.

- *PROM,* or *programmable read-only memory,* is typically used for information or programs relating to an engine's specific installation (when one engine family is found in a range of different vehicle models). The electronically erasable variety *(EEPROM)* is relatively easy to access and modify, provided you have the applicable password. This memory contains data that's likely to be changed by a maintenance technician (like tire measurement) or accessed in the course of repairing a vehicle. It's also where the ECM stores fault codes and related data.

- *Flash memory* serves the same basic purpose as EEPROM, except that the flash memory storage device is one to or from which data is transferred in large chunks, rather than in smaller units known as *bytes.* Data transfers to or from these devices more quickly than is the case with EEPROM memory.

As you've already read, while data supplied to the computer may arrive in one of two formats, as an analog or a digital signal, the computer's evaluation work requires that the information it handles be in digital format. This conversion process occurs in the computer's *analog-to-digital* or *A/D converter.* The A/D converter may reside inside the ECM or exist as a separate component. In addition to the analog input signal being modified, it's also often made more powerful, or *amplified,* to fall within a band that's usable by the CPU (Figure 6).

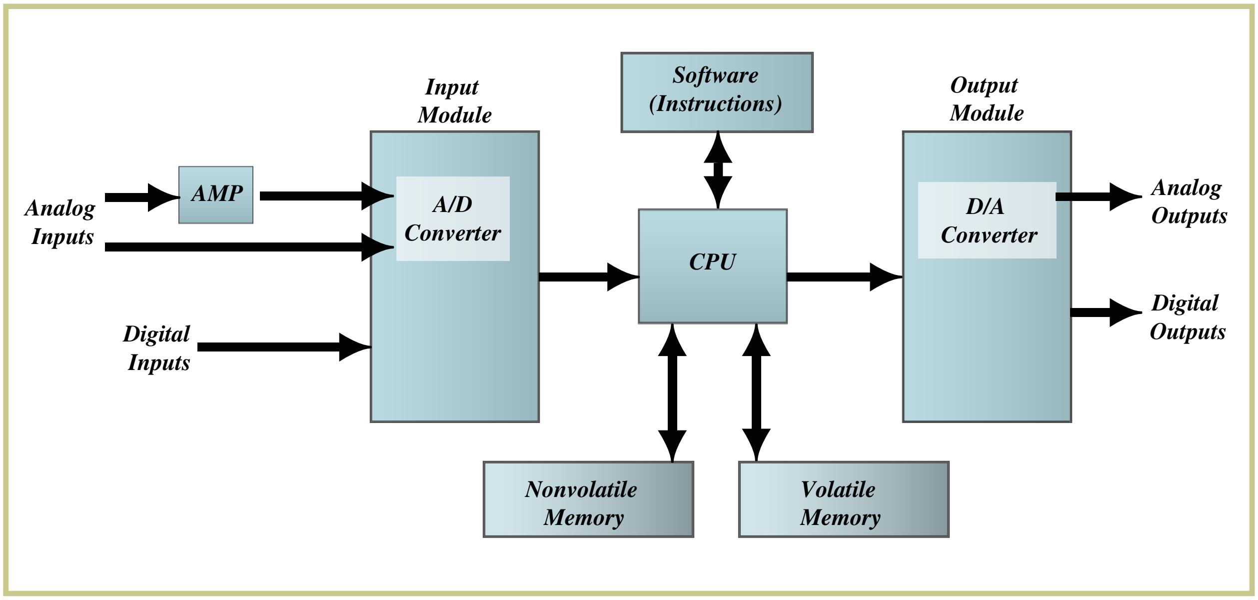


FIGURE 6—Input signals sent to the ECM often require conversion, from analog to digital, or amplification.

Since a computer's CPU works with digital data, it would be logical (and correct) to assume that the CPU's outputs are also in digital format. However, the computer's outputted signals, about which you'll learn more later in this study unit, often control analog devices such as variable-position airflow or EGR valves. Remember, these devices are considered to require analog control because their position varies continuously and can rest anywhere between two limits. On the other hand, a digitally controlled valve would only stop at preset locations such as fully open or fully closed. To control analog devices, the ECM's output is routed through a *digital-to-analog (D/A) converter.*

The Computer's Output

As a result of the CPU's work, the ECM outputs signals that might be used to turn on fuel injectors for a specified period of time, position the EGR valve, cause an electric motor to rotate, or illuminate a dashboard warning light. The type of signal that ultimately arrives at the computer-controlled output device depends on the device's operating characteristic.

One simple method of digital control is the *on-off method.* Here, the computer simply produces an output voltage, at a specific level, to turn the device on. Similarly, this type of output device can be turned off when the computer removes the voltage. This type of on/off control can be thought of occurring with a constant voltage that's on or off for a long period of time or with a single *electrical pulse,* a voltage level that's emitted for a fraction of a second.

Other output devices are controlled through a series of multiple pulses. The use of pulse signals to control a device is often called *pulse-width modulation (PWM).* The computer changes *pulse width,* which equates to the amount of time the electrical signal rests at its nonzero level, to increase or decrease the operating speed of the device being controlled. A PWM signal is shown in Figure 7. As the computer varies the output signal from wide to narrow pulses, the output device's motion changes from full speed to a very slow speed. If the computer removes the output pulses entirely, the output device is turned off.

FIGURE 7—A wider pulse powers the output device for a longer period of time, resulting in a higher-speed or longer-duration operation.

A computer can also control an output device by changing the number of pulses sent to the output device each second. An example of this method is shown in Figure 8. When the pulses sent to the output device are tightly packed together, the output device spins faster. As the space, which equates to time, between pulses widens, the output device begins to slow. When the pulses stop, the output device turns off.

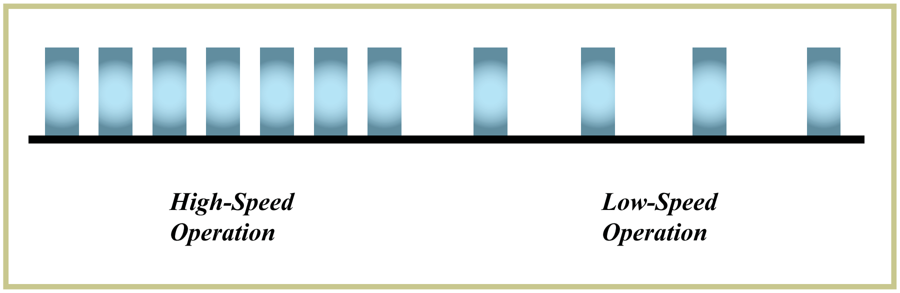


FIGURE 8—A computer can change the speed of a controlled output device by varying the number of pulses sent to the device over a period of time.

As you've already learned, many digital signals are based on analog voltages. Analog voltages that originate at an input device are converted to digital signals within the computer or sensor so that the computer can handle the information. Similarly, many output devices can only be controlled by analog signals. The computer converts the digital information to an analog signal for output to the analog device. A typical example of digital-to-analog signal conversion appears in Figure 9.

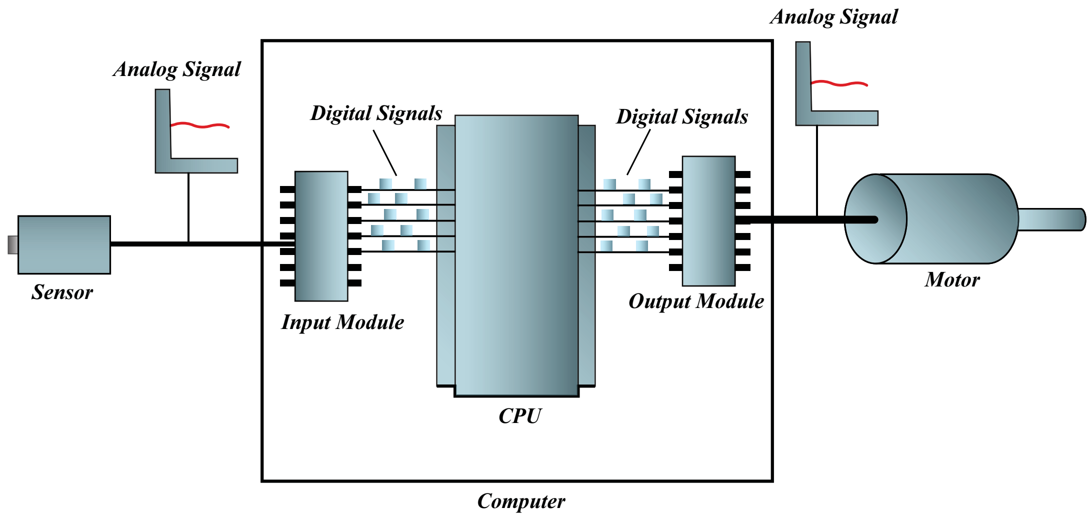


FIGURE 9—Just as an analog input signal must be converted to a digital signal before it's evaluated by a computer, the computer's digital output signal can also be converted to an analog output when controlling analog output devices.

Control Fundamentals

While many controlled vehicle systems are linked in one or more ways, it's easier to begin your study of control systems by thinking of each vehicle system as if it's independently controlled.

Control Loops

To properly control the emissions system or any other vehicle system, the computer uses *control loops.* Control loops are simply signal paths through which input devices, computers, and output devices communicate.

A simple example of a control loop can be found in most homes. The wall thermostat that controls the heating system and sometimes the air conditioner works in the following way:

1. A human or a temperature-scheduling program (in the case of a programmable thermostat) sets a desired temperature. This *set-point* temperature directly represents the heating system's *desired output* while the actual temperature reading on the face of the thermostat represents the *measured output.*

2. A temperature-sensitive spring in the thermostat contracts when the air around it becomes too cold and closes a set of contacts. The temperature-sensitive spring (or electronic temperature sensor, in the case of a digital device) serves as the system's sensor.
3. The closing contacts act as the system's controller, sending a signal to the furnace and blower motor, turning the furnace on, and producing the heated air that warms the house.
4. When the house is warm enough, the thermostat spring expands, opening the set of contacts.
5. Since the contacts are open, the thermostat continues its function as the system's controller by stopping the signal it had been sending to the motor. This switches the furnace and blower motor off.
6. When the house cools off again, the air around the thermostat becomes too cold and the cycle repeats.

As you can see in Figure 10, the system described above represents a control loop, and the controlled process is the addition of heat to the air inside the house. The thermostat's temperature-sensing element is a sensor, which sends an input signal to the thermostat. The thermostat, serving as the controller, outputs a signal to the furnace's heater and blower motor circuits, turning them on when the interior temperature is low enough to call for heat.

The operation of any computer is itself a control loop. The computer serves as a controller, receiving an input and producing an output. On a laptop or tablet, the input is provided when the operator presses a key on the keyboard or taps an on-screen command key; the output might be a visible change in the device's display screen. Notice that the laptop or tablet (both types of computers) requires a person to take action before the control-loop operation starts.

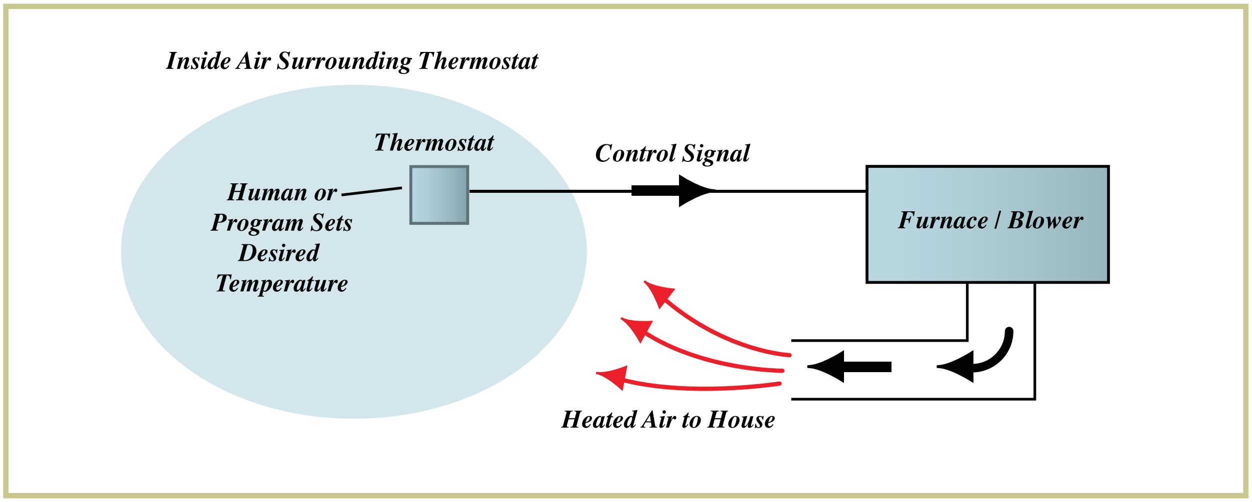


FIGURE 10—The control loop in this example is formed by the thermostat, which serves as the furnace's controller and the device used by the homeowner to indicate the desired temperature (or setpoint), the furnace/blower/air-duct assembly, and the air moving around the house.

The computers that govern the operation of engines or vehicles aren't directly controlled by an operator. Once the driver starts the vehicle, the computer makes its decisions based on input from the vehicle sensors. The only control that the driver has over the computer is indirect, such as when he or she pushes the accelerator pedal, depresses the brake pedal, changes transmission gears, or acts on one of many dashboard controls. As a change in engine operation occurs, the computer receives new information from the sensors. This change causes the computer to modify the output signal to compensate for the new sensor input. A complete cycle of operation is created by the control loop between the computer, sensing device, and output device. Today's trucks have many control loops, often with several sensors within each loop.

Closed- and Open-Loop Modes

Before concluding the discussion of control loops, note the two control loop modes found in modern vehicles—the closed-loop mode and the open-loop mode. Under normal engine operation, the computer-controlled systems operate in *closed-loop control mode.* In this mode, the computer receives input from one or more sensors, consults data and mathematical operations stored in its memory, and produces an output. The controller evaluates feedback data from the input sensor or sensors to determine whether further adjustments are required. Figure 11 represents an emissions-control system, which works to limit the amount of NO_x pollution in an engine's exhaust by spraying diesel exhaust fluid (DEF) into the exhaust stream. Shortly, you'll learn much more about this system.

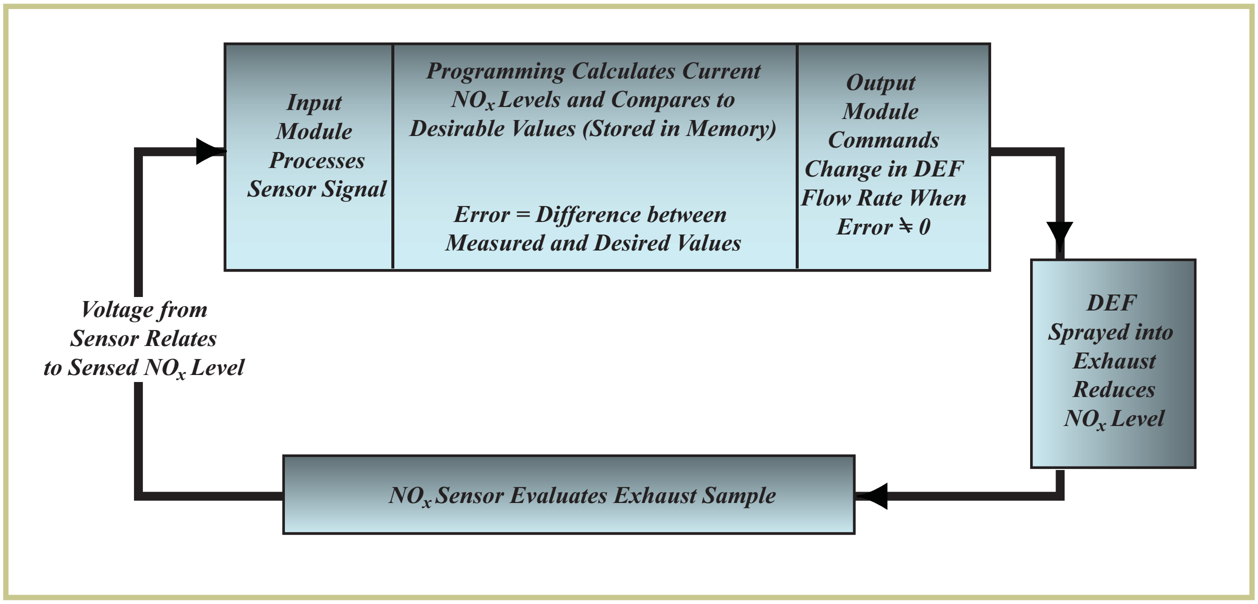


FIGURE 11—The NO_x sensor measures the amount of pollutant in the exhaust and supplies the detected value to the ECM. The ECM compares the measured value to data stored in its programmed memory. Based on this comparison, the ECU decides whether to change the amount of NO_x-reducing DEF sprayed into the flow of exhaust gas.

