Knowing R_m, the stoichiometric mass flow rate for the fuel, R_{fm}, can be calculated as follows:

$$R_{fm} = \frac{R_m}{14.7}$$

It is the function of the fuel metering actuator to set the fuel mass flow rate at this desired value based on the value of R_a. The control system continuously calculates R_m from R_a and d_a at the temperature involved, and generates an output electrical signal to operate the fuel injectors to produce a stoichiometric mass fuel flow rate. For a practical engine control system, it completes such a measurement, computation, and control signal generation at least once for each cylinder firing.

ELECTRONIC IGNITION

The engine ignition system exists solely to provide an electric spark to ignite the mixture in the cylinder. As explained earlier in this chapter, the engine performance is strongly influenced by the spark timing relative to the engine position during the compression stroke (see also Chapter 1). The spark advance (relative to TDC) is determined in the electronic engine control based on a number of measurements made by sensors. As will be explained in Chapter 7, the optimum spark advance varies with intake manifold pressure, RPM, and temperature.

However, in order to generate a spark at the correct spark advance the electronic engine control must have a measurement of the engine position. Engine position is determined by a sensor coupled to the camshaft or the crankshaft, or a combination of each, depending on the configuration for the electronic ignition.

Electronic ignition can be implemented as part of an integrated system or as a stand-alone ignition system. A block diagram for the latter system is shown in Figure 5.22. Based on measurements from the sensors for engine position, mass air flow or manifold pressure, and RPM, the electronic controller computes the correct spark advance for each cylinder. At the appropriate time the controller sends a trigger signal to the driver circuits, thereby initiating spark. In many modern electronic spark systems, spark plugs are fired in pairs through a common coil, or high-voltage transformer. Before the spark occurs, the driver circuit sends a relatively large current through the primary (P) of the coil. When the spark is to occur, a trigger pulse is sent to the driver circuit for the coil associated with the appropriate spark plug. This trigger causes the driver circuit to interrupt the current in the primary. A very high voltage is induced at this time in the secondary (S) of the coil. This high voltage is applied to the spark plugs, causing them to fire. Typically, one of the two cylinders will be in this compression stroke. Combustion will occur in this cylinder, resulting

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

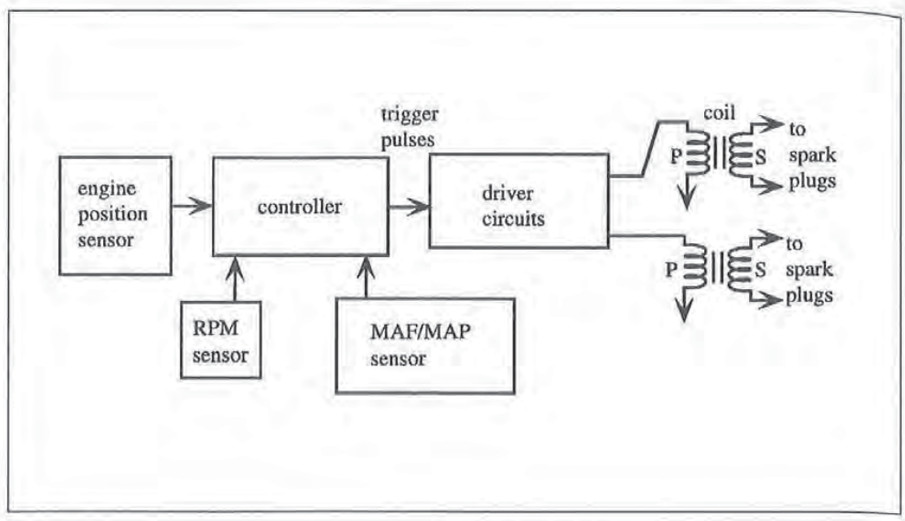


Figure 5.22 Electronic Distributorless Ignition System

in power delivery during its power stroke. The other cylinder will be in its exhaust stroke and the spark will have no effect. Most engines have an even number of cylinders and there will be a separate driver circuit and coil for each pair of cylinders.

An ignition system such as this is often called a *distributorless ignition system* (DIS) because the multiple coil packs and drivers are a modern replacement for the (now essentially obsolete) distributor (see Chapter 1).

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Quiz for Chapter 5

1. What is the primary motivation for engine controls?
   - **a.** consumer demand for precise controls
   - **b.** the automotive industry's desire to innovate
   - **c.** government regulations concerning emissions and fuel economy
2. What is the primary purpose of fuel control?
   - **a.** to minimize fuel economy
   - **b.** to eliminate exhaust emissions
   - **c.** to optimize catalytic converter efficiency
   - **d.** to maximize engine torque
3. What is the primary purpose of spark timing controls?
   - **a.** to maximize fuel economy
   - **b.** to minimize exhaust emissions
   - **c.** to optimize catalytic converter efficiency
   - **d.** to optimize some aspect of engine performance (e.g., torque)
4. What does exhaust gas recirculation do?
   - **a.** improves fuel economy
   - **b.** reduces NO_x emission
   - **c.** increases engine torque
   - **d.** provides air for the catalytic converter
5. What does secondary air do?
   - **a.** dilutes the air/fuel ratio
   - **b.** helps oxidize HC and CO in the exhaust manifold
   - **c.** helps oxidize NO_x and CO in the catalytic converter
   - **d.** helps reduce the production of NO_x
6. What is air/fuel ratio?
   - **a.** the mass of air in a cylinder divided by the mass of fuel
   - **b.** the volume of air in a cylinder divided by the volume of fuel
   - **c.** the ratio of the mass of HC to mass of NO_x
7. What electronic device is used in engine controls?
   - **a.** AM radio
   - **b.** catalytic converter
   - **c.** microcomputer
8. What air/fuel ratio is desired for a three-way catalytic converter?
   - **a.** 12:1
   - **b.** 17:1
   - **c.** 14.7:1
   - **d.** none of the above

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

9. What is the desired operation of a catalytic converter on HC emissions?
   a. oxidation to H_2O and CO_2
   b. reduction to H and C
   c. reaction with NO_x
   d. none of the above

10. What is the desired operation of a catalytic converter on NO_x emissions?
   a. reaction with HC
   b. oxidation to N_2 and O_2
   c. reduction to N_2 and O_2
   d. none of the above

11. What is stoichiometry?
   a. a very lean air/fuel ratio
   b. a very rich air/fuel ratio
   c. an air/fuel ratio for which complete combustion is theoretically possible
   d. none of the above

12. How is CO emission affected by air/fuel ratio?
   a. it generally decreases with increasing air/fuel ratio
   b. it increases monotonically with air/fuel ratio
   c. it is unaffected by air/fuel ratio
   d. none of the above

13. What is MBT?
   a. mean before top-center
   b. miles per brake torque
   c. mean spark advance for best torque
   d. none of the above

14. What is the function of electronic fuel control in a vehicle having a three-way catalyst?
   a. to maximize brake-specific fuel consumption
   b. to maintain the average air/fuel ratio at stoichiometry
   c. to always keep the air/fuel ratio within ±0.05 of stoichiometry
   d. to minimize NO_x emissions

15. What is the fuel flow rate for an electronic fuel control system for a vehicle having a three-way catalyst?
   a. $R_{fm} = R_m/14.7$
   b. $R_a/14.7$
   c. $R_v - R_{EGR}/14.7$
   d. none of the above

16. What engine quantities are measured to determine spark advance for an electronic ignition system?
   a. manifold pressure, RPM, and temperature
   b. coolant temperature and mass air flow
   c. manifold position and crankshaft position
   d. none of the above

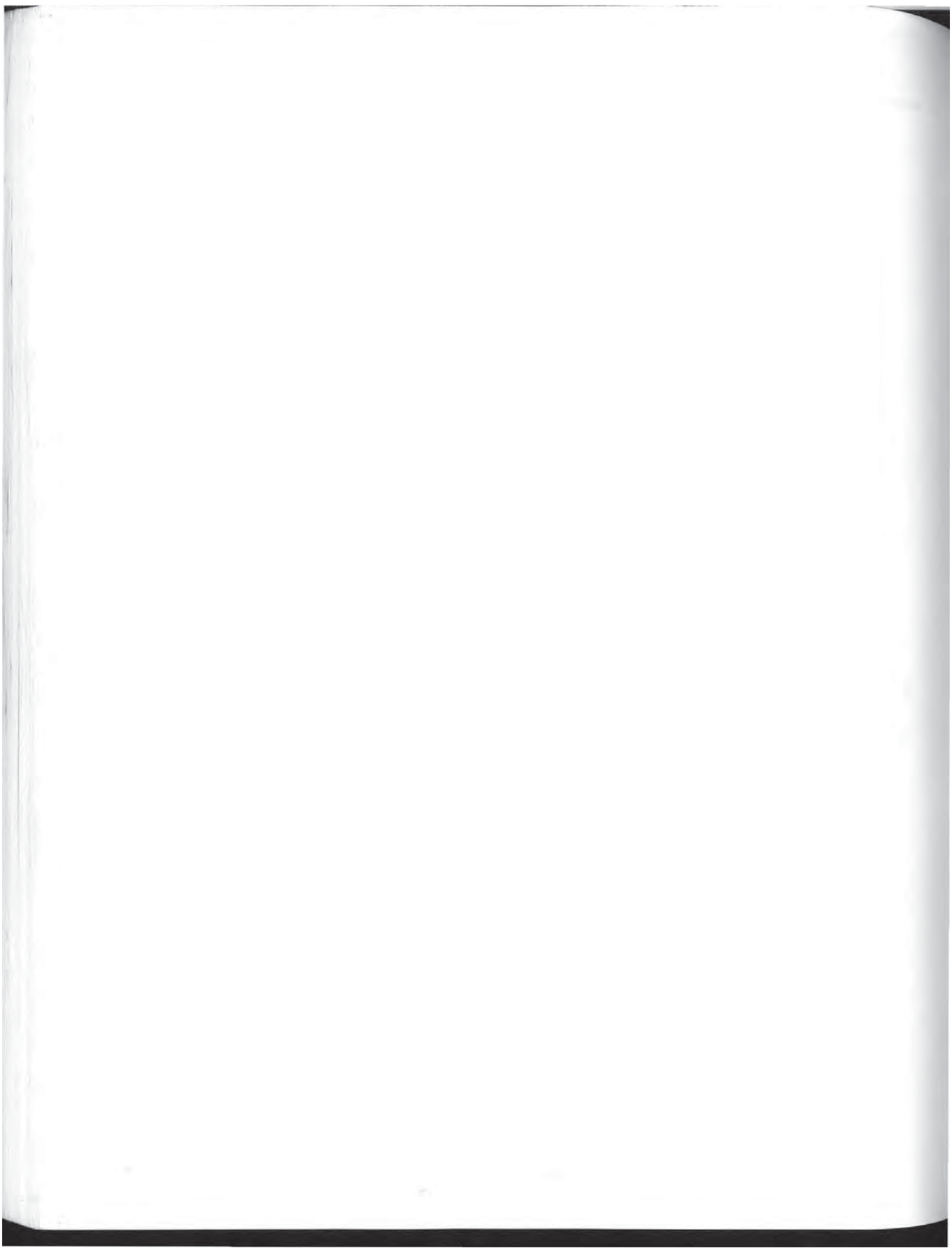
17. In an electronic fuel control system, what causes the time delay between fuel metering and the EGO sensor response?
   a. dynamic response of the electronics
   b. transport time of the air and fuel through the engine
   c. limit-cycle theory
   d. none of the above

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

18. Brake power of an engine is
- **a.** the power required to decelerate the car
- **b.** an electronic system for stopping the car
- **c.** the difference between indicated power and power losses in the engine
- **d.** none of the above

19. What is engine calibration?
- **a.** adjustment of air/fuel ratio, spark timing, and EGR
- **b.** instrumentation parameter setting
- **c.** electronic control system parameters
- **d.** none of the above

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565



Sensors and Actuators

The previous chapter introduced two critically important components found in any electronic control system: sensors and actuators. This chapter explains the operation of the sensors and actuators used throughout a modern car. Special emphasis is placed on sensors and actuators used for power train (i.e., engine and transmission) applications since these systems normally employ the largest number of such devices. However, this chapter will also discuss sensors found in other subsystems on modern cars.