The closed-loop mode of operation begins after the engine reaches operating temperature, has been operating for at least a minimum amount of time, and typically, isn't going through a large acceleration or deceleration. Whenever these conditions are met, the computer operates in closed-loop mode.

The *open-loop mode* of operation occurs when the computer controls the output devices with few, if any, input signals from sensors. In this mode, the computer scans its internal memory for values and uses these values in place of sensor measurements. Often, open-loop mode is relied on for very short time periods during startup and transient operation.

Sensor failure can also cause a computer to operate in open-loop or, as it's often called, *limp-in mode.* If a sensor's value is lost, or if it's far out of range, then the computer enters the open-loop mode. When sensor failure occurs, the computer system's diagnostic program normally sets a *diagnostic trouble code (DTC)* in memory, and illuminates a dashboard warning light. As you know, the trouble code will aid you in troubleshooting the source of the sensor failure.

Self-Check 1

At the end of each section of *Diesel Engine Computer Systems*, you'll be asked to pause and check your understanding of what you've just read by completing a "Self-Check" exercise. Writing the answers to these questions will help you to review what you've studied so far. Please complete *Self-Check 1* now.

Complete the following statements with the correct answer.

1. *True or False?* The functions performed by vehicle computers include receiving data, processing data, and analyzing data.

2. A pressure sensor measures a fluid's pressure level and converts that measurement to a specific ________.

3. *True or False?* The ECM uses OEM data, specific to the vehicle in which the engine is installed, while controlling an electronic unit fuel injection system.

4. The _______ system adjusts cylinder valve opening points and fuel-injection system behavior to slow the vehicle without relying on the wheel brakes.

5. *True or False?* NO_x is a pollutant, found in engine emissions, which is partially controlled through the use of an exhaust gas recirculation system.

6. In engine computer control systems, a(n) ______ signal is one whose amplitude can fall anywhere within a predetermined acceptable range.

7. *True or False?* Digital input is required by a CPU, while CPU output is always in the form of a digital signal that's unable to be converted to an analog signal.

8. An output device that operates in only an on or off state, is most likely controlled by the ECM with a _______ output signal.

9. During normal engine operation, the computer-controlled systems perform in ______ control mode.

Check your answers with those on page 63.

SENSORS

Right now, you're using at least one of your five senses: you're relying on your sense of sight to read these words. The input your sight provides to your brain is necessary for you to understand the meaning of the words on this page. Like your brain, a computer needs information to make decisions. That's why proper sensor operation is vital to the ECM's ability to control a vehicle's engine and other systems.

As you've already learned, a sensor is a device that measures a physical property, then converts that measurement into an electrical signal. You'll find input sensors mounted throughout a modern truck including on the body, engine, transmission, and brake systems. These sensors monitor position, motion, temperature, chemical content, flow rate, and pressure.

This part of your study unit introduces several types of sensors followed by several examples of how each type is typically used in a truck. For instance, after learning about each type of temperature sensor, you'll study various applications and the role the temperature sensors play in controlling a modern diesel engine. However, a few of the sensors described won't apply to all engines (especially older ones). Also, it's common that some sensors are given different names by different OEMs, even though they serve the same basic function in each installation.

Temperature Sensors

The devices used to sense temperature in a vehicle are thermistors, thermocouples, or RTDs. A *thermistor* is a variable-resistance device made of a material whose internal resistance changes with differences in temperature. *Thermocouples* incorporate two dissimilar metals joined together only at their ends. An *RTD,* or *resistance temperature detector,* incorporates a thin wire whose electrical resistance changes with changes in temperature.

Thermistor Sensors

This variable resistance sensor receives a reference voltage signal from the ECM, which typically measures 5 VDC (Figure 12). Since the sensor is wired in series with the ECM's circuit, it returns a voltage that's different from the reference level. Depending on the type of thermistor, resistance can either increase or decrease with an increase in temperature. Because the system designer knows how the resistance of a particular type of thermistor varies with temperature, the ECM is programmed to interpret the change in voltage as a specific temperature. One disadvantage of a thermistor-type sensor is that it delivers precise readings over a relatively narrow range of temperatures.

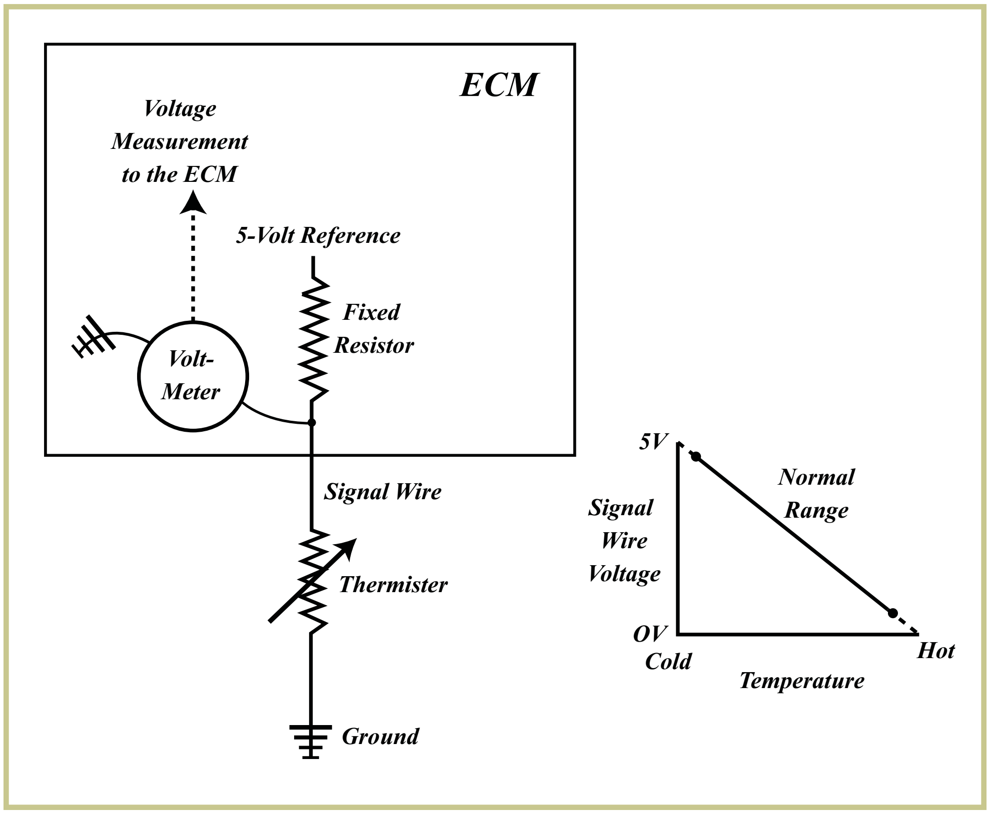


FIGURE 12—As the thermistor's resistance varies with temperature while the reference voltage remains constant at 5 VDC, the ECM-monitored voltage also varies. Notice that the fixed resistor and voltmeter represented in this diagram are actually just part of the ECM's signal-processing capabilities.

Thermocouple Sensors

A thermocouple is made from two different metallic conductors, joined together at each end but otherwise insulated from each other. The different or *dissimilar metals* in the type of thermocouples you'll encounter are most often iron and *constantan*, an alloy of copper and nickel (Figure 13). The thermocouple produces a very small voltage whenever the temperature at one of the joined ends, known as a *junction* or *node,* differs from the temperature at the other junction. In a practical application, the *hot junction* is located where temperature must be measured while the other end, the *reference* or *cold junction,* is maintained at a known temperature. Voltage measured at the reference junction varies with changes in the measured temperature at the hot junction. One key benefit of using a thermocouple sensing device is its ability to withstand very high temperatures. This makes thermocouples popular for exhaust manifold and aftertreatment system applications.

One practical disadvantage of thermocouple sensors comes from the fact that the level of voltage produced relates directly to temperature at the point where the dissimilar metals join. This means that a location where the sensing wires are spliced or allowed to make contact due to insulation failure becomes an unintentional temperature-sensing junction. For this reason, damage to a thermocouple wire usually requires replacement of the entire sensing assembly (wire, nodes, end connector, etc.) as a unit.

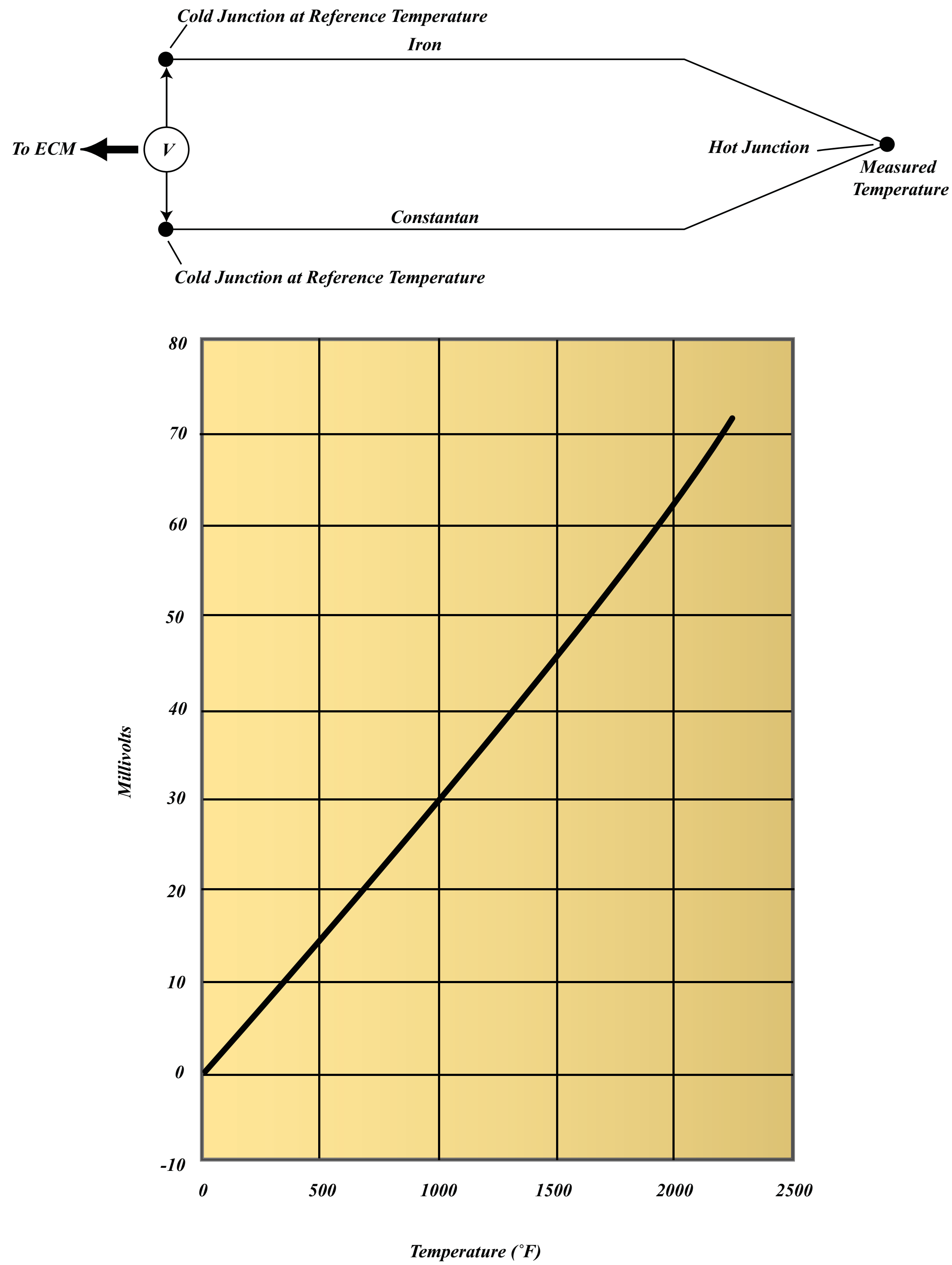


FIGURE 13—Thermocouples rely on two different metals joined only at the ends, which are then exposed to different temperatures. As long as one of these ends, known as junctions, remains at a known reference temperature, the voltage reading represented here will vary with the difference in temperature between hot and cold junctions. As you can see from the chart in this figure, an iron-constantan thermocouple produces a very small (measured in thousandths of a volt) voltage difference over a very large temperature range.

RTD Sensors

Resistance temperature detectors rely on a thin metal wire's predictable change in electrical resistance, which occurs when the wire's temperature changes (Figure 14). RTDs are used in relatively high-temperature locations since they function up to about 1150°F. Unlike a thermistor, an RTD can precisely evaluate changes over a wide range of temperatures.

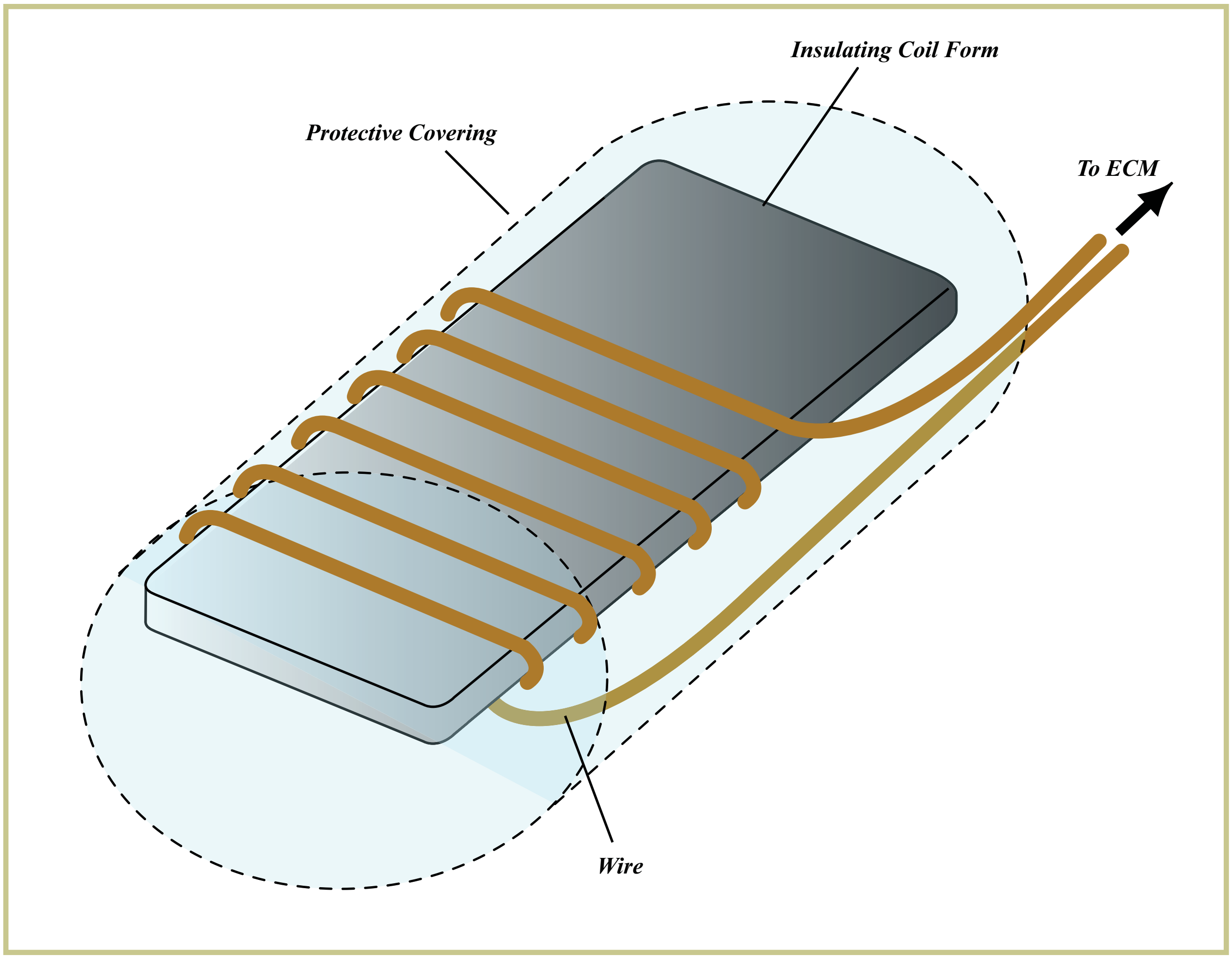


FIGURE 14—The thin coiled wire's resistance changes, in a very predictable way, with changes in temperature. ECM circuitry applies a reference voltage to the RTD, much as it does to a thermistor, then monitors the voltage change across an internal resistance. This internally monitored voltage change allows the ECM to determine how much the RTD's resistance changed due to increasing or decreasing temperature.

Common Temperature-Sensor Applications

The *air-inlet-temperature (IAT) sensor* is often referred to as a *charge temperature sensor,* or, due to its position in the air stream supplied to the turbocharger, as the *turbocharger inlet temperature sensor.* The ECM relies on the data from this sensor, as well as the *intake manifold temperature sensor (IMT),* to manage fuel flow, which varies not only according to power requirements, but also based on the temperature and pressure of air supplied to the combustion process. For the ECM to turn on heat to the *diesel exhaust fluid (DEF) system* when outside air temperatures are sufficiently low for freezing to occur, it relies on data from the *ambient air temperature sensor (AT).* IAT and IMT are often thermistor sensor types.

Engine-coolant-temperature (ECT) sensors are located in one of the upper engine passages through which coolant flows. The temperature data provided by this sensor allows the ECM to control the cooling fan and, for fuel-scheduling purposes, determine whether the engine has reached a steady operating temperature. The supplied data warns the ECM of potential dangers related to high operating temperatures. This sensor also supplies temperature data displayed by the dashboard temperature gauge. Note that in some engine designs, rather than using the coolant temperature sensor, the ECM relies on oil temperature data, supplied by the *engine oil temperature sensor (EOT),* to perform these tasks. Engine coolant and oil temperature sensors are usually thermistor types.

The ECM's control of fuel delivery is so precise that even very small differences in fuel density, resulting from changes in fuel temperature, are taken into account. To make these adjustments, the ECM relies on data from the *fuel temperature sensor (FTS),* which is typically a thermistor located on the incoming fuel line or filter.

Many of the temperature sensors described so far deliver data that allows the ECM to precisely schedule the amount of fuel supplied to meet engine loads, a very effective way to indirectly reduce engine emissions. Those sensors that monitor temperatures at various locations in the exhaust system deliver data that allows for direct ECM control of several emissions-reducing systems. As you're probably aware, the *EGR system* recirculates exhaust gas back into the cylinder as a way to reduce oxygen available for the combustion process and, therefore, reduce the emission of NO_x pollutants. You'll learn more about computer control of the EGR system later in this study unit.

The *EGR exhaust temperature sensor (EGRT),* collects data on the temperature of the exhaust gas and is typically located near the outlet of the EGR cooler. The ECM uses this temperature data to adjust the EGR valve and the *variable geometry turbocharger (VGT).*

The *diesel particulate filter* is an aftertreatment system that reduces soot from the engine exhaust by collecting it in filter elements, then regenerating the filter by burning off the collected material. The process of burning off the collected soot sometimes relies on the application of diesel fuel to the filter. Current state-of-the-art systems incorporate three *exhaust-gas temperature sensors (EGT1 through EGT3)* at various locations within this system. The ECM relies on the data they supply to determine the need for the filter regeneration cycle and control delivery of fuel to the aftertreatment system's diesel particulate filter. These temperature sensors also supply data used by the ECM when adjusting turbocharger geometry and EGR valve position. Temperature sensors in the exhaust-aftertreatment and EGR systems can be either thermocouple or RTD types.

Pressure Sensors

Pressure sensors are an important part of many ECM control loops. Pressure sensors monitor ambient-air and intake-manifold pressures to help the ECM gauge engine load at any time, ensure engine safety by monitoring oil pressure, and continuously evaluate the operation of various emission-control systems. Most pressure sensors are variable-capacitance types while some incorporate strain gauges.

Variable-Capacitance Sensors

Earlier in your training program, you learned that a *capacitor* is a current-storing device made up of two plates separated by some distance. Filling this plate-to-plate distance is a nonconductive material known as a *dielectric,* which is sometimes nothing more than air. One of the capacitor's plates stores electrical charge until sufficiently loaded to *discharge,* allowing the built-up charge to move across the dielectric to the second plate. The rate at which the capacitor builds or discharges electrical charge is a measure of its *capacitance.* One way to vary the capacitance (and therefore discharge rate) of a capacitor is to change the distance between its two plates. If one of a capacitor's plates is attached to a membrane that flexes when exposed to changes in pressure, the plate-to-plate distance and, therefore, capacitance also changes. When processed by the right circuitry, this changing capacitance can be transformed into a change in voltage, which is of more use to the ECM.

The *variable-capacitance pressure sensor* measures the difference between two pressures by routing each of them to a different side of the flexible membrane (Figure 15). These are known as *delta-P* or *delta-pressure measurements.* Alternatively, one side of the flexible membrane can be exposed to atmospheric pressure (which will result in it sensing *gauge pressure,* or *psig)* or to a complete vacuum. If one side of the membrane is exposed to a complete vacuum, then the device will evaluate the pressure applied to the membrane's other side in terms of *absolute pressure, psia.*

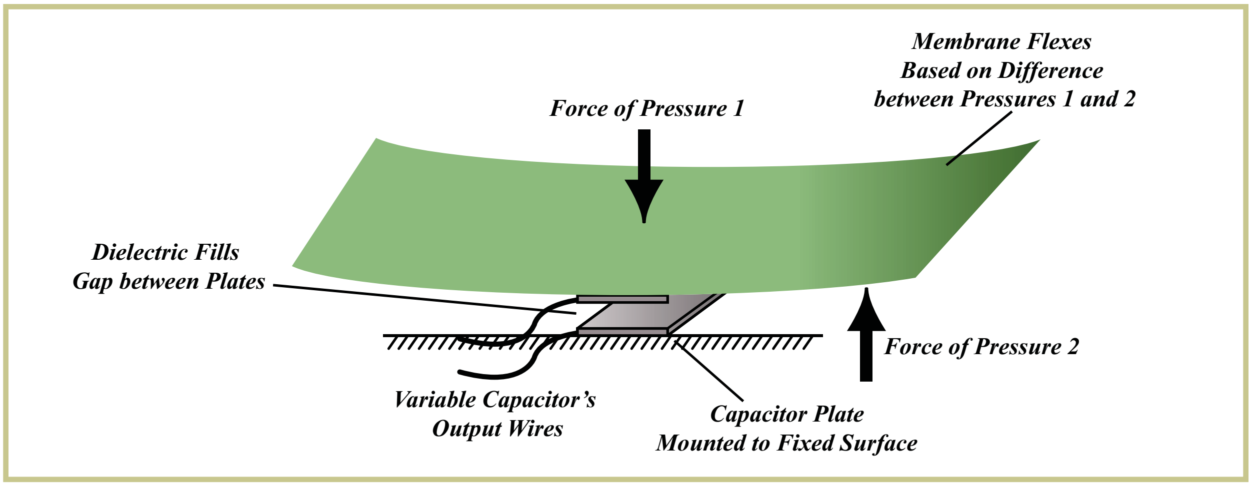


FIGURE 15—The two measured pressures act separately on opposite sides of the flexible membrane. As one capacitor plate moves with changes in the pressure difference, the gap between it and the fixed capacitor plate changes. This changing dielectric-filled gap changes the sensor's capacitance. Signal-processing circuitry allows the ECM to view this as a change in voltage.

Strain-Gauge Pressure Sensors

Conductors in a *strain gauge* change shape when acted on by an outside force and therefore offer changing resistance to the flow of electricity. *Strain-gauge pressure sensors* incorporate thin conductive elements on a flexible membrane. In this case, the outside force results when the membrane to which the conductors are mounted flexes because one of its sides is exposed to a higher pressure (Figure 16). Either the sensor or supplemental circuitry converts the strain gauge's relatively small change in resistance into a change in voltage, which the ECM's circuitry then amplifies. The fact that it incorporates a membrane makes a strain-gauge pressure sensor useful for evaluating delta-P values. These values are especially important when the ECM must consider differences in pressure between two locations such as before and after a filter or at various locations along the path taken by intake air. Of course, one side of the membrane can be exposed to atmospheric pressure, resulting in a gauge pressure measurement.

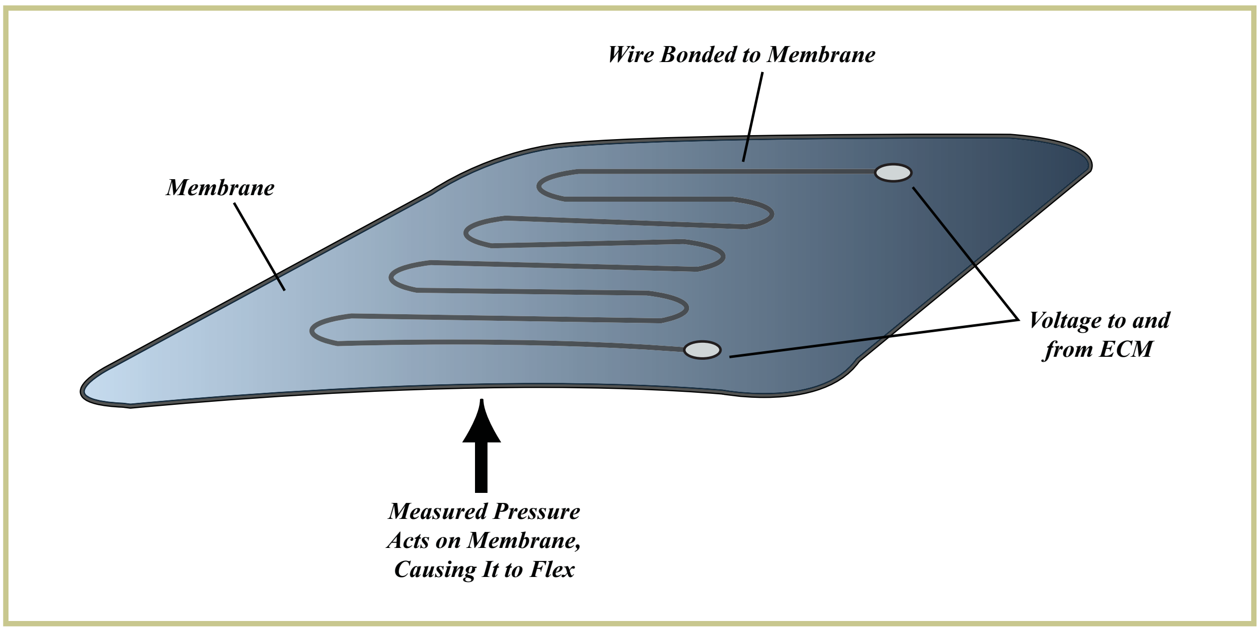


FIGURE 16—Strain-gauge pressure sensors rely on changes in wire diameter, and therefore resistance, to measure the pressure applied to a flexible membrane.

Piezoelectric Pressure Sensors

Piezoelectric pressure sensors, or *transducers,* rely on an element which, when exposed to physical force, emits a voltage. In Figure 17, the sensor's element, or *piezoelectric crystal,* and circuit wires are separated from the sensed pressure by a flexible membrane. When applied pressure causes the membrane to flex against the crystal, it emits a voltage signal proportionate to the pressure level. This voltage signal is then returned to the ECM, which in turn converts the change in voltage into a pressure reading.

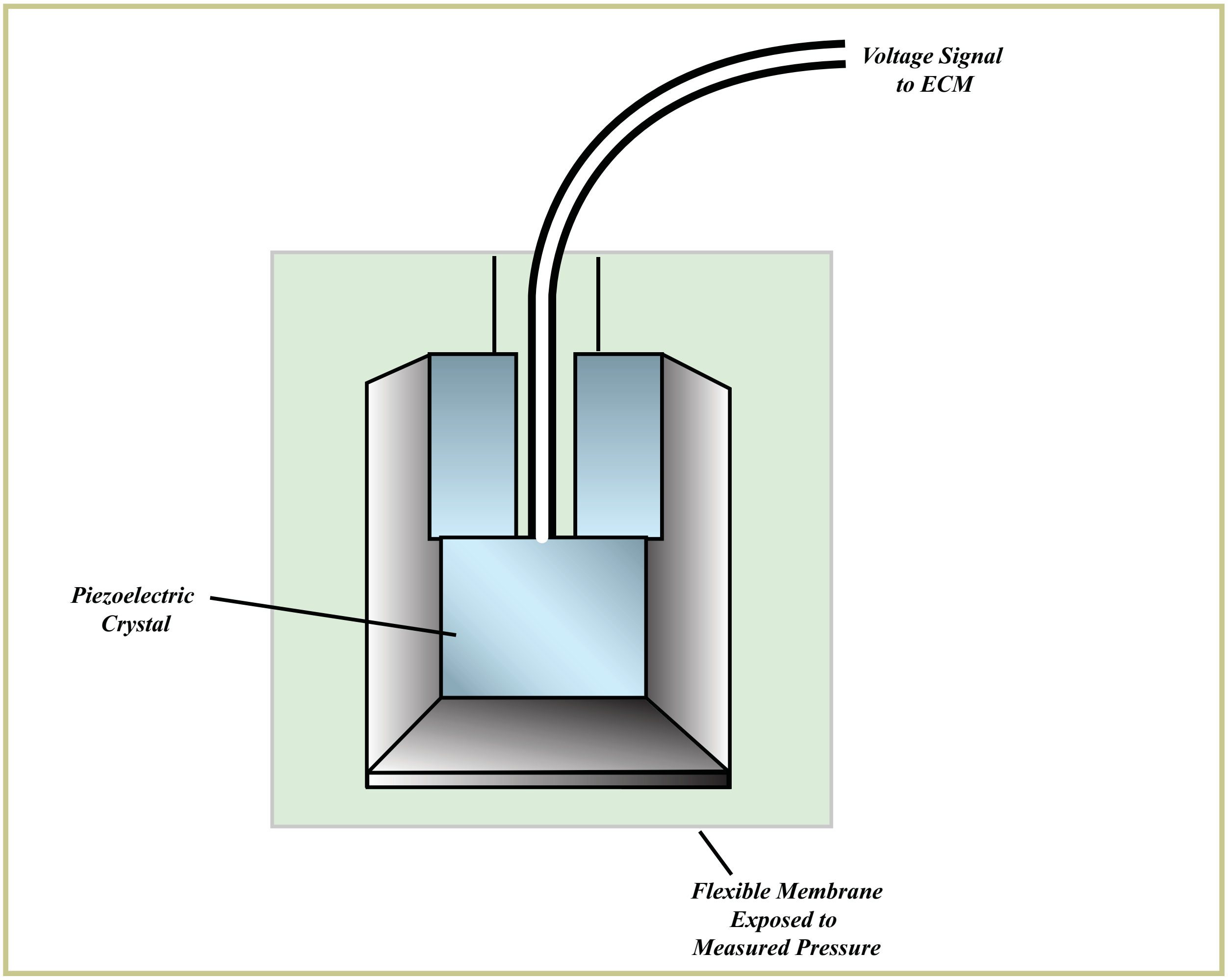


FIGURE 17—Piezoelectric crystals convert force into a proportionate output voltage.