In any control system, sensors provide measurements of important plant variables in a format suitable for the digital microcontroller. Similarly, actuators are electrically operated devices that regulate inputs to the plant that directly control its output. For example, as we shall see, fuel injectors are electrically driven actuators that regulate the flow of fuel into an engine for engine control applications.

Recall from Chapter 2 that fundamentally an electronic control system uses measurements of the plant variable being regulated for feedback control. The measured variable is compared with a desired value for the variable to produce an error signal. The electronic controller generates output electrical signals that regulate inputs to the plant in such a way as to reduce the error to zero.

As will be shown throughout the remainder of this book, automotive electronics have many examples of electronic control in virtually every subsystem. Modern automotive electronic control systems use microcontrollers based on microprocessors (as explained in Chapter 4) to implement almost all control functions. Each of these subsystems requires one or more sensors and actuators in order to operate.

AUTOMOTIVE CONTROL SYSTEM APPLICATIONS OF SENSORS AND ACTUATORS

In control system applications, sensors and actuators are in many cases the critical components for determining system performance. This is especially true for automotive control system applications. The availability of appropriate sensors and actuators dictates the design of the control system and the type of function it can perform.

Sensors and actuators play a critical role in determining automotive control system performance.

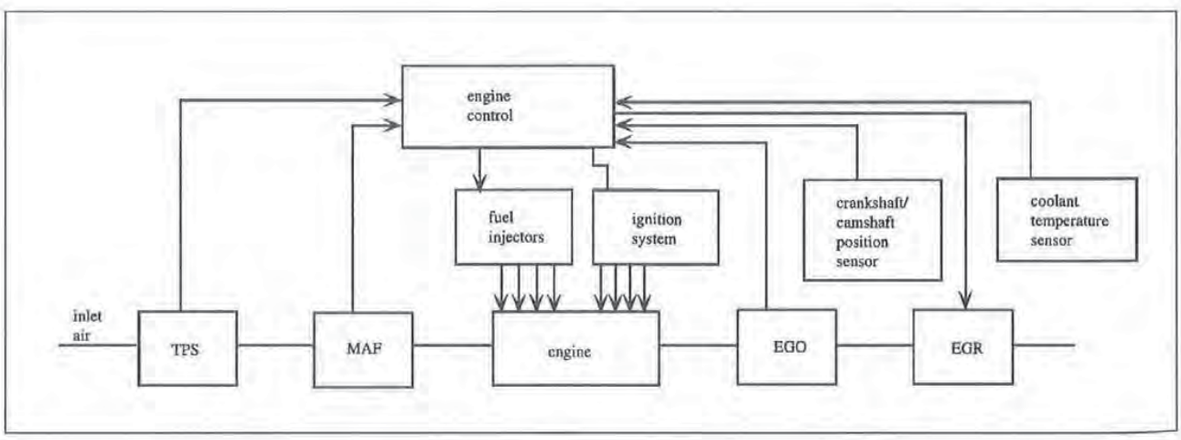
The sensors and actuators that are available to a control system designer are not always what the designer wants, because the ideal device may not be commercially available at acceptable costs. For this reason, often special signal processors or interface circuits are designed to adapt to an available sensor or actuator, or the control system is designed in a specific way to fit available

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

sensors or actuators. However, because of the large potential production run for automotive control systems, it is often worthwhile to develop a sensor for a particular application, even though it may take a long and expensive research project to do so.

Although there are many subsystems on automobiles that operate with sensors and actuators, we begin our discussion with a survey of the devices for power train control. To motivate the discussion of engine control sensors and actuators it is helpful to review the variables measured (sensors) and the controlled variables (actuators). Figure 6.1 is a representative block diagram of a typical electronic engine control system illustrating most of the relevant sensors used for engine control. The position of the throttle plate, sensed by the throttle position sensor (TPS), directly regulates the air flow into the engine, thereby controlling output power. A set of fuel injectors (one for each cylinder) delivers the correct amount of fuel to a corresponding cylinder during the intake stroke under control of the electronic engine controller. A fuel injector is, as will presently be shown, one of the important actuators used in automotive electronic application. The ignition control system fires each spark plug at the appropriate time under control of the electronic engine controller. The exhaust gas recirculation (EGR) is controlled by yet another output from the engine controller. All critical engine control functions are based on measurements made by various sensors connected to the engine in an appropriate way. Computations made within the engine controller based on these inputs yield output signals to the actuators. We consider inputs (sensors) to the control system first, then we will discuss the outputs (actuators).

Figure 6.1
Typical Electronic Engine Control System



PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Variables to be Measured

The set of variables sensed for any given engine is specific to the associated engine control configuration. Space limitations for this book prohibit a complete survey of all engine control systems and relevant sensor and actuator selections for all car models. Nevertheless, it is possible to review a superset of possible sensors, which is done in this chapter, and to present representative examples of practical digital control configurations, which is done in the next chapter.

The superset of variables sensed in engine control includes the following:

1. Mass air flow (MAF) rate
2. Exhaust gas oxygen concentration (possibly heated)
3. Throttle plate angular position
4. Crankshaft angular position/RPM
5. Coolant temperature
6. Intake air temperature
7. Manifold absolute pressure (MAP)
8. Differential exhaust gas pressure
9. Vehicle speed
10. Transmission gear selector position

In addition to measurements of the above variables, engine control is also based on the status of the vehicle as monitored by a set of switches. These switches include the following:

1. Air conditioner clutch engaged
2. Brake on/off
3. Wide open throttle
4. Closed throttle

AIR FLOW RATE SENSOR

In Chapter 5 we showed that the correct operation of an electronically controlled engine operating with government-regulated exhaust emissions requires a measurement of the mass flow rate of air (R_m) into the engine. The majority of cars produced since the early 1990s use a relatively simple and inexpensive mass air flow rate (MAF) sensor. This is normally mounted as part of the air cleaner assembly, where it measures air flow into the intake manifold. It is a ruggedly packaged, single-unit sensor that includes solid-state electronic signal processing. In operation, the MAF sensor generates a continuous signal that varies nearly linearly with true mass air flow R_m.

The MAF sensor is a variation of a classic air flow sensor that was known as a hot wire anemometer and was used, for example, to measure wind velocity

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

for weather forecasting. In the MAF, the hot-wire, or sensing, element is replaced by a hot-film structure mounted on a substrate. On the air inlet side is mounted a honeycomb flow straightener that "smooths" the air flow (causing nominally laminar air flow over the film element). At the lower portion of the structure is the signal processing circuitry.

The film element is electrically heated to a constant temperature above that of the inlet air. The latter air temperature is sensed using a solid-state temperature sensor (explained later in this chapter). The hot-film element is incorporated in a Wheatstone bridge circuit (Figure 6.2a). The power supply for the bridge circuit comes from an amplifier.

The Wheatstone bridge consists of three fixed resistors R_1, R_2, and R_3 and a hot-film element having resistance R_{HW}. With no air flow the resistors R_1, R_2, and R_3 are chosen such that voltage v_a and v_b are equal (i.e., the bridge is said to be balanced). As air flows across the hot film, heat is carried away from the film by the moving air. The amount of heat carried away varies in proportion to the mass flow rate of the air. The heat lost by the film to the air tends to cause the resistance of the film to vary, which unbalances the bridge circuit, thereby producing an input voltage to the amplifier. The output of the amplifier is connected to the bridge circuit and provides the power for this circuit. The amplified voltage changes the resistance in such a way as to maintain a fixed hot-film temperature relative to the inlet temperature.

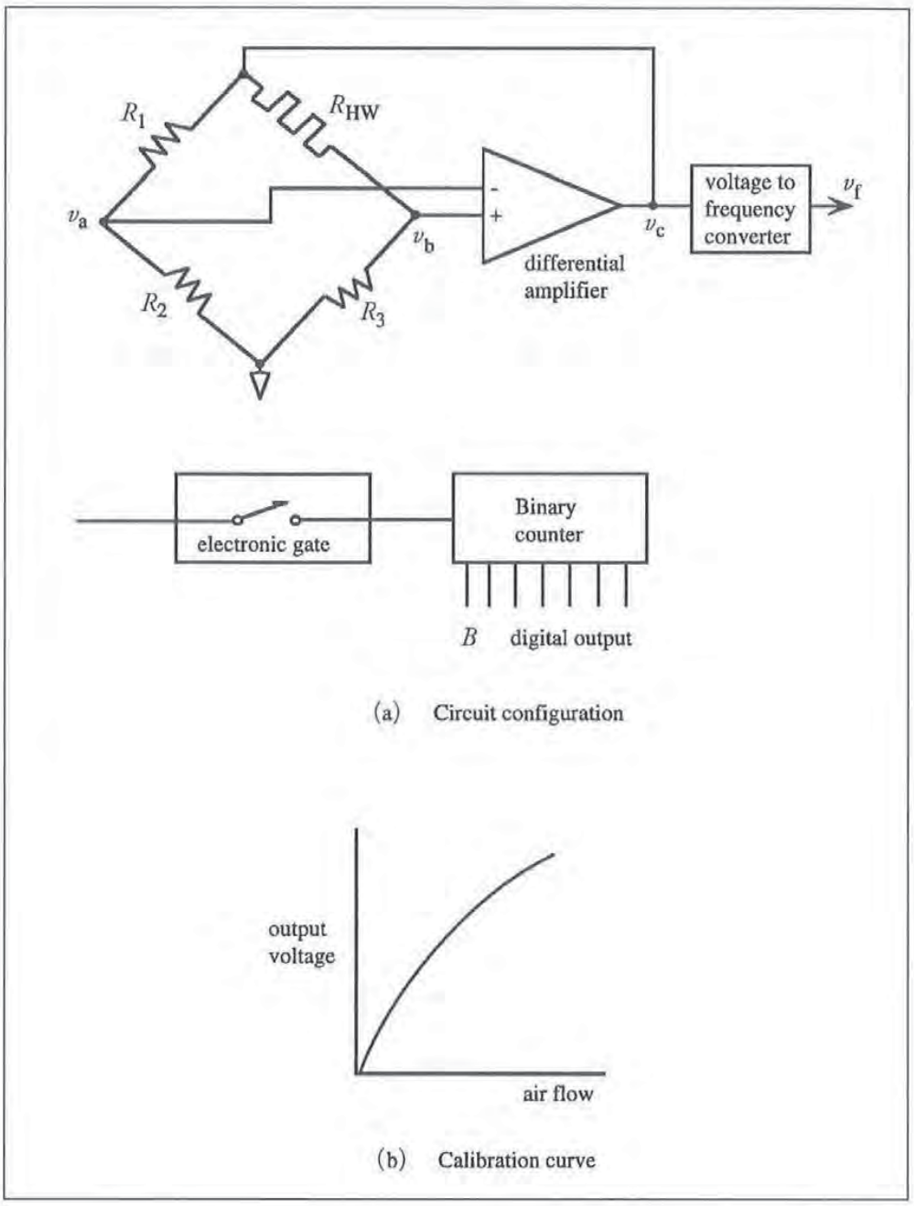
The amplifier output voltage v_c varies with MAF and serves as a measure of R_m. Typically the conversion of MAF to voltage is slightly nonlinear, as indicated by the calibration curve depicted in Figure 6.2b. Fortunately, a modern digital engine controller can convert the analog bridge output voltage directly to mass air flow by simple computation. As will be shown in Chapter 7, in which digital engine control is discussed, it is advantageous to convert analog sensor voltages to a digital format within the solid-state electronics associated with the sensor. This conversion is convenient since it eliminates the need for an analog-to-digital converter, which can be relatively expensive (see Chapter 4).

One scheme for converting the analog output voltage to a digital signal uses a device that is known as a voltage-to-frequency (v/f) converter. This circuit is a variable-frequency oscillator whose frequency f is proportional to the input voltage (in this case, the amplifier output voltage).

The variable-frequency output voltage (v_f) is applied through an electronic gate, which is essentially an electrically operated switch. Control circuitry (also part of the sensor solid-state electronics) repeatedly closes the switch for a fixed interval t. Then it opens it for another fixed interval. During the first interval the variable-frequency signal from the v/f circuit is connected to the binary counter (BC) (see Chapter 3). The BC counts (in binary) at the instantaneous frequency of the v/f, which is proportional to the amplifier output voltage v_f, which in turn varies with mass air flow rate.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Figure 6.2
Mass Air Flow Sensor



During each cycle of the electronic gate, the BC contains a binary number given by the product of the v/f frequency and the time interval. For example, if the mass air flow were such that the v/f frequency were 1000 cycles/sec and the switch were closed for .1 sec, then the BC would contain the binary equivalent of decimal 100 (i.e., $1000 \times .1 = 100$). If the mass air flow increased

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

such that the v/f frequency were 1500 cycles/sec, then the BC count would be the binary equivalent of 150. In mathematical terms, the BC count B is given by the binary equivalent of

$$B = ft$$

where

B = BC count
f = frequency of v/f
t = duration of closure of electronic gate

After the engine controller reads the count, the BC is reset to zero to be ready for the next sample. In actual operation, repeated measurements of frequency f are made under control of the digital engine control module (see Chapter 7).

This conversion of voltage to frequency is advantageous in digital engine control applications because the frequency is readily converted to digital format without requiring an analog-to-digital converter.

Indirect Measurement of Mass Air Flow

Recall that Chapter 5 presented an alternative to direct mass air flow measurement in the form of the so-called speed-density method. This method computes an estimate of mass air flow from measurements of manifold absolute pressure (MAP), RPM, and inlet air temperature. We consider first sensors for measuring manifold absolute pressure.

MAP Sensor Concepts

Several MAP sensor configurations have been used in automotive applications. The earliest sensors were derived from aerospace instrumentation concepts, but these proved more expensive than desirable for automotive applications and have been replaced with more cost-effective designs.

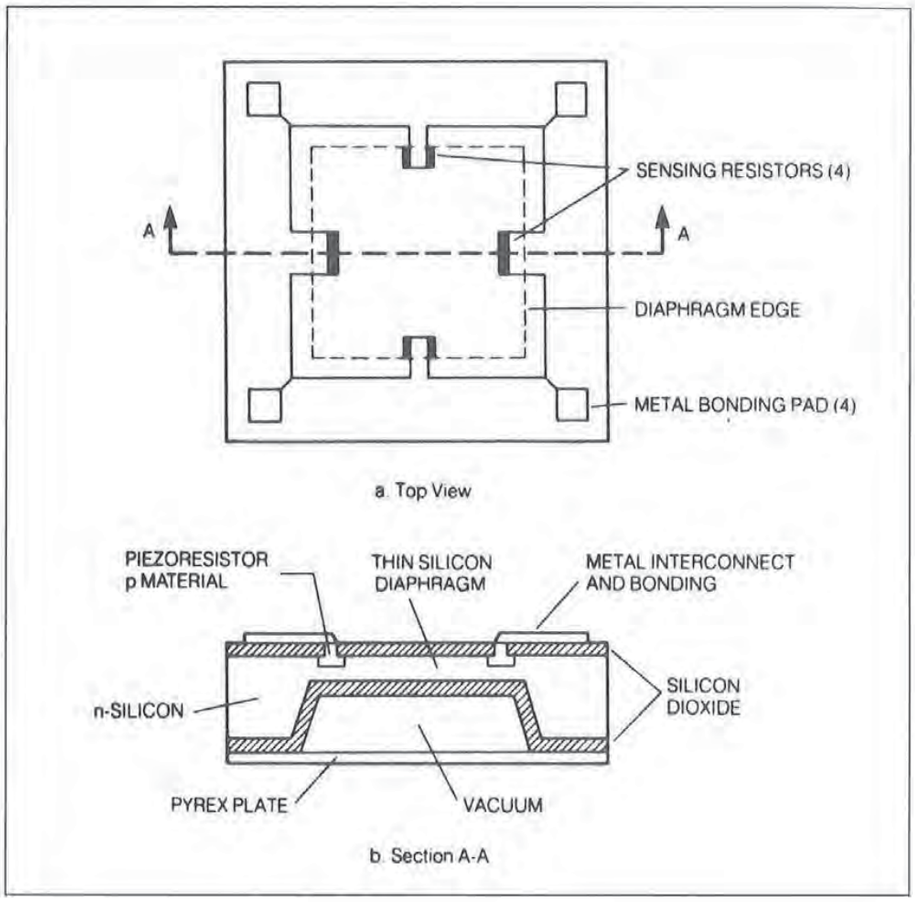
It is interesting to note that none of the MAP sensors in use measure manifold pressure directly, but instead measure the displacement of a diaphragm that is deflected by manifold pressure. The details of the diaphragm displacement and the measurement of this displacement vary from one configuration to another.

Strain Gauge MAP Sensor

One relatively inexpensive MAP sensor configuration is the silicon-diaphragm diffused strain gauge sensor shown in Figure 6.3. This sensor uses a silicon chip that is approximately 3 millimeters square. Along the outer edges, the chip is approximately 250 micrometers (1 micrometer = 1 millionth of a meter) thick, but the center area is only 25 micrometers thick and forms a diaphragm. The edge of the chip is sealed to a pyrex plate under vacuum, thereby forming a vacuum chamber between the plate and the center area of the silicon chip.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Figure 6.3
Typical Silicon-Diaphragm Strain Gauge MAP Sensor



In the strain gauge MAP sensor, manifold pressure applied to the diaphragm causes a resistance change within the semiconductor material that corresponds to the manifold pressure.

A set of sensing resistors is formed around the edge of this chamber, as indicated in Figure 6.3. The resistors are formed by diffusing a doping impurity into the silicon. External connections to these resistors are made through wires connected to the metal bonding pads. This entire assembly is placed in a sealed housing that is connected to the intake manifold by a small-diameter tube. Manifold pressure applied to the diaphragm causes it to deflect.

The resistance of the sensing resistors changes in proportion to the applied manifold pressure by a phenomenon that is known as *piezoresistivity*. Piezoresistivity occurs in certain semiconductors so that the actual resistivity (a property of the material) changes in proportion to the strain (fractional change in length). The strain induced in each resistor is proportional to the diaphragm deflection, which, in turn, is proportional to the pressure on the outside surface of the diaphragm. This pressure is the manifold pressure.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

A pressure sensor having the configuration of Figure 6.3 is also used for measuring absolute atmospheric pressure. It will be shown in Chapter 7 that this absolute pressure can be used in engine control applications, as can the manifold pressure.

The resistors in the strain gauge MAP sensor are connected in a Wheatstone bridge circuit. Output voltage of the circuit varies as the resistance varies in response to manifold pressure variations.

An electrical signal that is proportional to the manifold pressure is obtained by connecting the resistors in a circuit called a Wheatstone bridge, as shown in the schematic of Figure 6.4a. Note the similarity in the Wheatstone bridge of Figure 6.4a with that employed in the MAF sensor of Figure 6.2. The voltage regulator holds a constant dc voltage across the bridge. The resistors diffused into the diaphragm are denoted R_1, R_2, R_3, and R_4 in Figure 6.4a. When there is no strain on the diaphragm, all four resistances are equal, the bridge is balanced, and the voltage between points A and B is zero. When manifold pressure changes, it causes these resistances to change in such a way that R_1 and R_3 increase by an amount that is proportional to pressure; at the same time, R_2 and R_4 decrease by an identical amount. This unbalances the bridge and a net difference voltage is present between points A and B. The differential amplifier generates an output voltage proportional to the difference between the two input voltages (which is, in turn, proportional to the pressure), as shown in Figure 6.4b.

ENGINE CRANKSHAFT ANGULAR POSITION SENSOR

Crankshaft angular position is an important variable in automotive control systems, particularly for controlling ignition timing and fuel injection timing.