Common Pressure-Sensor Applications

Barometric-pressure sensors, normally called *BARO sensors,* tell the computer the pressure of the air outside the engine. This outside pressure, called *atmospheric pressure,* changes with weather conditions and altitude. The ECM relies on data from the BARO sensor to adjust fuel metering and timing. It may also affect EGR valve position.

The ECM evaluates data from the *engine oil-pressure (EOP) sensor* any time the engine is running. This variable capacitance sensor, often located on top of the oil filter housing, provides data that the ECM transmits to the dashboard oil-pressure gauge and monitors for signs of an extreme decrease in pressure. If oil pressure drops to very low levels, indicating a major lube-system failure or significant loss of oil, the ECM launches a failure-mode strategy that reduces engine power (or completely shuts down the engine) to protect it from the damage that will certainly occur if operated without a supply of lube oil.

Other sensors monitor air pressure at various locations within the engine. The ECM uses intake manifold boost pressure data, supplied by the *intake manifold pressure sensor (IMP),* to control fuel injection timing and duration as well as turbocharger geometry. Data related to the pressure in the exhaust manifold is delivered to the ECM by the *exhaust backpressure sensor (EBP).* Similarly, the crankcase pressure level, and the condition of its ventilation system, is monitored through the *crankcase pressure sensor (CPS).* Both of the CPS and EBP pressure sensors are the variable capacitance type.

As you've already learned, a differential-pressure sensor compares two pressures of interest to the ECM and delivers data on the difference between the two. For instance, the *EGR differential pressure sensor (EGR Delta P)* compares the pressure on either side of the EGR valve, supplying the measured difference to the ECM. The ECM uses this data to determine the rate at which exhaust gas is flowing through the valve and compare this calculated value with the pre-programmed ideal. If the current value differs from ideal, the ECM adjusts the EGR valve position and/or turbocharger variable geometry to compensate. Similarly, a differential pressure sensor monitors each side of the *aftertreatment diesel particulate filter (DPF Delta P).* As you probably remember, this exhaust aftertreatment system traps soot, otherwise known as *particulate,* in a honeycomb chamber capable of withstanding very high temperatures. The filter *regenerates* when the trapped soot either burns off during normal engine operation, in what's known as *passive regeneration,* or with the injection of diesel fuel. The ECM monitors DPF operation, in part, by comparing the pressure on either side of this filter. When the pressure drop across the filter exceeds the allowable limit, and the ECM determines the filter is obstructed, it commands the injection of fuel to wet the filter and accelerate the *active regeneration* process. You'll soon learn more about the output signals sent by the ECM to actively regenerate the DPF.

Position and Speed Sensors

Electro-mechanical sensors monitor mechanical motion or position by converting a motion or a position into an electric signal. This is often accomplished by sending electricity through a variable resistor, connected to the monitored part, which changes its resistance as the part moves. When resistance changes, current flow is affected and the modified voltage level is returned to the computer. Sensors can also be placed in series between a current source from the computer and a ground connection. By modifying the current as it flows to ground, the sensors modify the electric signal at the computer.

Examples of electro-mechanical sensors include the following:

- Accelerator-pedal position sensors
- Throttle-plate position sensors
- Vehicle speed sensors
- Crankshaft and camshaft position and speed sensors
- Exhaust-gas-recirculation (EGR) valve position sensors

Variable Resistors—Potentiometers and Rheostats

As you know, a *resistor* is an electrical device that limits the flow of current. When electrical current flows through a resistor in a *series* or *voltage divider circuit,* it's possible to measure a drop in voltage across the individual resistor. Your earlier studies extensively covered the concepts of voltage, current, and series circuits. It's simple enough to remember that a resistor's ability to limit the flow of electrical current is measured by its *resistance,* which is given the units of *ohms.* A *variable resistor* is one whose resistance value changes due to some outside influence. In the case of potentiometers and rheostats, this outside influence takes the form of motion (Figure 18).

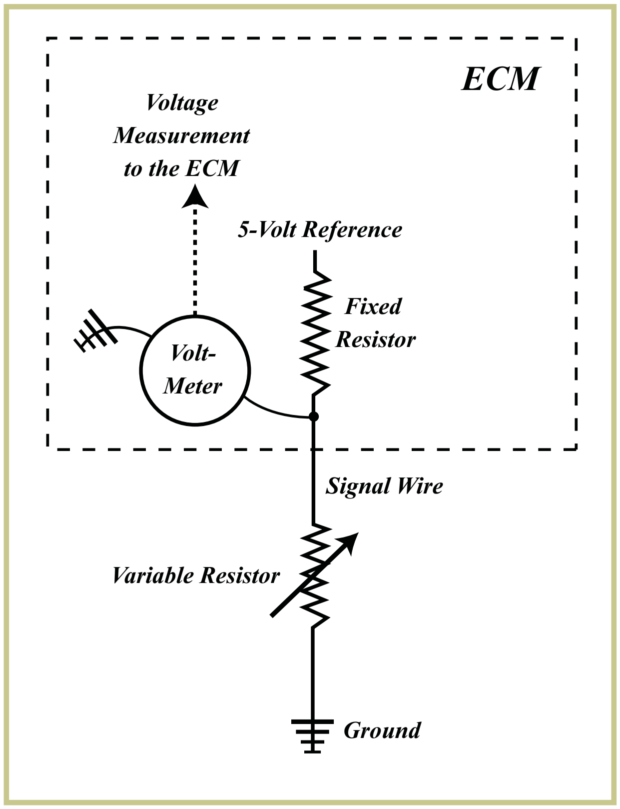


FIGURE 18—The variable resistor in this diagram, attached to a movable part, offers a different level of resistance depending on its physical position. As its resistance varies while the reference voltage remains constant at 5 VDC, the ECM-monitored voltage also varies. Remember, the fixed resistor and voltmeter represented in this diagram are actually just part of the ECM's signal-processing capabilities.

When the mechanical motion acts on a variable-resistance sensor, its conductive *wiper* moves against a fixed-resistance element. One side of the fixed-resistance element is supplied with a voltage, and the opposite side is grounded. If the wiper is connected to the device's output circuit, then its position on the element determines the amount of resistance positioned between it and the voltage supply. This means that each wiper position results in the ECM being sent a unique voltage level, which identifies that physical position (Figure 19).

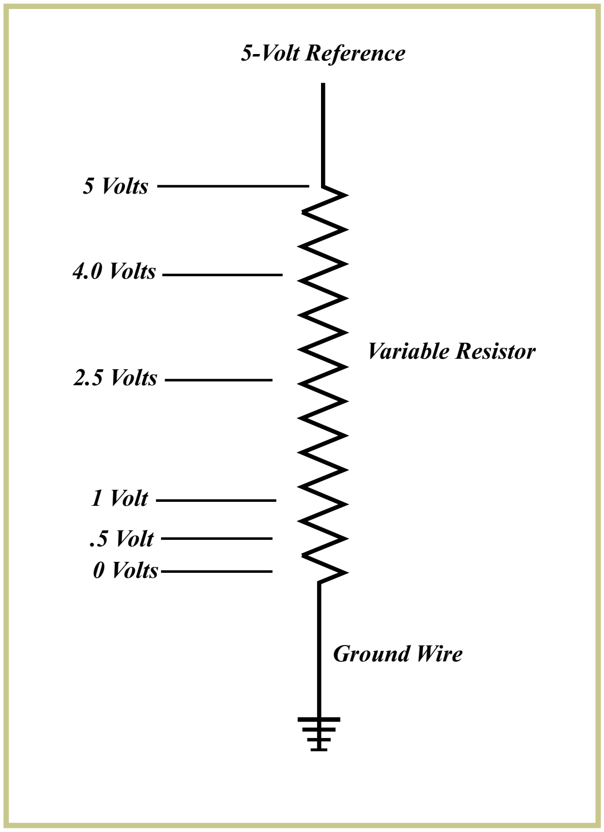


FIGURE 19—When measuring voltage at different points along this variable resistor, 5 volts registers at the top while you'll measure 0 volts (ground voltage) at the bottom. The voltage measured between these extremes will vary based on the precise physical positon at which the reading is taken.

While both potentiometers and rheostats are variable resistors, a *potentiometer* is more typically used as a sensor in a computer-controlled vehicle. You're more likely to find a *rheostat* in use as a variable-control device, such as what lets the vehicle operator dim or brighten dash or cabin lighting. The device that dims incandescent lighting in your home, for instance, contains a rheostat. A potentiometer is a three-terminal device to which a reference voltage (typically 5 V) and ground are connected. The potentiometer's variable resistor is wired as a voltage-divider circuit. Therefore, its third terminal delivers a voltage level to the ECM that corresponds to the sensed value. For instance, in Figure 20 the proportion of the 5 V reference voltage returned to the computer indicates the wiper arm's position along the variable resistor.

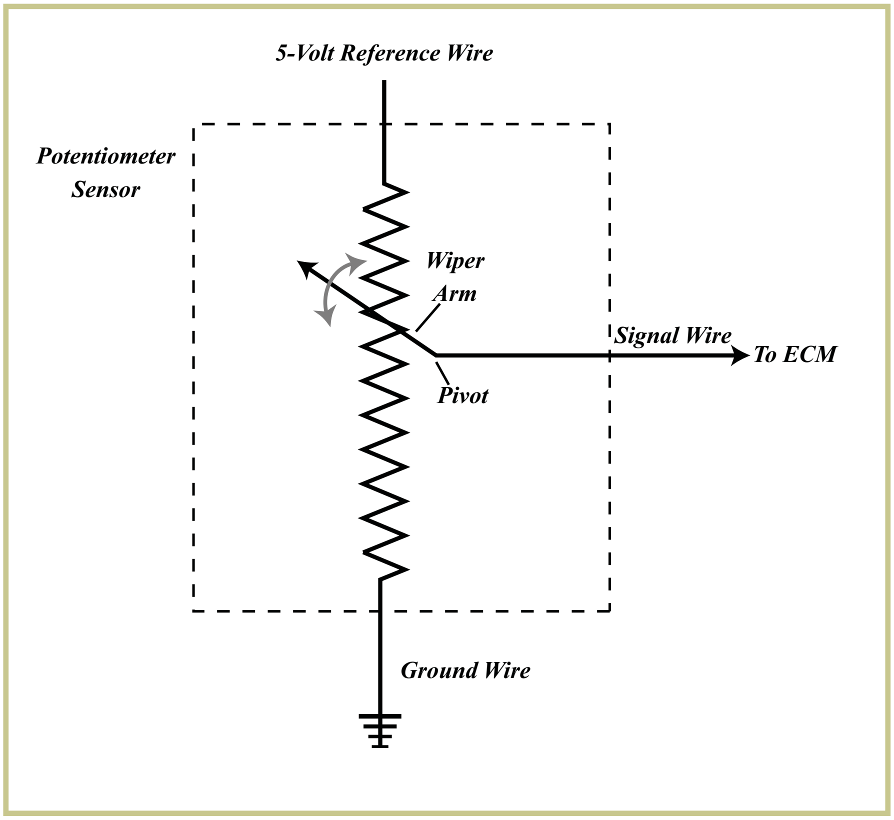


FIGURE 20—The voltage signal emitted to the ECM corresponds with the wiper's positon along the potentiometer's variable resistor.

Variable-Reluctance Sensors

A *variable-reluctance sensor (VRS),* also called a *monopole* or *magnetic sensor,* measures the position and speed of a moving metal component. This sensor consists of a permanent magnet that's wrapped with a wire coil and a rotating target such as a toothed wheel. All magnets produce a *magnetic field.* When a conductor is coiled about a magnet, changes in the magnet's field induce a voltage on the coiled conductor. Consider the toothed wheel in Figure 21. Each time a tooth, which is made of magnetic material, aligns with the permanent magnet, it affects the magnet's field. However, between each tooth is an empty space, which has a different effect on the field.

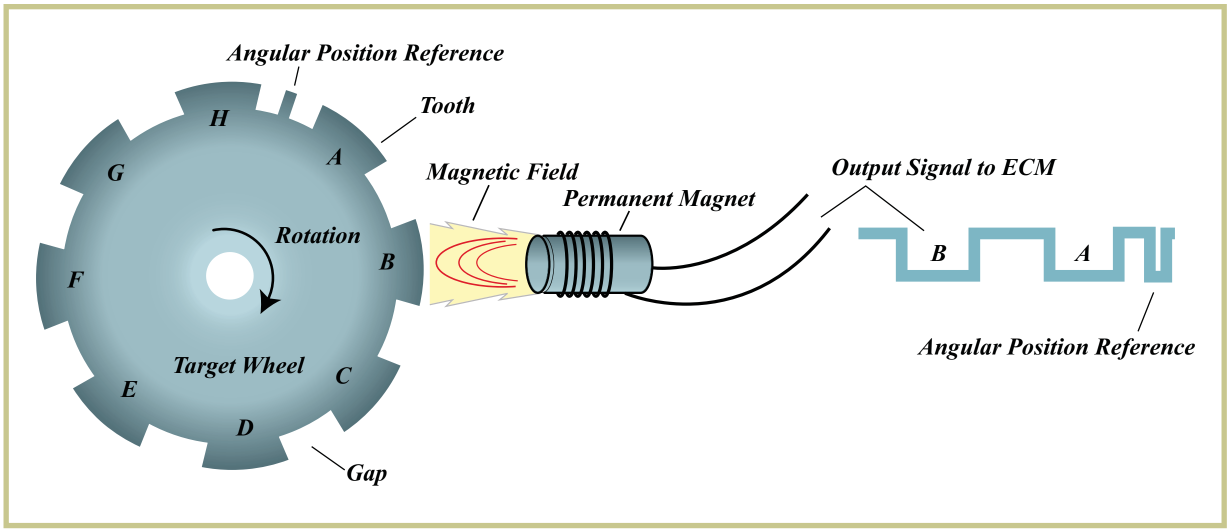


FIGURE 21—Changes in the field generated by the permanent magnet induces a voltage in the coil, which translates into a signal sent to the ECM. Specific to a VRS sensor, the strength of the signal depends on the speed with which the field changes. Notice that the position reference allows the ECM to determine the rotating target wheel's precise angular position.

As the teeth and empty spaces of the rotating wheel (or other *target*) pass closely by the face of the magnet, the magnetic field varies, which changes the voltage present in the coil. The higher the rate at which the field changes, the greater the induced voltage level. Therefore, voltage measurement ultimately tells the ECM how quickly the teeth are passing by the end of the magnet. This is the effect achieved when the teeth on a truck wheel's tone ring pass an ABS wheel-speed sensor. It's also possible, by omitting one tooth from the ring, for the ECM to determine the exact angular positon of the device that's attached to the ring. This very important feature allows both the crankshaft and camshaft position to be precisely monitored with multitooth targets installed on each component.

Because the magnitude of the voltage developed by the VRS is proportional to target speed, it's difficult for this type of sensor to evaluate low-speed systems. This sets a definite limit of how slow the target can move and still develop a usable signal. And because the magnetic fields involved are comparatively week, the permanent magnet and target must be separated by only a short, consistent distance. This means that anything that alters the sensor or target position, such as bent sensor-mounting hardware or mispositioned tone ring, will alter the magnet-to-target gap and impact the sensor's ability to properly function.

Hall Effect Sensors

An alternative to the VRS is the *Hall effect sensor.* Unlike the VRS, which relies on enough relative motion between the sensor and target to generate a voltage, Hall effect sensors provide a signal even when there's no motion (Figure 22). The sensor contains a semiconductor material that generates a voltage when placed in the presence of a magnetic field. The signal's voltage level is based only on the power of the magnetic field, not whether or not the field is changing. This important characteristic means that Hall effect sensors are often used for proximity probes, which sense when even a slow-moving target approaches the sensing element, as well as accelerator pedal position in some vehicles. Of course, these sensors are also used for sensing camshaft and crankshaft position and speed. The ECM determines the speed of the monitored system simply by counting the number of magnetic-field changes in a specific amount of time.