Besides pressure, the position of shafts, valves, and levers must be sensed for automotive control systems. Measurements of the angular position or velocity of shafts are common in automotive electronics. It is highly desirable that these measurements be made without any mechanical contact with the rotating shaft. Such noncontacting measurements can be made in a variety of ways, but the commonest of these in automotive electronics use magnetic or optical phenomena as the physical basis. Magnetic means of such measurements are generally preferred in engine applications since they are unaffected by oil, dirt, or other contaminants.

The principles involved in measuring rotating shafts can be illustrated by one of the most significant applications for engine control: the measurement of crankshaft angular position or angular velocity (i.e., RPM). Imagine the engine as viewed from the rear, as shown in Figure 6.5. On the rear of the crankshaft is a large, heavy, circular steel disk called the *flywheel* that is connected to and rotates with the crankshaft. Let's mark a point on the flywheel, as shown in Figure 6.5, and draw a line through this point and the axis of rotation. Let's draw another line through the axis of rotation parallel to the horizontal center line of the engine as a reference line. The crankshaft angular position is the angle between the reference line and the mark on the flywheel.

Imagine that the flywheel is rotated so that the mark is directly on the reference line. This is an angular position of zero degrees. For our purposes, assume that this angular position corresponds to the No. 1 cylinder at TDC (top dead center). As the crankshaft rotates, this angle increases from zero to

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

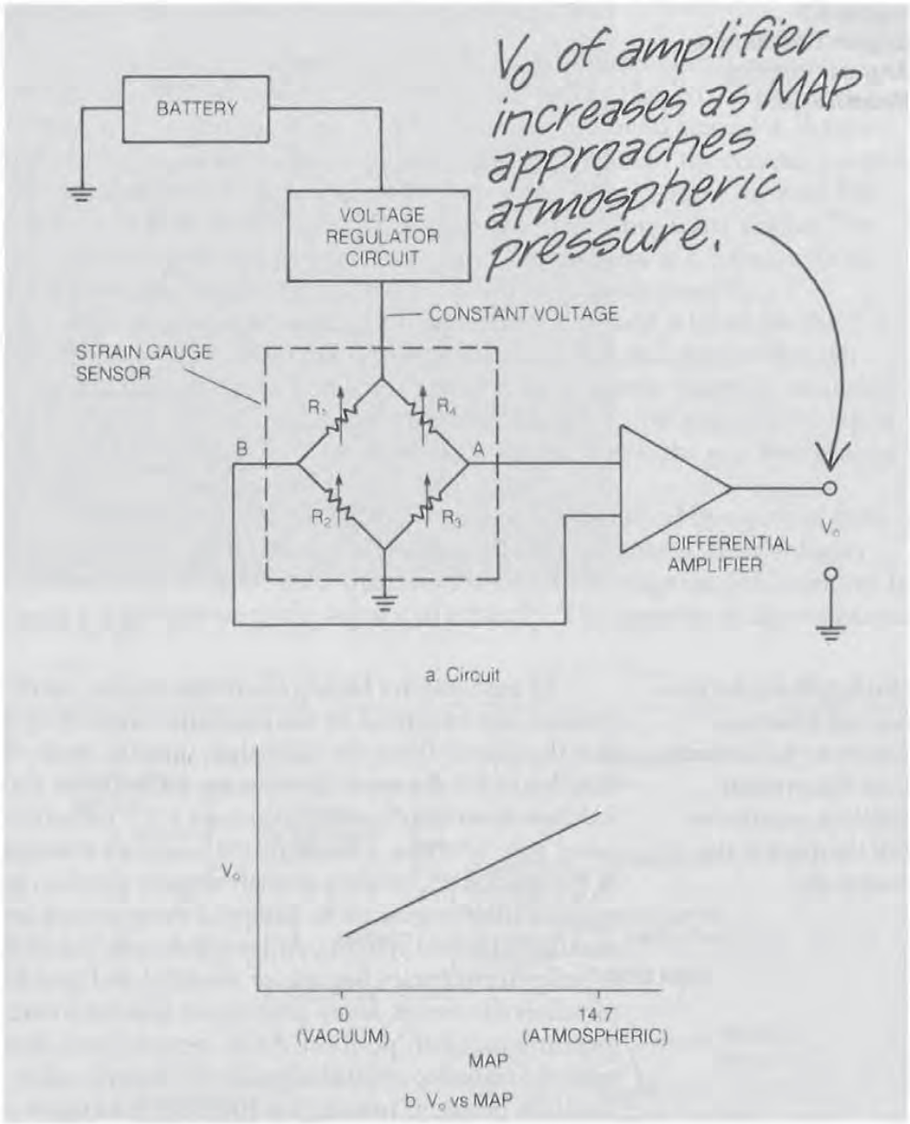
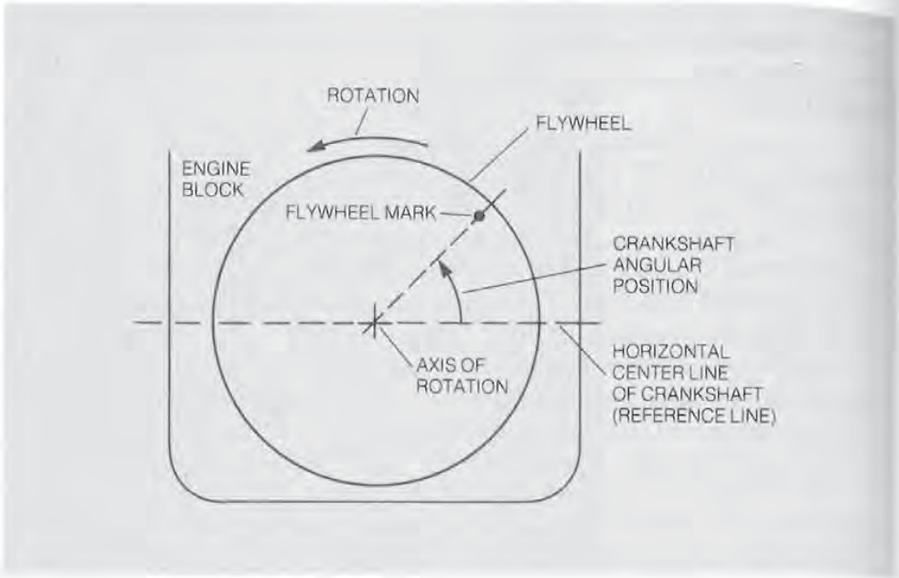


Figure 6.4
Circuit Diagram for MAP Sensor Using Strain Gauges

360° in one revolution. However, one full engine cycle from intake through exhaust requires two complete revolutions of the crankshaft. That is, one complete engine cycle corresponds to the crankshaft angular position going from zero to 720°. During each cycle, it is important to measure the crankshaft position with reference to TDC for each cylinder. This information is used by the electronic engine controller to set ignition timing and, in most cases, to set the fuel injector pulse timing.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Figure 6.5
Engine Crankshaft Angular Position Measurement



Crankshaft angular position can be sensed directly at the camshaft, since the camshaft rotates at exactly one-half the speed of the crankshaft.

In automobiles having electronic engine control systems, angular position can be sensed on the crankshaft directly or on the camshaft. Recall that the piston drives the crankshaft directly, while the valves and the distributor for the spark ignition are driven from the camshaft. The camshaft is driven from the crankshaft through a 1:2 reduction drivetrain, which can be gears, belt, or chain. Therefore, the camshaft rotational speed is one-half that of the crankshaft, so the camshaft angular position goes from zero to 360° for one complete engine cycle. Either of these sensing locations can be used in electronic control systems. Although the crankshaft location is potentially superior for accuracy because of torsional and gear backlash errors in the camshaft drivetrain, many production systems locate this sensor such that it measures camshaft position. At the present time, there appears to be a trend toward measuring crankshaft position directly rather than indirectly via camshaft position. In fact, it is sufficient for engine control purposes to measure crankshaft/camshaft position at a small number of fixed points. The number of such measurements (or samples) is determined by the number of cylinders.

It is desirable to measure engine angular position with a noncontacting sensor to avoid mechanical wear and corresponding changes in accuracy of the measurement. The two most common methods for noncontact coupling to a rotating shaft employ magnetic fields or optics. Let's consider the concepts used for magnetically coupled sensors first.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Magnetic Reluctance Position Sensor

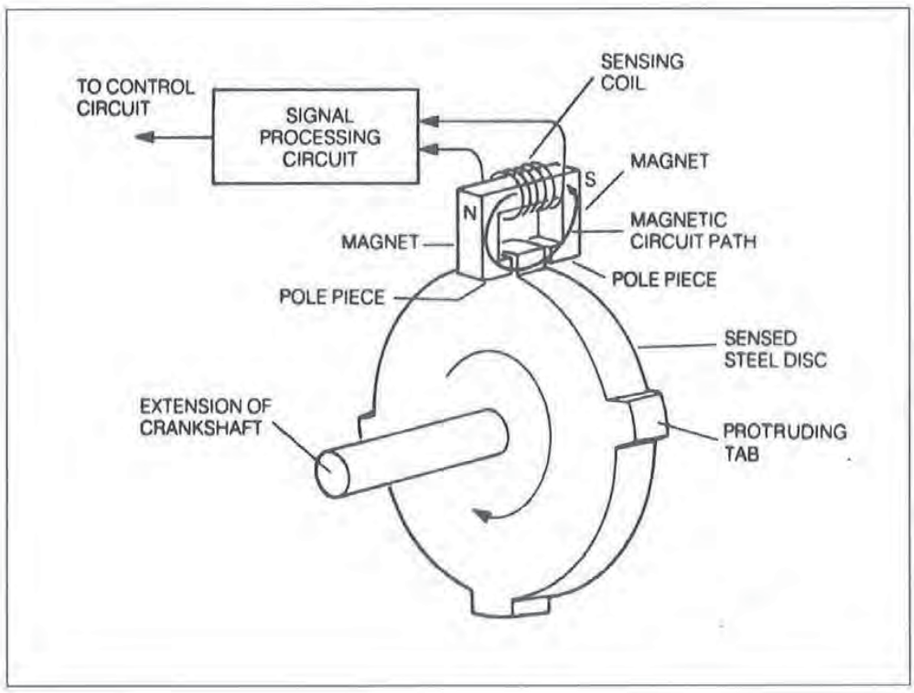
In the magnetic reluctance position sensor, a coil wrapped around the magnet senses the changing intensity of the magnetic field as the tabs of a ferrous disk pass between the poles of the magnet.

One engine sensor configuration that measures crankshaft position directly (using magnetic phenomena) is illustrated in Figure 6.6. This sensor consists of a permanent magnet with a coil of wire wound around it. A steel disk that is mounted on the crankshaft (usually in front of the engine) has tabs that pass between the pole pieces of this magnet. In Figure 6.6, the steel disk has four protruding tabs, which is appropriate for an 8-cylinder engine. The passage of each tab can correspond to the TDC position of a cylinder on its power stroke, although other reference positions are also possible.