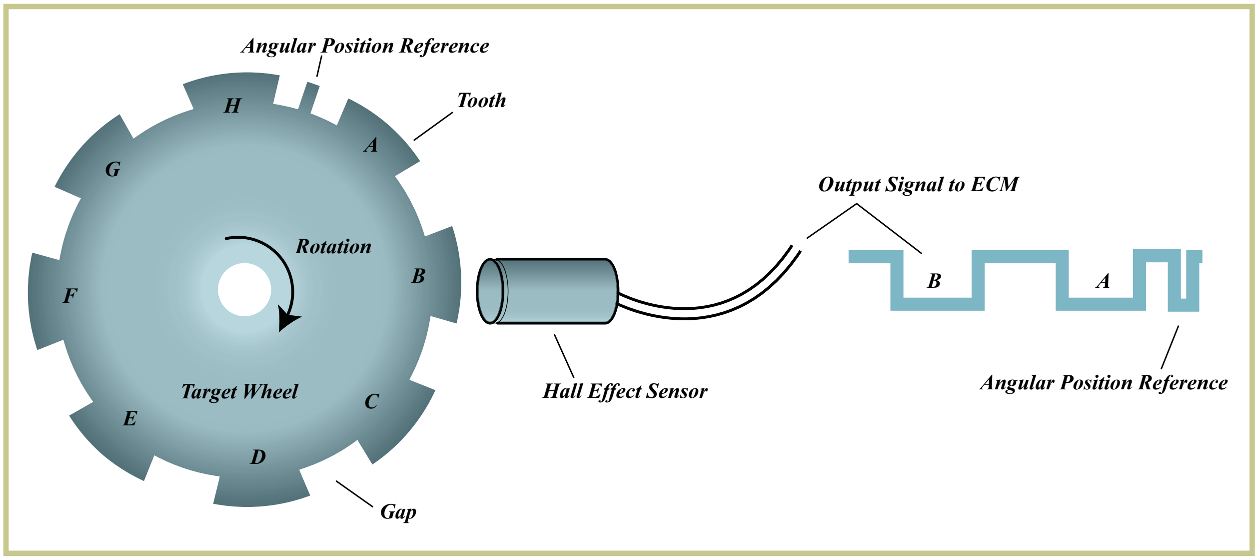


FIGURE 22—A Hall effect sensor generates an output signal in the presence of a magnetic field with the signal's strength depending on the strength of the field. In these applications, the target wheel, or other targeting feature, is magnetic. Therefore, a stronger magnetic field is present when a tooth passes close to the sensor compared to the field present when a gap passes the sensor.

Common Speed and Position Sensor Applications

A *accelerator pedal position (APP)* sensor tells the computer the position of the accelerator pedal. This is one of the few sensors that interacts directly with the vehicle operator. As the operator presses or releases the accelerator pedal, the pedal position is monitored by one or more Hall effect sensors or potentiometers. The ECM interprets the sensor's signal to determine desired engine rpm and operating power. As you can imagine, failure of an APP sensor is a serious problem. Designs incorporating multiple sensors allow the ECM to compare the value supplied by each, defaulting to idle fuel flow or other fail-safe operating condition when the signals from different sensors disagree. Similarly, systems often incorporate an *idle validation switch* set to actuate as soon as the driver places any pressure on the accelerator pedal. This allows the ECM to detect if a faulty APP sensor calls for excessive fuel flow when the driver intends for the engine to operate at idle rpm.

There's a potential point of confusion you should keep in mind. The development of diesel-engine EGR systems, which can use a *throttle plate* to meter the flow of exhaust gas into the intake manifold, has caused some OEMs to incorporate a *throttle plate position sensor (TPS).* This sensor allows the ECM to monitor and limit the flow of EGR gas into the intake manifold. For many generations of computer-controlled trucks, up to the present in some cases, the abbreviation TPS was used to describe what we've just referred to as the accelerator pedal position sensor. You'll need to rely on careful examination when working with OEM documentation or training programs to be sure that you're properly interpreting the specific function of the TPS sensor in your application.

While *exhaust-gas-recirculation (EGR)* valves have been used on automotive engines for many years, they're now common emissions-control equipment on diesel-powered trucks. It's worth noting that partly because of the maintenance headaches caused by EGR components, beginning in 2010 most OEMs rely more heavily on *SCR (selective catalytic reduction)* systems to control a pollutant known as NO_x. The ECM controls the flow of recirculated exhaust gas into the intake manifold, in part, by positioning the EGR valve. Feedback circuitry allows the ECM to monitor the actual *EGR valve position (EGRP)* through a potentiometer-type sensor.

Earlier, you read about the existence of *camshaft* and *crankshaft position sensors* (*CMP* and *CKP,* respectively). Also known as *engine position sensor one* (camshaft) and *two* (crankshaft), these Hall effect or VRS type sensors supply data the ECM uses to calculate fuel injection starting point and duration. A *vehicle-speed sensor (VSS)* functions in the same way as these sensors. However, instead of sensing targets mounted to engine components, the VSS senses the teeth on a gear mounted on the transmission's output shaft. The ECM uses VSS data for certain transmission-control functions, cruise control, engine-brake operation, and some antilock-braking system functions.

Later in this study unit, you'll learn how the ECM interprets information from various sensors to control the configuration of a *variable-geometry turbocharger (VGT),* which delivers to the combustion process the high volume of air required for optimal engine performance. One of these inputs is a *turbocharger-shaft speed sensor,* which can be either a Hall effect or VRS type.

Specialized Sensors

The *water-in-fuel sensor* relies on the difference in resistance to electrical flow offered by water and fuel. This sensor has two electrodes located in the fuel-filter housing or in the fuel-water separator. Reference voltage travels through one electrode, passes through the fluid separating the two, and is picked up by the second electrode from which it's routed back to the ECM. When sufficient water is present in the contained fluid, the ECM detects the change in voltage level and triggers a water-in-the-fuel warning indication.

Relatively recent upgrades to diesel engines include EGR and SCR systems to limit the NO_x level present in the exhaust. Later in this study unit, you'll learn more about these emissions-control systems. For now, it's useful for you to recognize how the ECM relies on sensor input when controlling the operation of related systems. *NO_x sensors* are positioned in the exhaust stream where they chemically evaluate an exhaust sample to determine the amount of NO_x present in the exhaust. Since the newest trucks all contain *SCR (selective catalytic reduction) aftertreatment systems,* measurement of NO_x

has become more critical. In an SCR-equipped vehicle, an NO_x sensor is typically located before and after the SCR system. The sensor located in the exhaust stream before the SCR system provides the ECM with data that helps it determine how much *DEF (diesel exhaust fluid)* to add to the exhaust flow through the *DEF dosing injector.* The NO_x sensor located after the SCR system monitors system performance, allowing the ECM to trigger a maintenance warning when poor DEF condition or other system faults lead to excessive levels of NO_x present in the emissions.

While vehicles are already equipped with *DEF tank level sensors,* trucks you service will eventually be outfitted with *DEF quality sensors* to ensure the correct type of undiluted fluid is present. Because DEF of the sufficient quality and quantity is required to meet the newest emission standards, the ECM monitors the output from these DEF-related sensors and limits vehicle operation when the DEF tank is empty.

Mass-airflow (MAF) sensors measure the flow of air into an engine's cylinders. You'll encounter three types of MAF sensors. One type of mass-airflow sensor incorporates a heated wire that's placed in the path of incoming airflow. The wire's temperature is monitored, and the electrical current flowing through is adjusted to maintain constant wire temperature. The ECM uses a measurement of the electrical current flowing through the wire, along with the ambient air temperature, to calculate the incoming mass airflow.

Other MAF sensor designs rely on pressure sensors before and after a venturi, through which incoming air flows, to determine the mass of incoming airflow. As you may remember, a *venturi* is a narrowed section of pipe, through which fluid must accelerate. This change in fluid-flow velocity results in a difference in pressure before and after the narrowed pipe section. Because the difference in pressure relates to the fluid (in this case, air) velocity, the ECM uses the pressure data to calculate airflow rates.

A third type of MAF sensor relies on a ultrasonic sensing device that works like a microphone. By "listening" to the noise made by the incoming airflow as it passes over an obstruction in its path, the microphone sends a signal to the ECM, which interprets it as the mass flow rate of incoming air.

Self-Check 2

Complete the following statements with the correct answer.

1. *True or False?* A thermistor is a temperature-sensing device made from two dissimilar metals joined together only at their ends.

2. A(n) ______ temperature sensor is especially known for its ability to measure over a wide range of temperatures.

3. *True or False?* The ambient air temperature sensor indicates when the ECM needs to turn on heat to the diesel exhaust fluid system.

4. The distance between the two plates of a capacitor is filled with a nonconductive material called a(n)

5. *True or False?* Piezoelectric pressure sensors incorporate an element that, when exposed to physical force, transfers the resulting pressure directly to the ECM.

6. A sensor that provides data on the difference between two pressures is known as a(n) ______ sensor.

7. *True or False?* Electro-mechanical sensors work by converting a motion or position into an electrical signal.

8. The type of variable resistor used in an application to dim or brighten lighting is a(n)

9. *True or False?* A variable-reluctance sensor is well-suited to monitoring low-speed systems.

10. The ______ valve is common emissions-control equipment on both automotive and diesel-powered engines.

Check your answers with those on page 63.

OUTPUT DEVICES

An ECM or other vehicle computer controls the operation of various systems by sending electrical signals to *output devices*. These devices may convert this electrical signal into the force that moves a component, such as the spindle of a valve or the contacts of an electrical switch. This sort of computer-controlled motion is typically managed with the use of relays or solenoids. While you might not first think of them as such, dashboard warning and MIL lights are also output devices as their actions are controlled by a computer's output signal. This part of your study unit introduces the operating characteristics of several common output devices followed by examples of how they're employed in vehicle systems.

Solenoids and Relays

As you've already learned, engine and other vehicle systems are controlled by a computer, often through relays or solenoids. For instance, the cooling fan is often turned on and off by a relay that's reacting to a signal it receives from the ECM. The ECM decides when to send this signal based on inputs from the temperature sensors you studied earlier in this unit. Perhaps most importantly, the moment at which fuel flows into each cylinder, the duration during which it flows, and the precise time it stops is often controlled by the energizing or de-energizing of solenoids.

You've already studied the fundamental principles of magnetism, as well as several vehicle systems that rely on solenoids. A *solenoid* contains a moveable core, known as an *armature,* which typically passes through the center of a wire coil. When wire is coiled around an iron (or *ferrous metal)* core, electrical current flowing through the wire coil creates a magnetic field, turning the core into what's known as an *electromagnet* (Figure 23). Depending on the direction the current flows through the coil and the physical location of the components involved, the core's magnet force can cause it to move or to attract or repel other devices. In this way, the solenoid converts an electrical signal from the ECM to a mechanical output.

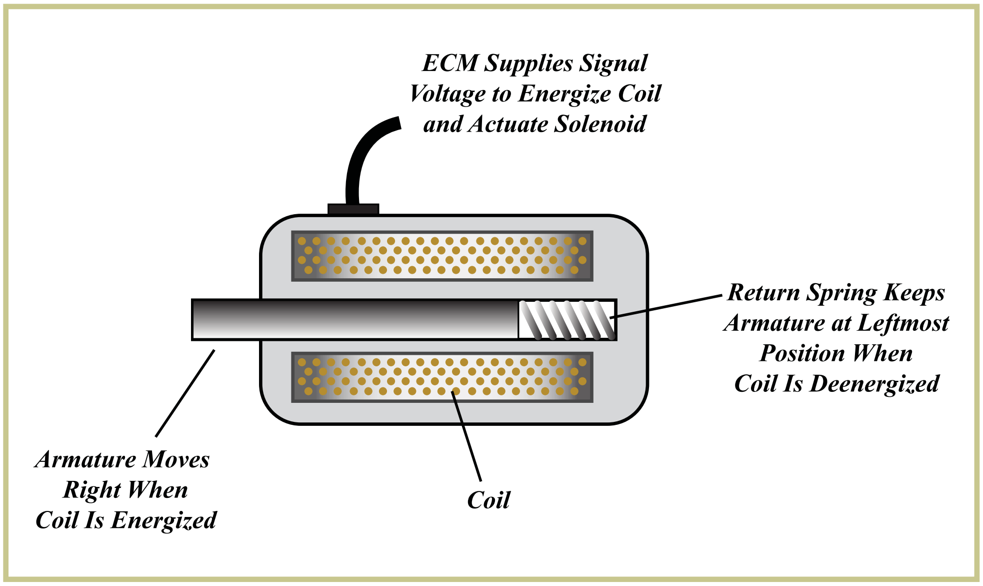


FIGURE 23—A solenoid's energized coil generates an electromagnetic force, converting the flow of electricity through a coil into a mechanical movement. In this case, whenever current flows through the coil the armature moves to the right.

For example, an engine-brake system (about which you'll soon learn more) relies on a solenoid-operated fluid-control valve to turn on or off the pressure required to open or close a cylinder's exhaust valve. In vehicles equipped with electronically controlled transmissions, movement of the torque-converter lockup clutch, shifting between gear ranges, and several other actions are carried out by computer-controlled solenoids.

A specific type of solenoid, known as a *proportioning solenoid,* utilizes a feedback circuit that "tells" the ECM its specific position. This feedback system works to control the amount of current flowing through the coil as a way to hold very precisely the solenoid's armature in the position specified by the ECM.

One limitation of solenoid operation is important for you to understand. Because the solenoid's ability to move the armature relies on the development or collapse of a magnetic field, and it takes time for these magnetic-field changes to occur, solenoids can't always cycle quickly enough between on and off conditions. This limits their usefulness for the most demanding fuel-injection applications. Perhaps more importantly from the perspective of a repair technician, solenoid-controlled fuel injectors are partly identified by the time delay that occurs while building or collapsing its magnetic field. Since the ECM factors this delay into the timing of its fuel scheduling signals, part of the job of changing certain types of fuel injector nozzles includes entering nozzle-specific data, or *calibration codes,* which "tell" the ECM about the replacement nozzle's performance characteristics including those related to time response. Piezo-actuated fuel injectors, which actuate with nearly instantaneous response rates, offer a solution to the time delay that's experienced with solenoids.

A *relay* is an electrically controlled switch. Like solenoids, *relays* rely on a coil-encircled iron core that turns into an electromagnet whenever electrical current flows through the coil. In this case, the electric current that generates the electromagnetic force, known as the *control* or *switching current,* moves an armature that causes a set of contacts to open or close (Figure 24). The opening or closing of the contacts controls the power circuit, which usually carries much higher current than the controlling circuit. In this way, a relatively weak electrical signal, such as you would expect to come from the ECM's output module, can switch on or off a much more powerful electrical current. You've almost certainly encountered many relays in all sorts of vehicle systems, controlling power to devices as different as horns and starter motors.

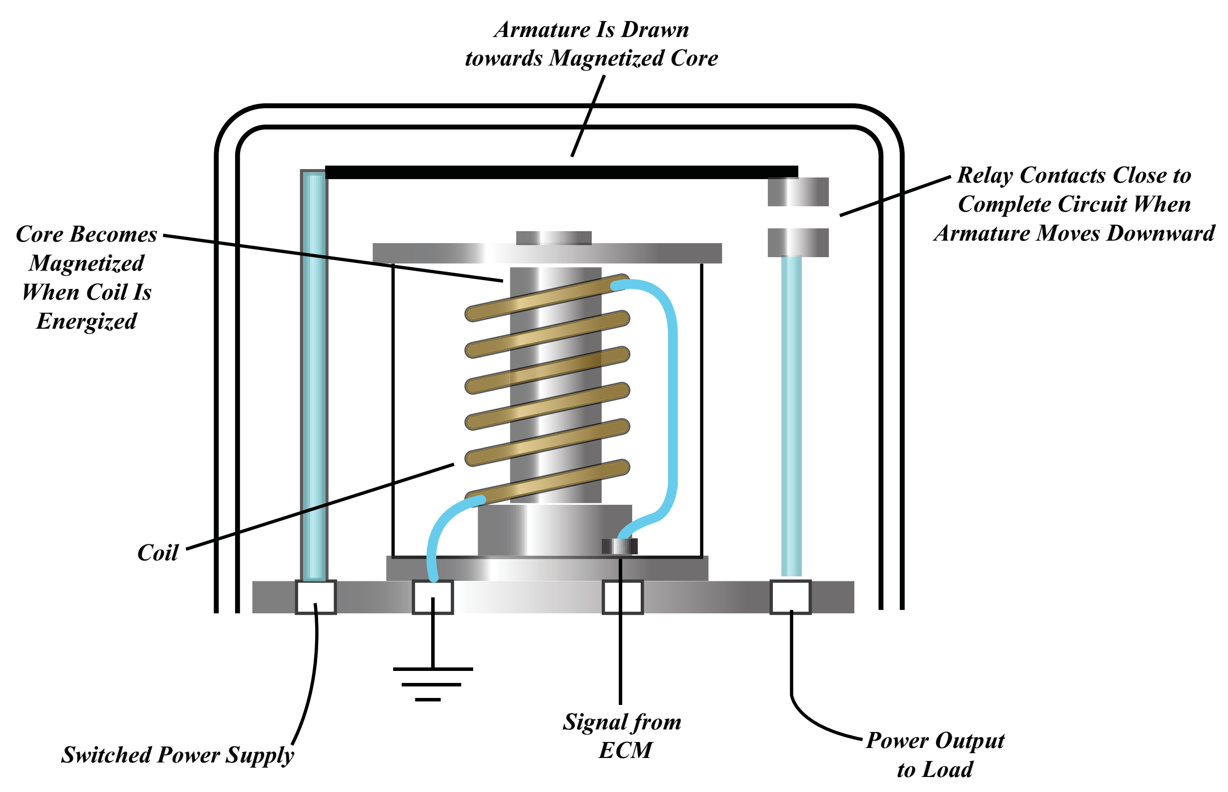


FIGURE 24—A relay uses a low-current signal (such as the output from an ECM) to control the flow of electricity to a relatively high-power electrical component, like as a motor.

Stepper Motors

A *stepper motor* offers precise circular motion. Unlike the conventional DC starter motors used in most trucks, a stepper motor has no brushes and doesn't continuously spin. Instead, it contains several stationary electromagnets arranged around a rotor that's part of the motor's shaft assembly (Figure 25). Applying and turning off current flow to each of the electromagnets causes the rotor to move precisely and (usually) by a very small angular amount to align with whichever electromagnet is currently charged. When accomplished in a controlled manner, this method of control allows the ECM to very exactly define the rotor's angular position. EGR, inlet air, and other swinging-gate type control valves are often positioned using a stepper motor.

A stepper motor itself doesn't normally have a feedback loop to the computer. This motor receives pulse-width-modulated

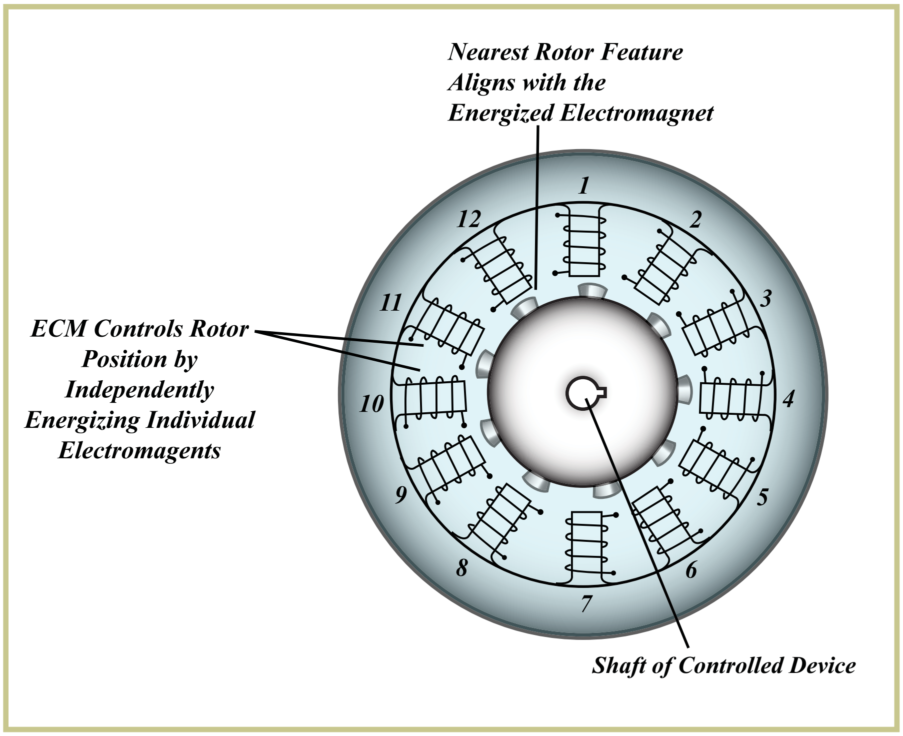


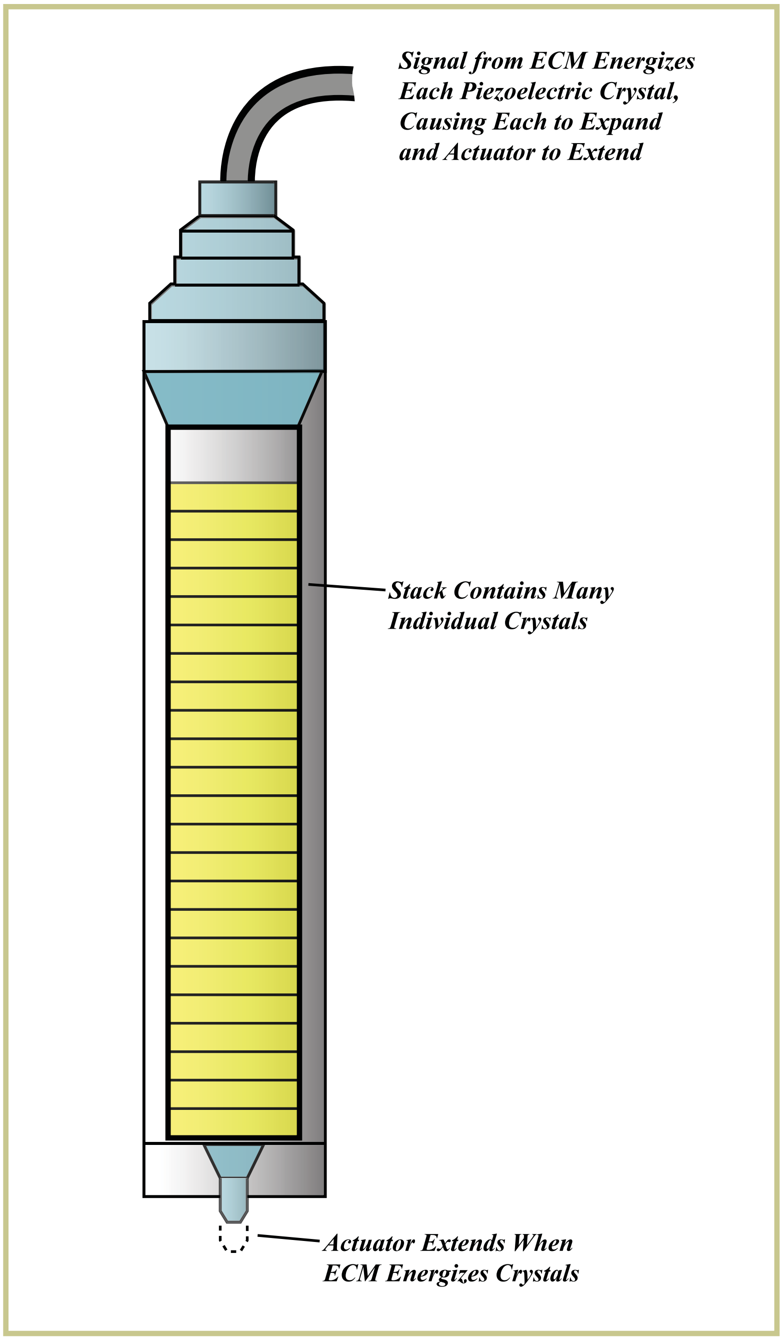
FIGURE 25—This simplified stepper motor illustrates how independently powering a single coil at a time allows the ECM to very precisely control the rotor position and motion. In this case, the rotor feature is aligned with coil 12. The ECM can command a clockwise rotation of only a few degrees by next powering coil 4.

control signals from the ECM. Each pulse, or group of pulses, causes the motor to make a single step of circular motion. To best understand how it operates, you might think of the stepper motor as an electric ratchet. The stepper motor has no velocity-controlling device attached to it. Position and speed control are based solely on the pulses sent by the computer.

Piezo-Actuated Injectors

As you learned when studying piezoelectric pressure sensors, when a piezoelectric crystal is subjected to a physical force, it emits a voltage that's proportionate to the force. One helpful characteristic of a piezo crystal is that the effect described above also works in reverse. This means that applying a voltage across a piezoelectric crystal makes it change shape and that the amount it changes shape is influenced by the magnitude and polarity of the applied voltage (Figure 26). Another characteristic of a piezo crystal's response to either force or voltage is that the resulting effect happens almost instantly—many times faster than the response rate of an electromagnetic solenoid for instance. Piezo-actuated fuel

FIGURE 26—Each of the stack of piezo crystals changes shape when subjected to an electrical signal from the ECM. In this case, actuation occurs due to the cumulative effect of these many expanding (or contracting) crystals.



injectors are relatively new to large truck applications and cost more than solenoid-controlled injectors. However, certain fast-acting characteristics such as the ability to deliver multiple injection pulses during each combustion cycle mean that they allow the ECM to produce a cleaner and more fuel-efficient combustion process. This is likely to result in increased future use of piezo-actuated fuel injectors.

Common Applications of Output Devices

This part of your study unit introduces common applications of each output device you've studied. Remember that while not all OEMs use the same sensors or output devices to control similar systems, their unique system designs mostly rely on similar operating principles.

HPCR Fuel Injection

As you learned earlier in your training program, the majority of modern ECM-controlled engines incorporate a *high-pressure common-rail (HPCR) fuel injection system.* These systems employ a low-pressure transfer pump to move fuel from the tank, through filters and other conditioners, to a high-pressure pump. The high-pressure pump feeds fuel to a holding container, known as a *rail,* which connects to all injectors (Figure 27). The term *common rail* originates from the fact that one rail connects to all injectors, and that the rail and all supply lines hold fuel at the same pressure.

The ECM monitors fuel pressure within the rail and outputs a signal to the proportioning-solenoid driven *rail pressure metering valve,* which meters the flow of fuel from the high-pressure pump. By adjusting the proportion of fuel flowing into the rail and drain systems, the ECM precisely maintains scheduled fuel pressure to each injector.

The fuel injector nozzle includes a series of passages through which pressurized fuel flows and an electrically activated, spring-loaded valve. Valve actuation is achieved by ECM controlled solenoids or piezo actuators. The ECM's programming requires that it evaluate many of the input signals you learned about earlier in this study unit when determining the required fuel injection timing and duration. *Injection timing* refers to when the injection occurs compared to the cylinder piston's motion, while the *duration* of the injection event determines how much fuel is injected.

While it's common to speak of the injection timing as if it were a single event, the injection process often includes multiple pulses of fuel or *injection events. Multipulse injection,* which refers to two or more injection events to the same cylinder during each combustion cycle, assists in reducing

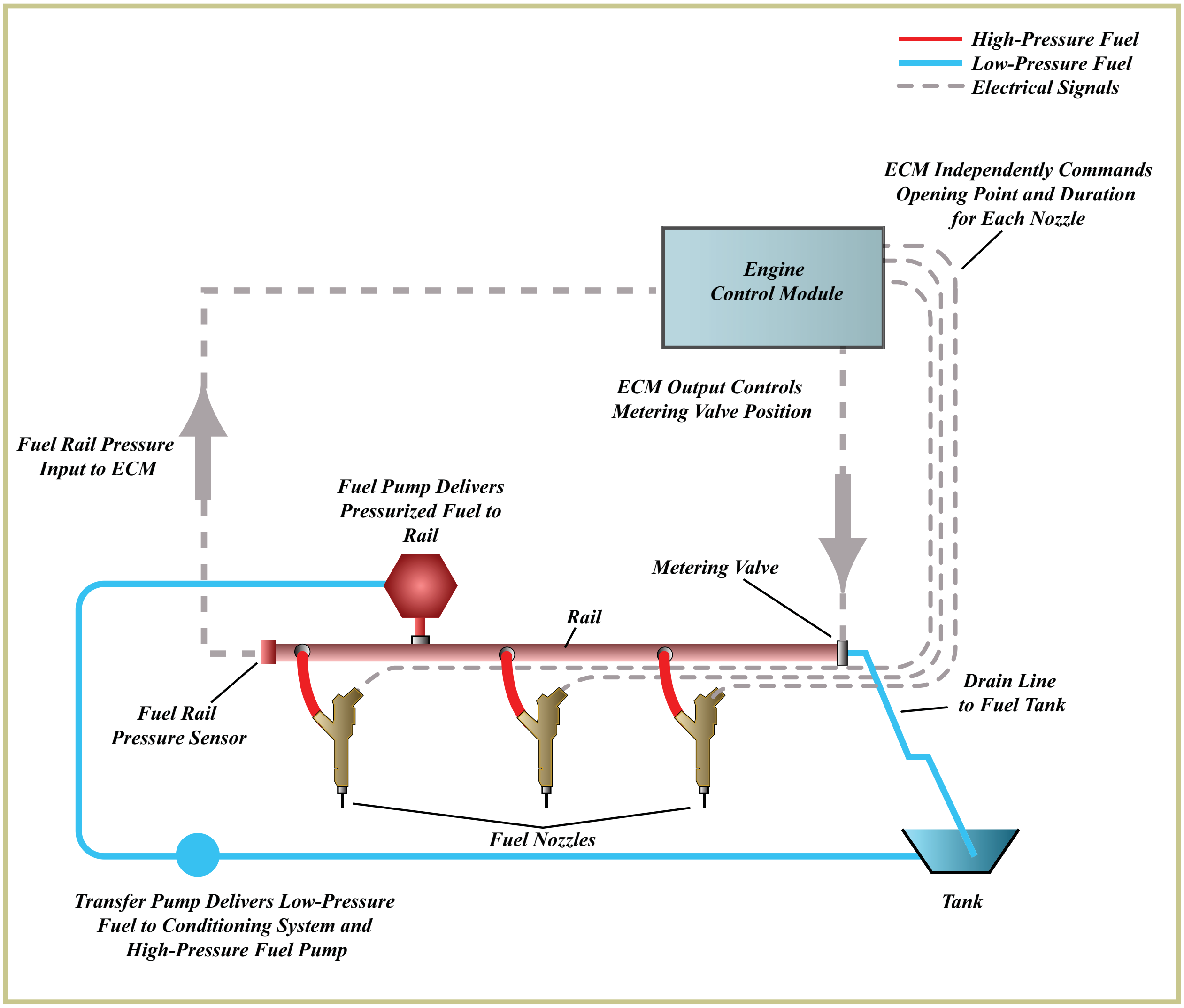


FIGURE 27—Common-Rail Fuel Injection System

emissions, improving operation during cold start, optimizing the combustion process, or even dosing the diesel particulate filter, as you'll soon learn.

Remember, because piezo-actuated valves operate with much less delay than solenoid-operated ones, nozzles equipped with piezo actuators are capable of delivering more injection events in the same amount of time. This characteristic of piezo-actuator equipped engines expands the ECM's ability to optimize fuel injection.

Variable Turbocharger Geometry

A diesel engine's air intake system delivers a large volume of air to the engine cylinders for the combustion process as well as for cylinder cooling and scavenging of exhaust gases. This volume of incoming air is delivered by the turbocharger, which in many ways greatly improves engine performance. A *turbocharger* can be thought of as two connected subsystems. As hot exhaust gas exits the exhaust manifold, it drives a turbine that's connected to an air-pumping device known as an *impeller*. A shaft serves as the connection between the exhaust-gas-driven turbine and the impeller, which serves as main working part of the turbocharger's compressor (Figure 28).