This sensor is of the magnetic reluctance type and is based on the concept of a magnetic circuit. A *magnetic circuit* is a closed path through a magnetic material (e.g., iron, cobalt, nickel, or synthetic magnetic material called ferrite). In the case of the sensor in Figure 6.6, the magnetic circuit is the closed path through the magnet material and across the gap between the pole pieces.

The magnetic field in a magnetic circuit is described by a pair of field quantities that can be compared to the voltage and current of an ordinary electric circuit. One of these quantities is called the *magnetic field intensity.* It exerts a force similar to the voltage of a battery. The response of the magnetic

Figure 6.6 Magnetic Reluctance Crankshaft Position Sensor



PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

circuit to the magnetic field intensity is described by the second quantity, which is called *magnetic flux*. A line of constant magnetic flux is a closed path through the magnetic material. The magnetic flux is similar to the current that flows when a resistor is connected across a battery to form a closed electrical circuit.

The voltage generated by the magnetic reluctance position sensor is determined by the strength of the magnetic flux. When a tab on the steel disk passes through the gap, the flow of the magnetic flux changes significantly.

As we shall see, the voltage generated by the reluctance sensor is determined by the strength of this magnetic flux. The strength of the magnetic flux is, in turn, determined by the reluctance of the magnetic circuit. *Reluctance* is to a magnetic circuit what resistance is to an electrical circuit.

The path for the magnetic flux of the reluctance sensor is illustrated in Figure 6.7. The reluctance of a magnetic circuit is inversely proportional to the magnetic permeability of the material along the path. The magnetic permeability of steel is a few thousand times larger than air; therefore, the reluctance of steel is much lower than air. Note that when one of the tabs of the steel disk is located between the pole pieces of the magnet, a large part of the gap between the pole pieces is filled by the steel. Since the steel has a lower reluctance than air, the "flow" of magnetic flux increases to a relatively large value.

On the other hand, when a tab is not between the magnet pole pieces, the gap is filled by air only. This creates a high-reluctance circuit for which the magnetic flux is relatively small. Thus, the magnitude of the magnetic flux that "flows" through the magnetic circuit depends on the position of the tab, which, in turn, depends on the crankshaft angular position.

The magnetic flux is least when none of the tabs is near the magnet pole pieces. As a tab begins to pass through the gap, the magnetic flux increases. It

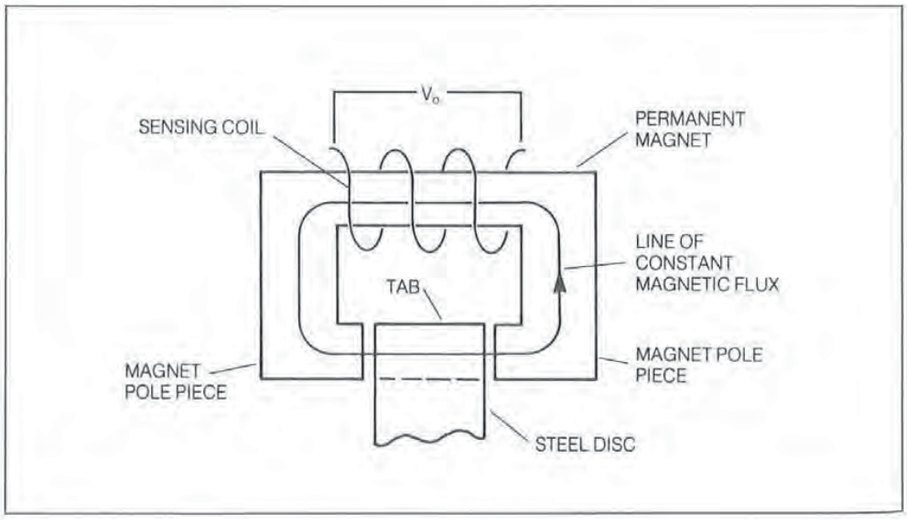


Figure 6.7 Magnetic Circuit of the Reluctance Sensor

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

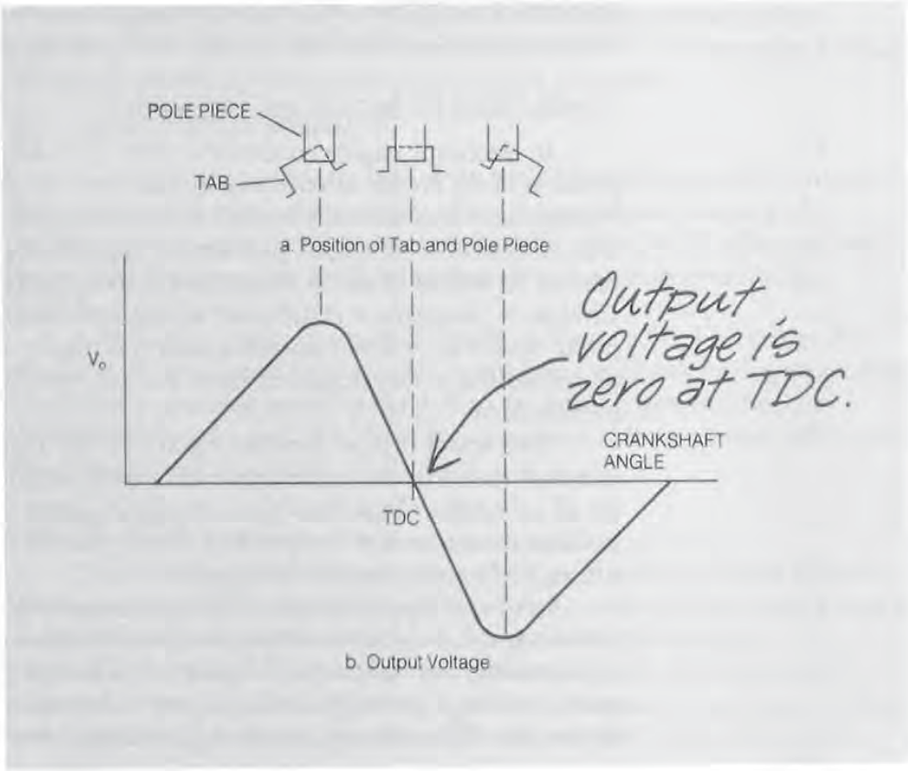
reaches a maximum when the tab is exactly between the pole pieces, and then decreases as the tab passes out of the pole piece region. In most control systems, the position of maximum magnetic flux has a fixed relationship to TDC for one of the cylinders.

The voltage induced in the sensing coil varies with the rate of change of the magnetic flux. When the tab is centered between the poles of the magnet, the voltage is zero because the flux is not changing.

The *change in magnetic flux* induces a voltage, V_o, in the sensing coil that is proportional to the *rate of change* of the magnetic flux. Since the magnetic flux must be changing to induce a voltage in the sensing coil, its output voltage is zero whenever the engine is not running, regardless of the position of the crankshaft. This is a serious disadvantage for this type of sensor because the engine timing cannot be set statically.

As shown in Figure 6.8, the coil voltage, V_o, begins to increase from zero as a tab begins to pass between the pole pieces, reaches a maximum, then falls to zero when the tab is exactly between the pole pieces (see Figure 6.8a). (Note that although the value of magnetic flux is maximum at this point, the rate of change of magnetic flux is zero; therefore, the induced voltage in the sensing coil is zero.) Then it increases with the opposite polarity, reaches a maximum, and falls to zero as the tab passes out of the gap between the pole pieces. The coil voltage waveform shown in Figure 6.8b occurs each time one of the

Figure 6.8 Output Voltage Waveform from the Magnetic Reluctance Crankshaft Position Sensor Coil



PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

cylinders reaches TDC on its power stroke. It should be noted that if the disk is mounted on the crankshaft, then the number of tabs for this crankshaft position sensor always will be half the number of cylinders because it takes two crankshaft rotations for a complete engine cycle.

Engine Speed Sensor

Engine speed can be calculated in a number of ways. Digital circuits use counters and crankshaft sensors to calculate actual engine speed.

An engine speed sensor is needed to provide an input for the electronic controller for several functions. The position sensor discussed previously can be used to measure engine speed. The reluctance sensor is used in this case as an example; however, any of the other position sensor techniques could be used as well. Refer to Figure 6.6 and notice that the four tabs will pass through the sensing coil once for each crankshaft revolution. Therefore, if we count the pulses of voltage from the sensing coil in one minute and divide by four, we will know the engine speed in revolutions per minute (RPM).

This is easy to do with digital circuits. Precise timing circuits such as those used in digital watches can start a counter circuit that will count pulses until the timing circuit stops it. The counter can have the divide-by-four function included in it, or a separate divider circuit may be used. In many cases, the actual RPM sensor disk is mounted near the flywheel and has many more than four tabs; in such cases, the counter does not actually count for a full minute before the speed is calculated, but the results are the same.

Timing Sensor for Ignition and Fuel Delivery

In electronic engine control it is often desirable to measure the angular position of the engine relative to a specific point in the cycle. For such measurement it is normally necessary to measure the position of the camshaft. The measurement of engine position via crankshaft and camshaft position sensors (as well as its use in timing fuel delivery and ignition) is described in Chapter 7. Normally it is sufficient to measure camshaft position at a fixed point. Such a sample of camshaft position is readily achieved by a magnetic sensor similar to that described above for the crankshaft position measurement.

This sensor detects a reference point on the angular position of the camshaft that defines a beginning to a complete engine cycle (e.g., power stroke for all cylinders). Once this reference point has been detected, crankshaft position measurements (as described above) provide sufficient information for timing fuel injection pulses and ignition.

In one scheme a variable-reluctance sensor is located near a ferromagnetic disk on the camshaft. This disk has a notch cut (or it can have a protruding tab), as shown in Figure 6.9. The disk provides a low-reluctance path (yielding high magnetic flux) except when the notch aligns with the sensor axis. Whenever the notch aligns with the sensor axis, the reluctance of

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

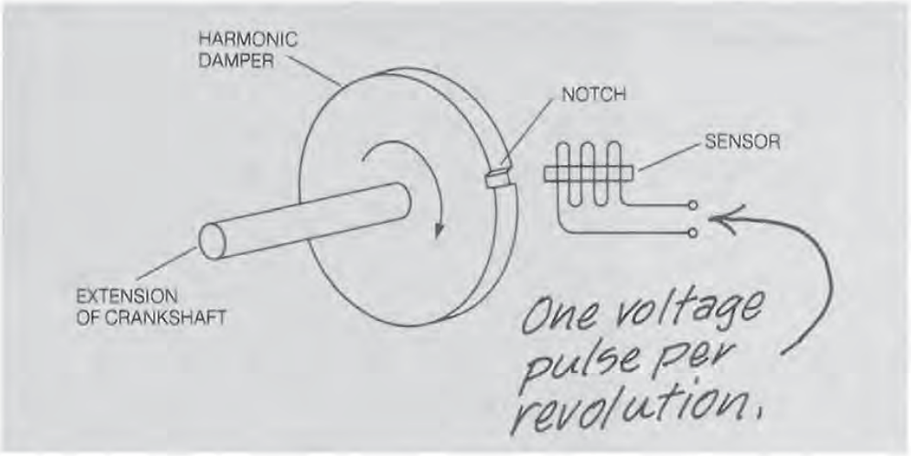


Figure 6.9 Crankshaft Position Sensor

The notched position sensor uses an effect opposite to that of the tab position sensor. As a notch in a rotating steel disk passes by a variable-reluctance sensor, the decrease in magnetic flux generates a voltage pulse in the sensor coil.

this magnetic path is increased because the permeability of air in the notch is very much lower than the permeability of the disk. This relatively high reluctance through the notch causes the magnetic flux to decrease and produces a change in sensor output voltage.