The turbine's speed depends mostly on the temperature of exhaust gas and the speed the gas travels after passing through a restriction that's known as a *volute*. Because the turbine connects directly with the impeller, this means that the impeller must also turn faster and therefore pump more air as engine speeds increase. Under some operating conditions, optimal engine operation relies on less (or more) intake airflow than would normally be delivered with a fixed-geometry turbine. Fortunately, through the use of computer controls and variable-geometry turbocharger technology, turbine speed can be tailored to meet engine operating conditions.

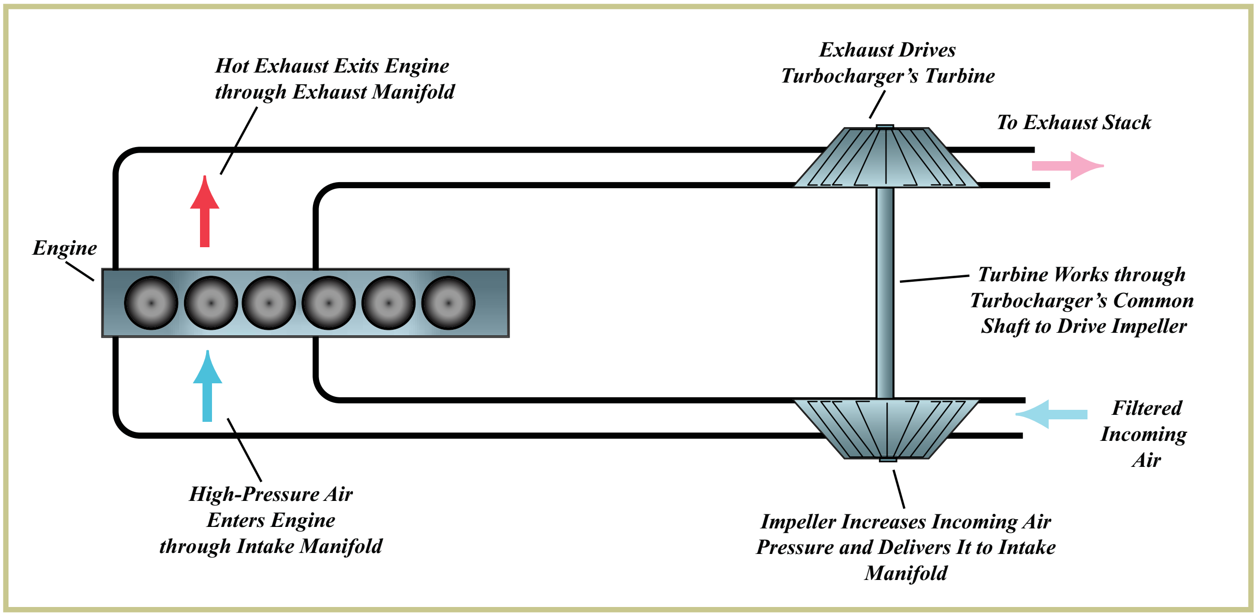


FIGURE 28—Turbocharger Operating Principle

A variable-geometry turbocharger employs one of two basic methods to control the delivery of intake air from the turbocharger to the intake manifold. *Wastegate-controlled turbochargers* open a gate to allow some of the exhaust gas to bypass the turbine, thus slowing the turbocharger's shaft speed, decreasing the flow of intake air, and "wasting" some of the high-energy exhaust gas (Figure 29). Electronically controlled wastegates rely on ECM-activated solenoids to open or close bypassing gates. Alternatively, the variable turbocharger geometry is managed with an ECM-controlled volute size.

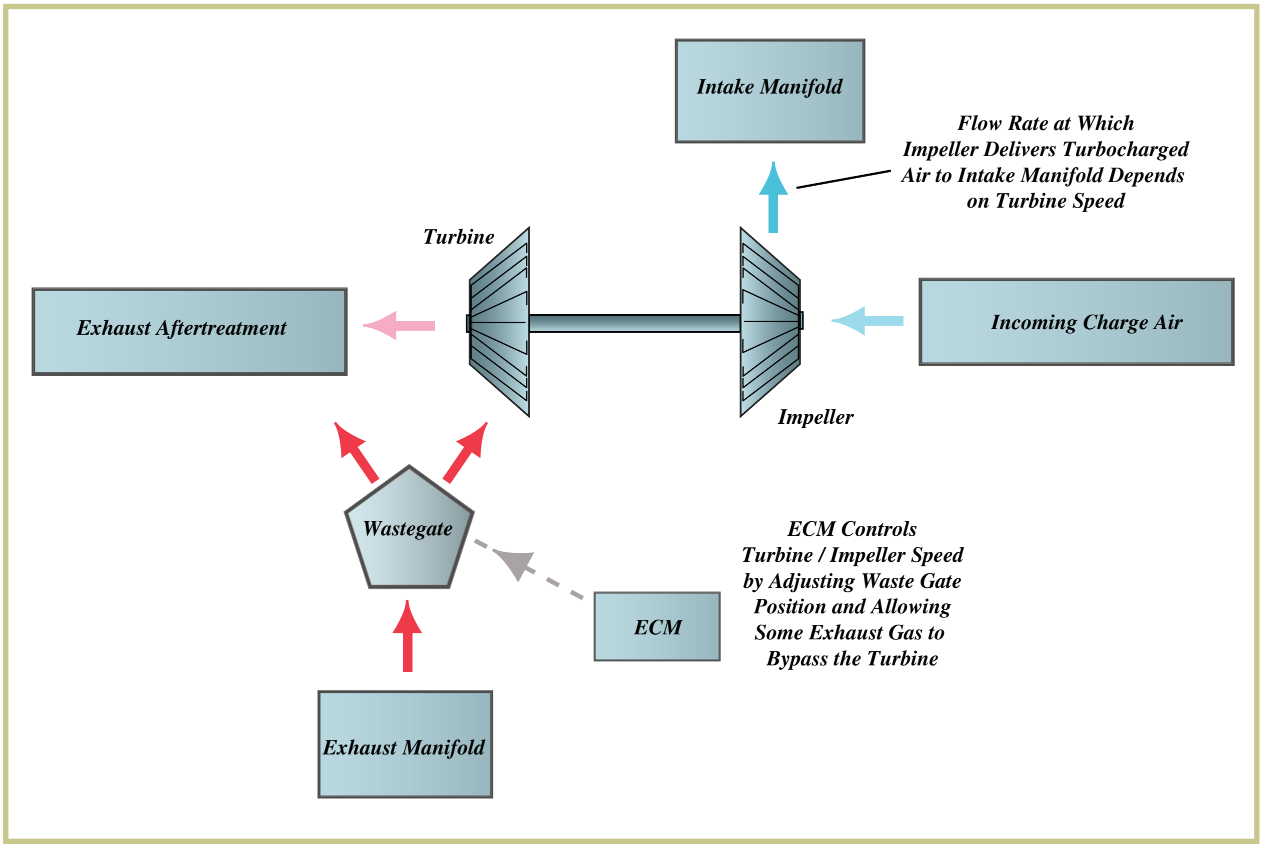


FIGURE 29—Wastegate-Controlled Turbocharger

Remember, the volute is a restriction through which exhaust gas passes before acting on the turbine. The smaller the volute area, the higher the speed with which the gas moves and the turbine rotates (Figure 30). The ECM may activate solenoid(s) to direct pressurized engine oil as a way to change volute size. Alternatively, the ECM calls on a stepper-motor-powered actuator to position the *variable vanes* whose spacing represents the volute.

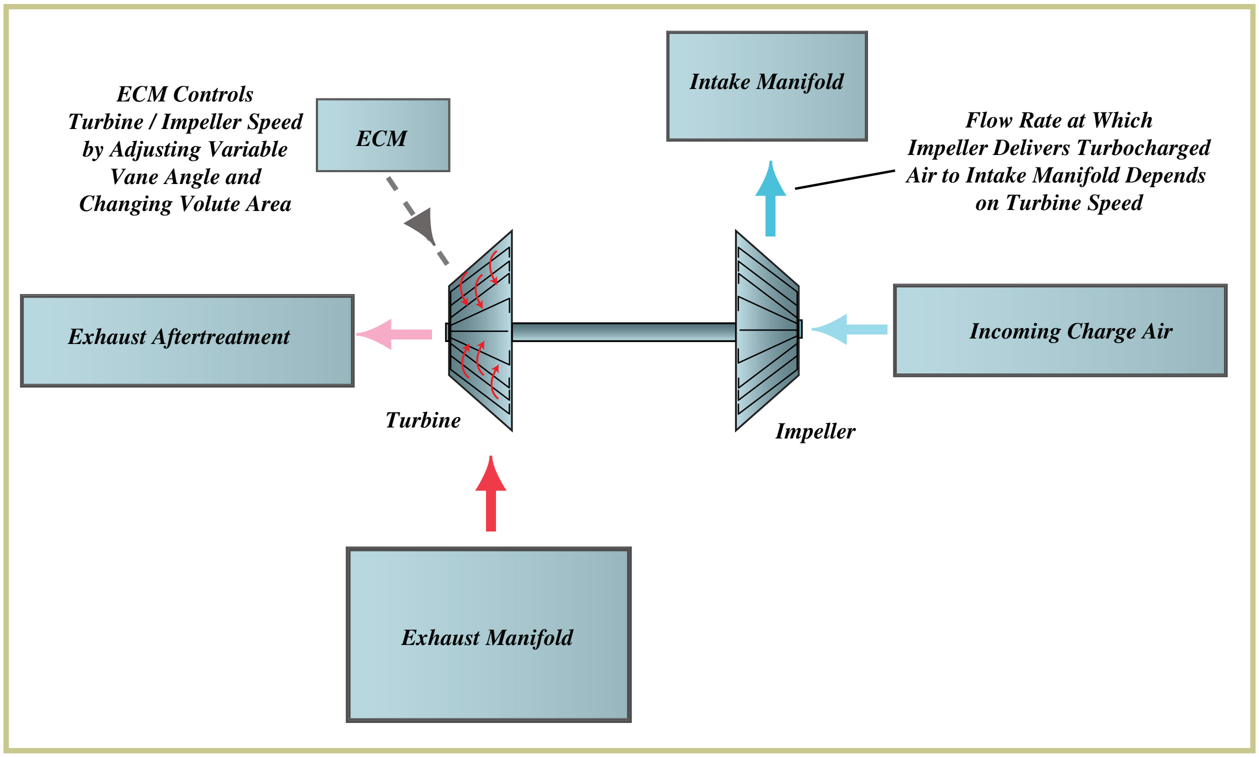


FIGURE 30—Turbocharger Speed Controlled with Variable Volute

Whichever volute controlling technology is employed, it's typical that the ECM receives a feedback signal indicating the actual volute configuration. Using this information, along with the Hall effect sensor signal indicating turbocharger shaft speed and many other inputs, the ECM adjusts the volute opening to increase or decrease intake airflow. At this point it's useful to also recognize that a reduced volute area offers more restriction to the passage of exhaust gas, which results in an increase in exhaust gas pressure. As you'll soon learn, this characteristic links the VGT and the EGR system configurations in determining the ratio of recirculated exhaust gas and intake air directed into the engine's cylinders.

Emission-Control Systems

The emission-control system of a modern vehicle uses input sensors, output devices, and computers to limit the emission of various pollutants. Engine manufacturers incorporate EGR, SCR, DPF, and other emission-controlling devices to reduce the amount of pollutants produced by the engine and delivered to the environment. To a large degree, these design changes have been successful, although the introduction of SCR technology means that engines built after 2010 depend less on EGR systems to reduce NO_x emissions. Their heavy reliance on engine-management computers means that modern emission-control systems operate more effectively than ever.

The *exhaust-gas-recirculation,* or *EGR,* system routes some exhaust gas through a cooler after which it mixes with pressurized intake air as it exists the turbocharger's compressor. This process reduces the quantity of oxygen in the combustion process by substituting some amount of "dead" or oxygen-free gas in place of oxygen-charged intake air. Less oxygen available for combustion results in a reduction of NO_x levels in the engine's exhaust.

The ECM typically controls the flow of recirculated exhaust gas in two ways (Figure 31). An ECM-controlled stepper motor positions the (usually) butterfly-style EGR valve. The amount this valve is open, as well as the exhaust gas pressure level, which varies with VGT configuration, determines how much gas flows from the exhaust system to the EGR system. EGR valve position is typically a closed-loop control system, with input data from the EGR-valve position sensor, intake manifold MAF sensor, exhaust manifold pressure sensor, the EGR flow sensor, and various temperature sensors serving as inputs to the ECM and the EGR valve position as an ECM output.

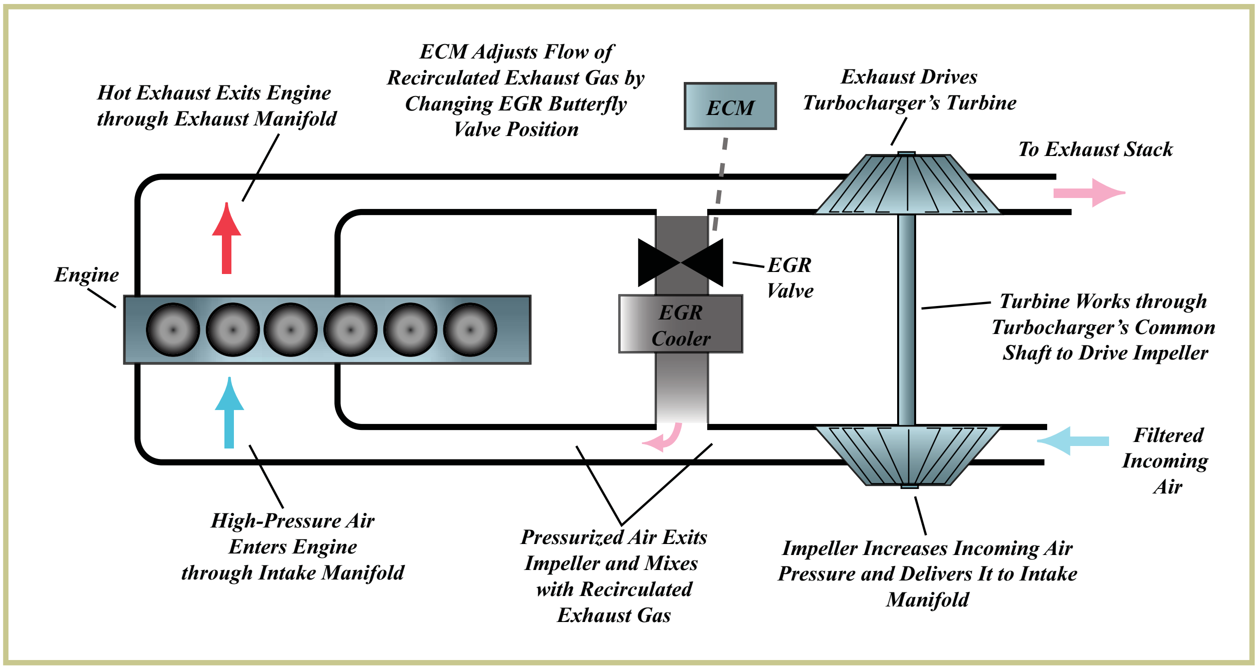


FIGURE 31—Operating Principle of a Typical Cooled EGR System

The *diesel particulate filter (DPF)* is an exhaust aftertreatment system intended to remove *soot* (also known as *particulate matter)* from diesel engine exhaust. This filter, which is contained in what looks most like a muffler, allows exhaust gas to pass but traps almost all soot. Because the filter would otherwise quickly fill with collected soot, a DPF system makes use of one or more techniques to burn off this material. The process of clearing collected soot from the DPF is known as *regeneration.*

The inside surfaces of certain DPF components are coated with compounds, known as *catalysts,* which chemically react with collected soot. This chemical reaction makes the soot burn at a lower temperature. Under operating conditions experienced by over-the-road diesel-powered trucks, most DPF-collected soot burns during normal full-load engine operation. This process, which happens without outside action, is known as *passive regeneration.*

While it's true that most DPF-collected soot is automatically removed during normal operation through passive regeneration, most truck engines rely on both active and passive regeneration processes. Computer-controlled regeneration, commonly referred to as *active regeneration,* in some cases occurs when a computer-controlled auxiliary fuel injector sprays fuel into a component upstream of the DPF, known as a *diesel oxidation catalyst (DOC).* Gas temperature exiting the DOC is sufficiently high to burn the soot contained in the downstream DPF.

Depending on the system's design, active regeneration often involves the addition of fuel to the soot that's collected in the DPF filter. This fuel may come from a computer-controlled, solenoid-operated *dosing fuel injector* that's actually part of the DPF system and sprays fuel directly on the filter, or by the ECM-commanded addition of extra fuel, through engine fuel-injection nozzles, after the combustion process is complete and as the exhaust gases are driven from the cylinder. In this case, the exhaust gas carries this extra fuel onto the particulate filter where it soaks the trapped soot.

Whichever method is employed to add fuel to the filter, the DPF must be hot enough for the collected soot to burn. During active regeneration, the ECM monitors various DPF system temperatures to be sure there's sufficient heat to burn the trapped soot. Where insufficient heat is present, the ECM may produce elevated exhaust temperature by temporarily adjusting the engine's air-fuel ratio. In other system designs, a computer-controlled spark plug ignites injected dosing fuel as it sprays on the collected soot.

To support the DPF regeneration process, the ECM (or DPF-dedicated computer module) receives information from various temperature sensors, described earlier in this study unit. The computer is also able to monitor the amount of soot load in the DPF with the use of a delta-pressure sensor. Data from these input sensors, together with collected engine operating data, allows the computer system to "know" when and if active regeneration is required.

Selective catalytic reduction (SCR) technology is a more up-to-date system that controls NO_x emissions more effectively than EGR, and without the negative impact on engine performance that results from the recirculation of exhaust gas into the combustion process. Like the diesel particulate filter, the SCR system is an exhaust aftertreatment process (Figure 32). In this case, urea-based *diesel exhaust fluid*

(DEF) is sprayed into the exhaust as it enters the SCR catalyst. As you already learned, DEF is carried on each truck in its own tank.

The ECM relies on data from SCR temperature sensors, as well as NO_x sensors, to determine the rate at which DEF should be sprayed into the exhaust and to monitor the system's proper operation. A computer-controlled electric pump and solenoid-controlled valve ensure delivery of a properly metered quantity of DEF as well as making sure that at engine shutdown, DEF is allowed to drain back into its tank. Since DEF is mostly *deionized* (purified) water, sufficiently low temperatures could cause it to freeze, rupturing its conducting tubes. The ECM also turns on tank and supply-line heat when ambient temperatures are low enough for the fluid to freeze and issues warnings when the tank's fluid level drops below a preset minimum. Finally, the newest systems include sensors that monitor the purity of the DEF, allowing the ECM to issue a warning when the system's operation is diminished due to the addition of nonpurified water or other contamination source. In these illustrations, operating with too low a level of DEF, or with contaminated DEF, results in the ECM limiting vehicle speed and, eventually, limiting engine operation above idle speed.

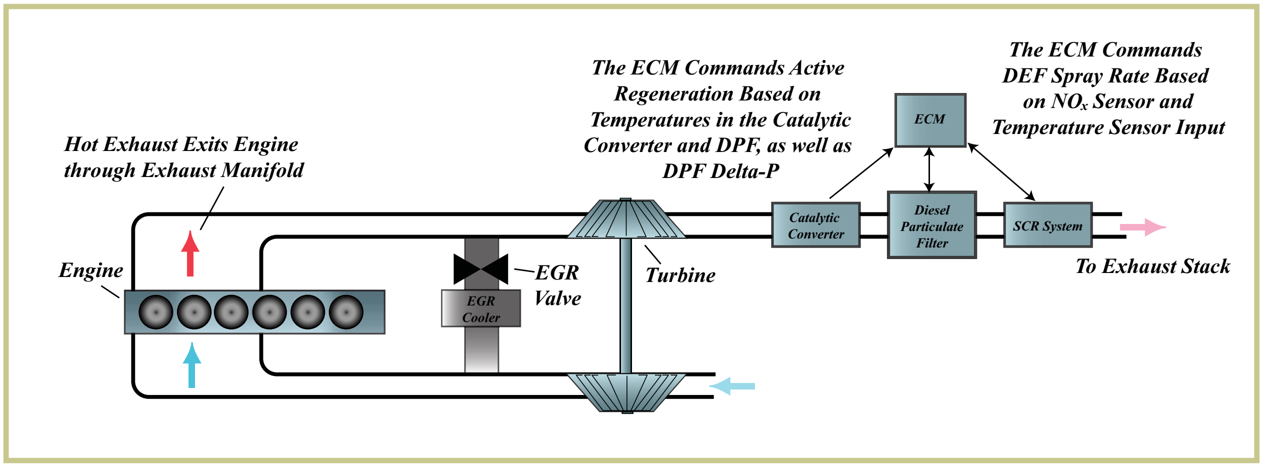


FIGURE 32—DPF and SCR Exhaust Aftertreatment Systems

Engine Cooling Fan System

Earlier in this study unit, you learned that the development and evolution of computer-controlled systems has produced engines that last longer, consume less fuel, and emit less pollution. A less obvious way that a computer-controlled system helps modern engines achieve these goals is by controlling the cooling fan. The engine's cooling system relies on the fan to help remove heat from the radiator and other heat-exchangers whenever the natural flow of air through the engine compartment, known as *ram air,* is insufficient. When an over-the-road truck engine's cooling fan is driven by the crankshaft, it consumes energy that could otherwise be spent powering the vehicle and its load of freight. For this and other reasons, it's preferable to operate the fan only as much as needed.

When an ECM system controls the engine cooling fan, it works to minimize the energy the engine puts into driving the fan while ensuring that the coolant and engine-compartment temperatures remain in an acceptable range. To decide when to turn on the fan, the ECM relies on data from various temperature sensors as well as other data indicating when more or less cooling will soon be required. For example, the engine fan may be engaged when the ECM senses the switching on of cabin air conditioning, which will in various ways eventually add heat to the engine compartment.

An engine operates most efficiently under constant conditions. Turning a high-output fan either fully on or off whenever a sensed temperature reaches a programmed limit doesn't result in very steady operating conditions. When the fan is turned fully on or off, several less-than-ideal things happen, including the following:

- An abrupt physical load is applied to the belts and other hardware responsible for carrying energy from the crankshaft to the fan.
- There are relatively large swings in engine coolant and compartment temperature, which increases the load on mechanical components as well as heat-sensitive electronic ones.

- The changing engine temperature, and therefore operating conditions, makes it more difficult for the ECM to precisely control engine operation and limit fuel consumption.

ECM control of cooling fan hubs now allows for *variable-speed cooling fans,* which can be precisely scheduled to deliver just the amount of airflow required by current or soon-to-take-effect heating loads. Also important is the ability for the ECM to gradually change the speed of these fans to prevent the large and rapid changes in engine and engine compartment temperature experienced with a full on / full off fan control system. In a variable-speed fan control system, an ECM controlled proportioning solenoid positions a fluid-controlled valve, which regulates fan speed by directing the flow of hydraulic fluid in the fan hub's drive system.

Engine Brake Solenoids

As you may remember from earlier studies, an *engine brake system* works to slow a vehicle without relying on the primary braking system that acts on the tractor and trailer wheels. By actuating a collection of solenoid-controlled valves, an engine brake system converts the engine from a power-producing device into a power-absorbing one. This is accomplished by using one or more of the engine's cylinders to compress air, exhaust gas, or both, without the addition of diesel fuel. In this way, the vehicle's drive wheels supply power through the drivetrain and crankshaft, driving the piston(s) to act as a compressor. The act of supplying power to the drivetrain causes the drive wheels to turn more slowly, thus reducing the speed of the vehicle.

Two specific categories of engine brakes, known as *compression braking systems,* convert some of the vehicle's energy of motion into pressurized (and thus heated) gas. In an *internal compression brake,* one or more cylinders complete the compression stroke *without* the addition of fuel. Instead, when the piston reaches the top of its compression stroke, a solenoid commands the exhaust valve to open, releasing the compressed air. If you consider that the piston requires power to compress the air in the cylinder, and that this power is supplied to the piston by the drive wheels, then it's easier to understand how this process would add resistance to the drive wheels' ability to turn and, therefore, slow the vehicle.

An *external compression engine brake* also draws power from the drive wheels to act on one or more cylinders, turning it into a compressor. However, in this case an activated solenoid blocks the passage of exhaust gas, converting the cylinder's exhaust stroke into a compression stroke and increasing the pressure of the trapped exhaust gas. Again, when the external engine brake is activated, the braking cylinder(s) isn't supplied with fuel.

In modern engine brake systems, the ECM withholds fuel from the cylinder(s) engaged in braking, actuates the valve-controlling solenoids, and adjusts the level of compression braking by increasing or decreasing the number of cylinders employed as engine brakes. In some designs, the engine brake system operates simultaneously as both an internal and external compression brake. While the level of compression braking applied is often based on driver input, the ECM can also automatically deploy the engine brake, and adjust its level of braking, to maintain a cruise-control speed set by the driver or to slow the vehicle during an accident-avoidance event.

Indicator Lights and Fault Codes

Much of your training is ultimately intended to help you more effectively maintain and troubleshoot engine and vehicle systems. As you've learned, computer-controlled systems depend on input devices, most notably sensors, to monitor operating characteristics like pressure and temperature and report their measurements back to the computer. The computer uses this input data, along with the instructions with which it has been programmed, to decide what actions to take. These actions are accomplished through the computer's command of output devices.

An ECM or other computer is programmed to "know" approximately what measurement signal it should receive from the sensor and what reaction it should observe after sending a specific command to an output device. When the computer observes an incoming measurement or response to an outgoing command that differs from the values it's programmed to expect, it sends a message to alert the driver and/or maintenance technician of a possible problem. While the type of message the computer sends depends on the type and severity of the problem, this message is typically viewed by the technician as a *fault* or *trouble code*.

Engine Fault Indicator Lamps

Even though the types of fault-code indicators visible to an operator vary depending on the age and OEM of a vehicle, fault indicator lights can be grouped into a few general categories. The ECM outputs a signal to illuminate the *check engine lamp,* which is yellow, when an engine fault is detected. This light warns the driver of a fault but doesn't require that the vehicle be shut down. In some cases, the type of sensed fault may lead the ECM to operate the engine in a derated mode. If the sensed fault poses an immediate danger of engine damage, the ECM illuminates the red *stop engine lamp.* This warns the driver to stop the vehicle as soon as is safely possible.

When either of these engine indictor lamps is illuminated, you can quickly determine the fault code set by the ECM. The required procedure varies depending on vehicle OEM, but usually you'll turn the ignition key on and off in a required pattern or activate a dashboard-mounted *diagnostic switch* to access the code. When either the check or stop engine lamps are illuminated, following the applicable procedure causes the indicator lamp, or an ECM-mounted diagnostic lamp, to flash a specific number of times. The number of flashes defines a *flash code,* which identifies the problem responsible for the lamp illuminating. OEM-provided lookup tables allow you to quickly identify the fault code based on the number of flashes. Of course you can also gain the same information (and more) with the use of a handheld electronic service tool or computer, as we'll discuss shortly.

Malfunction Indicator Lamps

Since 2010, all trucks are also equipped with a *malfunction indicator lamp (MIL).* The behavior of this indicator is the same in all newer vehicles. When the ECM sets certain trouble codes, it outputs a signal that illuminates the MIL lamp. These specific trouble codes are those that relate to the operation of an emission control system, such as SCR, or those that could result in damage to an emission-system component. This indicator light, and the ECM system that controls its operating logic, are mandated by the EPA (Environmental Protection Agency). Known as *HD-OBD,* or *heavy-duty on-board diagnostic system,* this government-required system ensures that an engine is capable of meeting the emissions requirements set by the EPA.

The EPA's requirements control how the MIL indicating system operates. This includes defining what sort of vehicle operation is counted (by the ECM) as a *drive cycle,* such as spending a specific amount of time with the engine running at idle, making a certain number of accelerations and decelerations, and operating at highway speeds for at least a defined time period. The HD-OBD drive cycle guarantees that the computer system has an opportunity to perform all of its diagnostic checks. The HD-OBD requirements also determine what happens to fault codes once they're set. and what happens to fault codes once they're set. Following are a few characteristics common to all MIL systems:

- Fault codes (with a few more-serious exceptions) are considered to be *pending* during the first drive cycle in which they're set by the ECM. Pending fault codes don't result in the MIL illuminating. Note that if a pending fault code isn't set by the ECM during the next consecutive drive cycle, it's cleared from the system.

- Fault codes set by the ECM during a second consecutive drive cycle are considered to be *confirmed*. A confirmed fault code results in illumination of the MIL and the ECM storing *freeze-frame data* describing engine operating characteristics at the time the fault code was set. At the same time a code is confirmed, it's also stored in the ECM as a *permanent code.*

- Repairing the engine so that the ECM no longer detects a problem clears the confirmed fault.

- Even when repairing the problem clears the confirmed fault, the MIL lamp remains lit for three more drive cycles, and the permanent fault remains stored. If the ECM doesn't detect the same problem for the next three drive cycles, the permanent fault is converted to a *previous fault* and stored in the ECM for a total of 40 drive cycles. After 40 problem-free drive cycles, the previous fault is also cleared.

Electronic Fault Evaluation

Handheld *electronic service tools (ESTs)* plug into a *data-bus access connector,* such as the *J1939,* whose location varies depending on vehicle OEM. As you've already read, these tools allow you to quickly read ECM-generated fault messages. However, depending on whether or not the handheld tool you use is a generic or OEM-specific model, it may not have access to all data on the vehicle's bus. More importantly, these tools offer much less functionality than a personal-computer-based electronic service tool.

A laptop or tablet outfitted with OEM-specific diagnostic software provides much more than a way to access fault codes. The most capable of these systems provide the technician with immediately accessible troubleshooting guidelines matched to a specific fault code. They also provide the ability to view the output of a specific sensor and compare it to historical data from that sensor or the output of a known good sensor. Finally, laptop-based systems can update software or equipment-related data in a vehicle computer and allow the user to electronically command certain actions that aid in many troubleshooting procedures such as purposefully preventing one cylinder from firing.

The ability for computer-based ESTs to communicate wirelessly with a vehicle's control computers is even more likely to significantly change how truck maintenance is performed. This wireless communication is already a normal occurrence in many shops. This and similar abilities are leading to remote access of diagnostic data stored in *electronic onboard recorders (EOBRs)* and similar methods of detecting and reading fault messages and related data while a vehicle is away from a repair facility.

Self-Check 3

Complete the following statements with the correct answer.

1. The movable core of a solenoid is referred to as its _______.

2. *True or False?* As it takes time for magnetic field changes to build in a solenoid, solenoids are less well suited than piezo actuators for the most demanding fuel-injection applications.

3. *True or False?* A stepper motor always has an attached velocity-controlling device.

4. ______ -actuated fuel injectors provide much faster response rates than those achieved by solenoid-controlled injectors.

5. *True or False?* The term *injection timing* refers to the point at which fuel injection begins.

6. A(n) ______ delivers a large volume of air to the engine cylinders for combustion and cylinder cooling.

7. *True or False?* Since 2010, engines have relied heavily on selective catalytic reduction technology to control quantities of certain types of emissions.

8. ______ is the name of the process for clearing collected soot from the diesel particulate filter in an exhaust aftertreatment system.

9. *True or False?* Operating with an empty diesel exhaust fluid tank will, in the newest engines, result in the ECM limiting vehicle speed.

10. An engine braking system that converts some of the vehicle's energy of motion into pressurized gas is known as a(n) ______ braking system.

Check your answers with those on page 64.

Self-Check 1

1. F
2. voltage
3. T
4. engine brake
5. T
6. analog
7. F
8. digital
9. closed-loop

Self-Check 2

1. F
2. resistance temperature detector (RTD)
3. T
4. dielectric
5. F
6. differential-pressure or delta-P
7. T
8. rheostat
9. F
10. exhaust-gas-recirculation (EGR)

Answers

Self-Check 3

1. armature
2. T
3. F
4. Piezo
5. T
6. turbocharger
7. T
8. Regeneration
9. T
10. compression