As the camshaft rotates, the notch passes under the sensor once for every two crankshaft revolutions. The magnetic flux abruptly decreases, then increases as the notch passes the sensor. This generates a voltage pulse that can be used in electronic control systems for timing purposes.

Hall-Effect Position Sensor

As mentioned previously, one of the main disadvantages of the magnetic reluctance sensor is its lack of output when the engine isn't running. A crankshaft position sensor that avoids this problem is the Hall-effect position sensor. This sensor can be used to measure either camshaft position or crankshaft position.

A Hall-effect position sensor is shown in Figure 6.10. This sensor is similar to the reluctance sensor in that it employs a steel disk having protruding tabs and a magnet for coupling the disk to the sensing element. Another similarity is that the steel disk varies the reluctance of the magnetic path as the tabs pass between the magnet pole pieces.

The Hall element is a thin slab of semiconductor material that is placed between the magnets so it can sense the magnetic flux variations as the tab passes. A constant current is passed through the semiconductor in one direction, and a voltage is generated that varies with the strength of the magnetic flux.

The Hall Effect

The Hall element is a small, thin, flat slab of semiconductor material. When a current, *I*, is passed through this slab by means of an external circuit as shown in Figure 6.11a, a voltage is developed across the slab perpendicular to the direction of current flow and perpendicular to the direction of magnetic flux. This voltage is proportional to both the current and magnetic flux density that flows through the slab. This effect—the

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

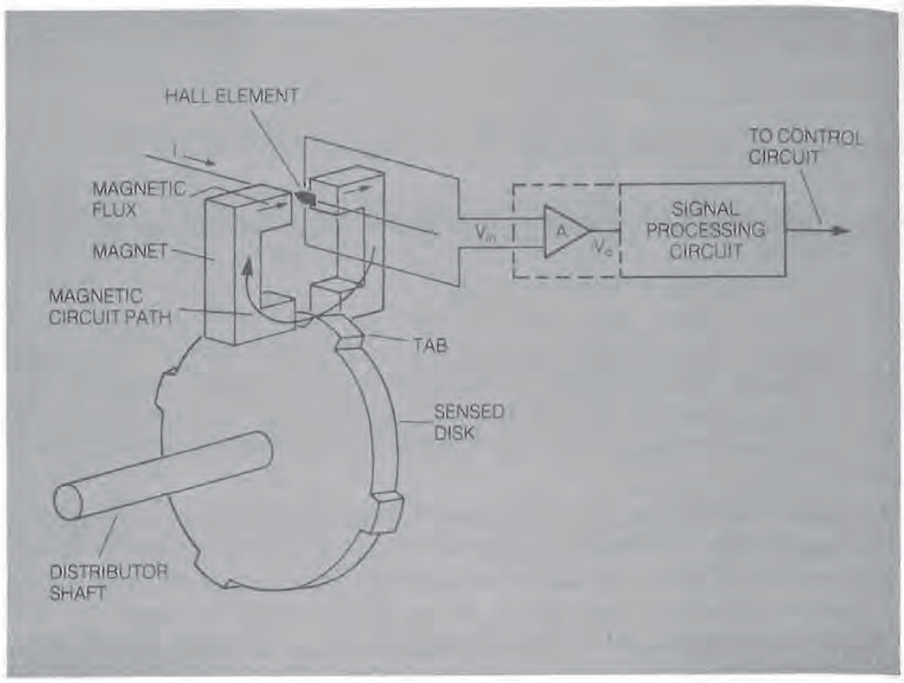


Figure 6.10
Hall-Effect Position Sensor

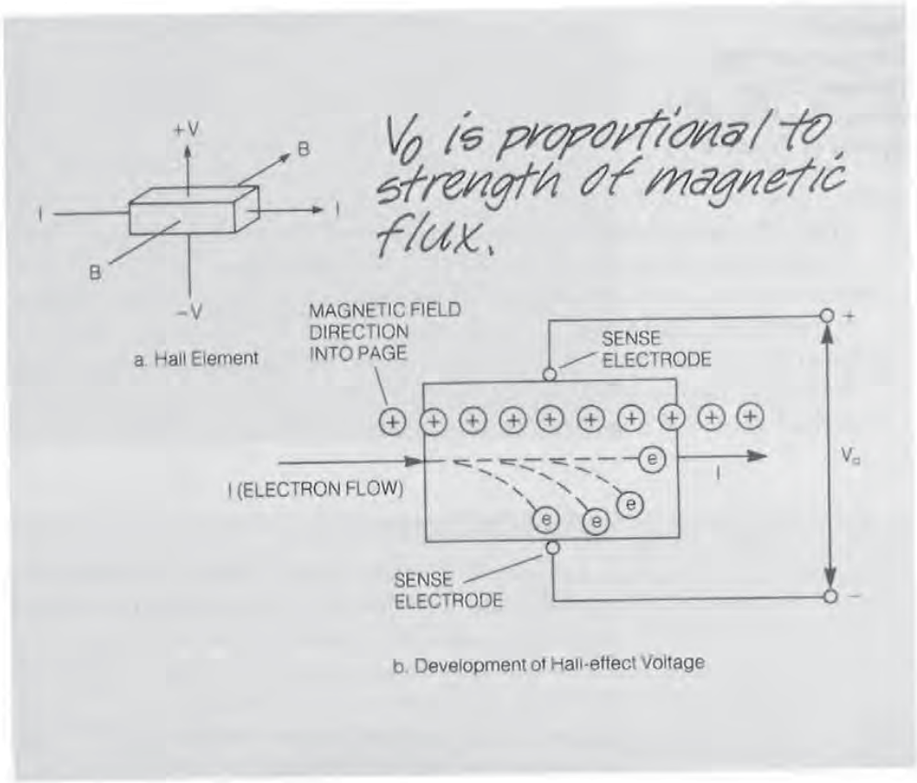
generation of a voltage that is dependent on a magnetic field—is called the *Hall effect.*

In Figure 6.11b, the current, *I*, is represented by electrons, *e*, which have negative charge, flowing from left to right. The magnetic flux flows along the legs of the magnet as indicated and is generally perpendicular to the face of the semiconductor Hall element. Whenever an electron moves through a magnetic field, a force (called the *Lorentz force*) that is proportional to the electron velocity and the strength of the magnetic flux is exerted on the electron. The direction of this force is perpendicular to the direction in which the electron is moving. In Figure 6.11b, the Lorentz force direction is such that the electrons are deflected toward the lower sense electrode. Thus, this electrode is more negative than the upper electrode and a voltage exists between the electrodes, having the polarity shown in Figure 6.11b.

As the strength of the magnetic flux density increases, more of the electrons are deflected downward. If the current, *I*, is held constant, then the voltage, V_o, is proportional to the strength of the magnetic flux density, which, in turn, is determined by the position of the tabs. This voltage tends to be relatively weak so it is amplified, as shown in Figure 6.10.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Figure 6.11
The Hall Effect



Output Waveform

It was shown in the discussion of the reluctance crankshaft position sensor that the magnetic flux density for this configuration depends on the position of the tab. Recall that the magnetic flux is largest when one of the tabs is positioned symmetrically between the magnet pole pieces and that this position normally corresponds closely to TDC of one of the cylinders.

Because the Hall-effect sensor produces the same output voltage waveform regardless of engine speed, the engine timing can be set when the engine is not running.

The voltage waveform V_o that is produced by the Hall element in the position sensor of Figure 6.10 is illustrated in Figure 6.12. Since V_o is proportional to the magnetic flux density, it reaches maximum when any of the tabs is symmetrically located between the magnet pole pieces (corresponding to TDC of a cylinder). If the disk is driven by the camshaft, then the disk must have as many tabs as the engine has cylinders. Therefore, the disk shown would be for a 4-cylinder engine. It is important to realize that voltage output versus crankshaft angle is independent of engine speed. Thus, this sensor can be used for setting the engine timing when the engine is not running (e.g., when it is being motored at the end of an assembly line).

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

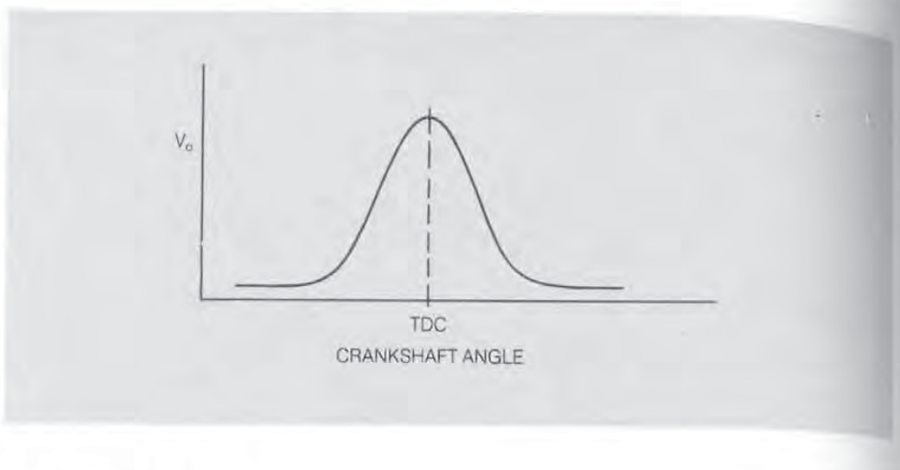


Figure 6.12 Waveform of Hall Element Output Voltage for Position Sensor of Figure 6.10

Shielded-Field Sensor

Figure 6.13 shows another concept that uses the Hall-effect element in a way different from that just discussed. In this method, the Hall element is normally exposed to a magnetic field and produces an output voltage. When one of the tabs passes between the magnet and the sensor element, the low reluctance of the tab and disk provides a path for the magnetic flux that bypasses the Hall-effect sensor element, and the sensor output drops to near zero. Note in Figure 6.13b that the waveform is just the opposite of the one in Figure 6.12.

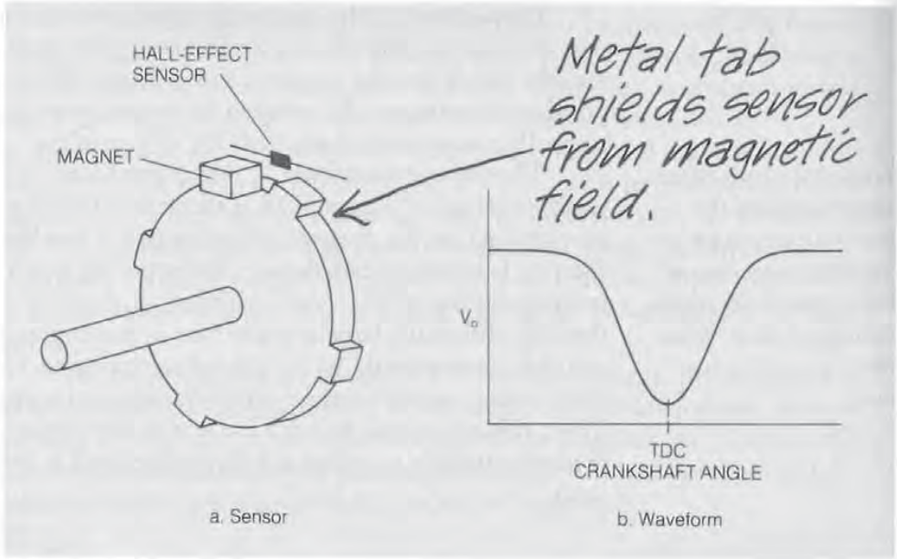


Figure 6.13 Hall-Effect Position Sensor That Shields the Magnetic Circuit

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

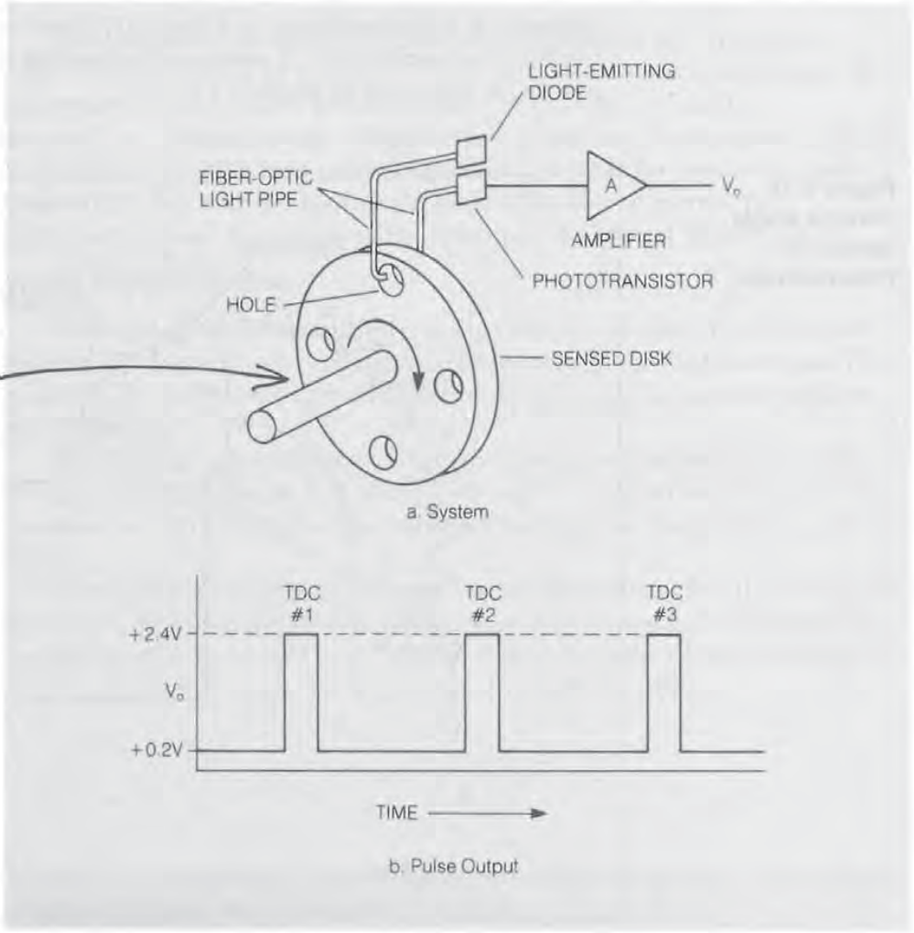
Optical Crankshaft Position Sensor

In the optical crankshaft position sensor, a disk coupled to the crankshaft has holes to pass light between the LED and the phototransistor. An output pulse is generated as each hole passes the LED.

In a sufficiently clean environment a shaft position can also be sensed using optical techniques. Figure 6.14 illustrates such a system. Again, as with the magnetic system, a disk is directly coupled to the crankshaft. This time, the disk has holes in it that correspond to the number of tabs on the disks of the magnetic systems. Mounted on each side of the disk are fiber-optic light pipes. The hole in the disk allows transmission of light through the light pipes from the light-emitting diode (LED) source to the phototransistor used as a light sensor. Light would not be transmitted from source to sensor when there is no hole because the solid disk blocks the light. As shown in Figure 6.14, the pulse of light is detected by the phototransistor and coupled to an amplifier to obtain a satisfactory signal level. The output pulse level can very easily be standard transistor logic levels of +2.4 V for the high level

Figure 6.14
Optical Position Sensor

Rotation of disk causes alternate blocking and transmission of light.



PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

and +0.8 V for the low level. Used as pulses, the signals provide time-referenced pulses that can be signal processed easily with digital integrated circuits.

One of the problems with optical sensors is that they must be protected from dirt and oil; otherwise, they will not work properly. They have the advantages that they can sense position without the engine running and that the pulse amplitude is constant with variation in speed.

THROTTLE ANGLE SENSOR

Still another variable that must be measured for electronic engine control is the throttle plate angular position. As explained in Chapter 1, the throttle plate is linked mechanically to the accelerator pedal. When the driver depresses the accelerator pedal, this linkage causes the throttle plate angle to increase, allowing more air to enter the engine and thereby increasing engine power.

Measurement of the instantaneous throttle angle is important for control purposes, as will be explained in Chapter 7. Most throttle angle sensors are essentially potentiometers. A *potentiometer* consists of a resistor with a movable contact, as illustrated in Figure 6.15.

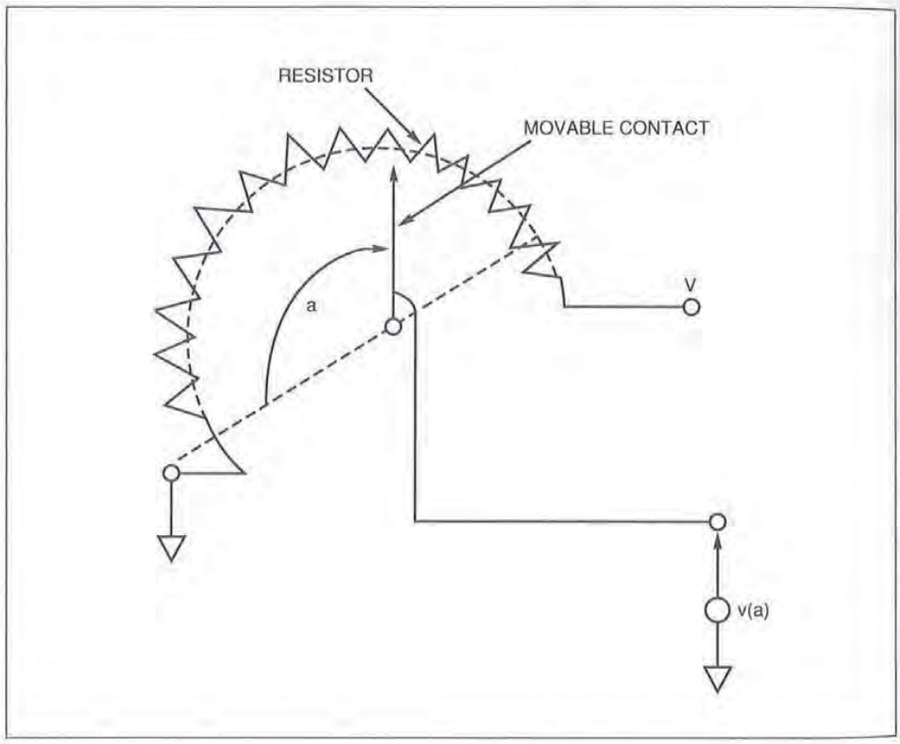


Figure 6.15 Throttle Angle Sensor: A Potentiometer

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

A section of resistance material is placed in an arc around the pivot axis for the movable contact. One end of the resistor is connected to ground, the other to a fixed voltage V (e.g., 5 volts). The voltage at the contact point of the movable contact is proportional to the angle (a) from the ground contact to the movable contact. Thus,

$$v(a) = ka$$

where $v(a)$ is the voltage at the contact point, k is a constant, and a is the angle of the contact point from the ground connection.

This potentiometer can be used to measure any angular rotation. In particular, it is well suited for measuring throttle angle. The only disadvantage to the potentiometer for automotive applications is its analog output. For digital engine control, the voltage $v(a)$ must be converted to digital format using an analog-to-digital converter.

TEMPERATURE SENSORS

Temperature is an important parameter throughout the automotive system. In operation of an electronic fuel control system it is vital to know the temperature of the coolant, the temperature of the inlet air, and the temperature of the exhaust gas oxygen sensor (a sensor to be discussed in the next section). Several sensor configurations are available for measuring these temperatures, but we can illustrate the basic operation of most of the temperature sensors by explaining the operation of a typical coolant sensor.

Typical Coolant Sensor

One kind of coolant sensor uses a temperature-sensitive semiconductor called a *thermistor.* The sensor is typically connected as a varying resistance across a fixed reference voltage. As the temperature increases, the output voltage decreases.

A typical coolant sensor, shown in Figure 6.16, consists of a thermistor mounted in a housing that is designed to be inserted in the coolant stream. This housing is typically threaded with pipe threads that seal the assembly against coolant leakage.

A *thermistor* is made of semiconductor material whose resistance varies inversely with temperature. For example, at –40°C a typical coolant sensor has a resistance of 100,000 ohms. The resistance decreases to about 70,000 ohms at 130°C.

The sensor is typically connected in an electrical circuit like that shown in Figure 6.17, in which the coolant temperature sensor resistance is denoted R_T. This resistance is connected to a reference voltage through a fixed resistance R. The sensor output voltage, V_T, is given by the following equation:

$$V_T = V\frac{R_T}{R + R_T}$$

The sensor output voltage varies inversely with temperature; that is, the output voltage decreases as the temperature increases.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

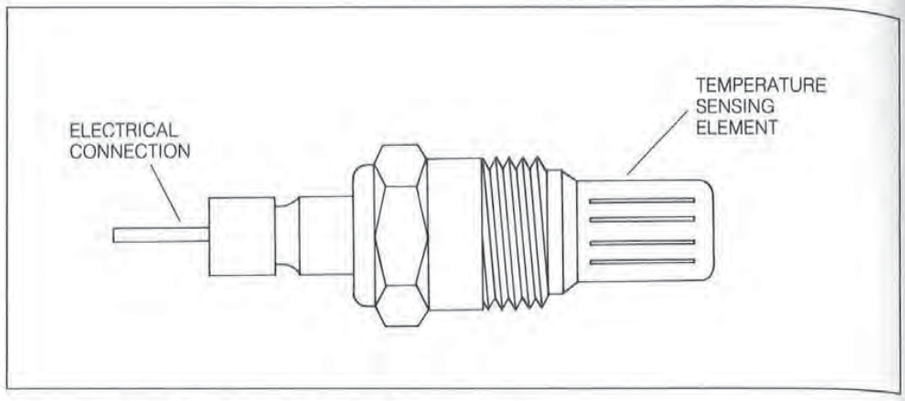


Figure 6.16
Coolant Temperature Sensor

SENSORS FOR FEEDBACK CONTROL

The sensors that we have discussed to this point have been part of the open-loop (i.e., feedforward) control. We consider next sensors that are appropriate for feedback engine control. Recall from Chapter 5 that feedback control for fuel delivery is based on maintaining the air/fuel ratio at stoichiometry (i.e., 14.7:1). The primary sensor for fuel control is the exhaust gas oxygen sensor.

Exhaust Gas Oxygen Sensor

Recall from Chapter 5 that the amount of oxygen in the exhaust gas is used as an indirect measurement of the air/fuel ratio. As a result, one of the most significant automotive sensors in use today is the exhaust gas oxygen (EGO) sensor. This sensor is often called a *lambda sensor* from the Greek letter lambda (λ), which is commonly used to denote the equivalence ratio:

$$\lambda = \frac{(\text{air/fuel})}{(\text{air/fuel at stoichiometry})}$$

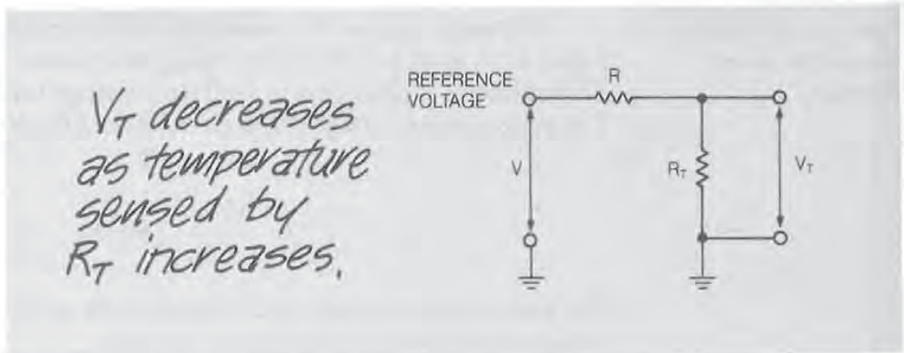


Figure 6.17
Typical Coolant Temperature Sensor Circuit

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Whenever the air/fuel ratio is at stoichiometry the value for λ is 1. When the air–fuel mixture is too lean, the condition is represented by lambda greater than one (denoted $\lambda > 1$). Conversely, when the air–fuel mixture is too rich, the condition is represented by an equivalence ratio of lambda less than one ($\lambda < 1$).

The two types of EGO sensors that have been used are based on the use of active oxides of two types of materials. One uses zirconium dioxide (ZrO_2) and the other uses titanium dioxide (TiO_2). The former is the most commonly used type today. Figure 6.18 is a photograph of a typical ZrO_2 EGO sensor and Figure 6.19 shows the physical structure. Figure 6.18 indicates that a voltage, V_o, is generated across the ZrO_2 material. This voltage depends on the exhaust gas oxygen concentration, which in turn depends on the engine air/fuel ratio.

The zirconium dioxide EGO sensor uses zirconium dioxide sandwiched between two platinum electrodes. One electrode is exposed to exhaust gas and the other is exposed to normal air for reference.

In essence, the EGO sensor consists of a thimble-shaped section of ZrO_2 with thin platinum electrodes on the inside and outside of the ZrO_2. The inside electrode is exposed to air, and the outside electrode is exposed to exhaust gas through a porous protective overcoat.

A simplified explanation of EGO sensor operation is based on the distribution of oxygen ions. An *ion* is an electrically charged atom. Oxygen ions have two excess electrons and each electron has a negative charge; thus, oxygen ions are negatively charged. The ZrO_2 has a tendency to attract the oxygen ions, which accumulate on the ZrO_2 surface just inside the platinum electrodes.

The platinum plate on the air reference side of the ZrO_2 is exposed to a much higher concentration of oxygen ions than the exhaust gas side. The air reference side becomes electrically more negative than the exhaust gas side; therefore, an electric field exists across the ZrO_2 material and a voltage, V_o, results. The polarity of this voltage is positive on the exhaust gas side and negative on the air reference side of the ZrO_2. The magnitude of this voltage depends on the concentration of oxygen in the exhaust gas and on the sensor temperature.

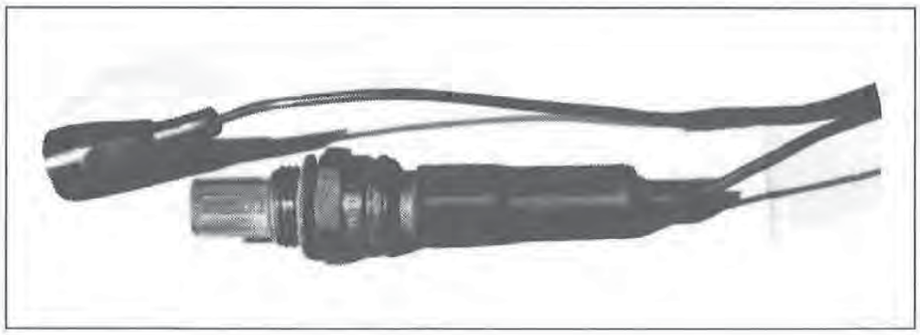
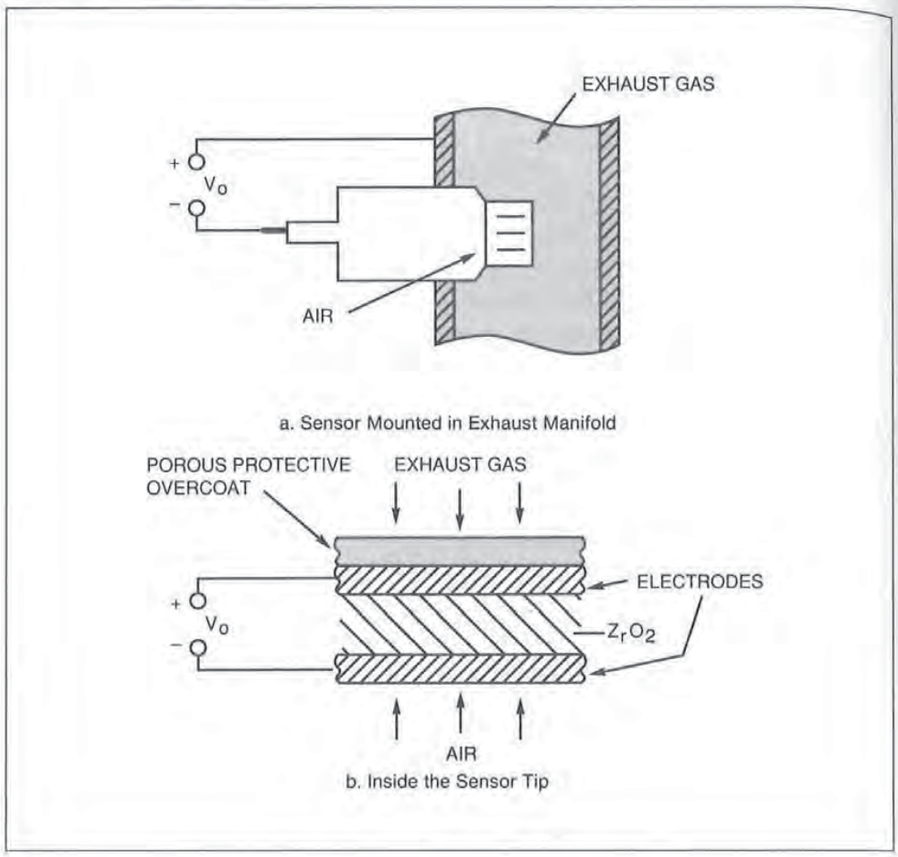


Figure 6.18 Zirconium Dioxide (ZrO_2) EGO Sensor

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Figure 6.19
EGO Mounting and Structure



Because the exhaust contains fewer oxygen ions than air, the "air" electrode becomes negative with respect to the "exhaust" electrode.

The quantity of oxygen in the exhaust gas is represented by the oxygen partial pressure. Basically, this partial pressure is that proportion of the total exhaust gas pressure (nearly at atmospheric pressure) that is due to the quantity of oxygen. The exhaust gas oxygen partial pressure for a rich mixture varies over the range of 10^{-16} to 10^{-32} of atmospheric pressure. The oxygen partial pressure for a lean mixture is roughly 10^{-2} atmosphere. Consequently, for a rich mixture there is a relatively low oxygen concentration in the exhaust and a higher EGO sensor output. Correspondingly, for a lean mixture the exhaust gas oxygen concentration is relatively high (meaning that the difference between exhaust gas and atmospheric oxygen concentrations is lower), resulting in a relatively low EGO sensor output voltage. For a fully warmed EGO sensor the output voltage is about 1 volt for a rich mixture and about .1 volt for a lean mixture.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

An *ideal* EGO sensor would have an abrupt, rapid, and significant change in output voltage as the mixture passes through stoichiometry. The output voltage would not change as exhaust gas temperature changes.

Hysteresis is the difference in the switching point of the output voltage with respect to stoichiometry as a mixture passes from lean to rich, as contrasted to a mixture that passes from rich to lean.

Desirable EGO Characteristics

The EGO sensor characteristics that are desirable for the type of limit-cycle fuel control system that was discussed in Chapter 5 are as follows:

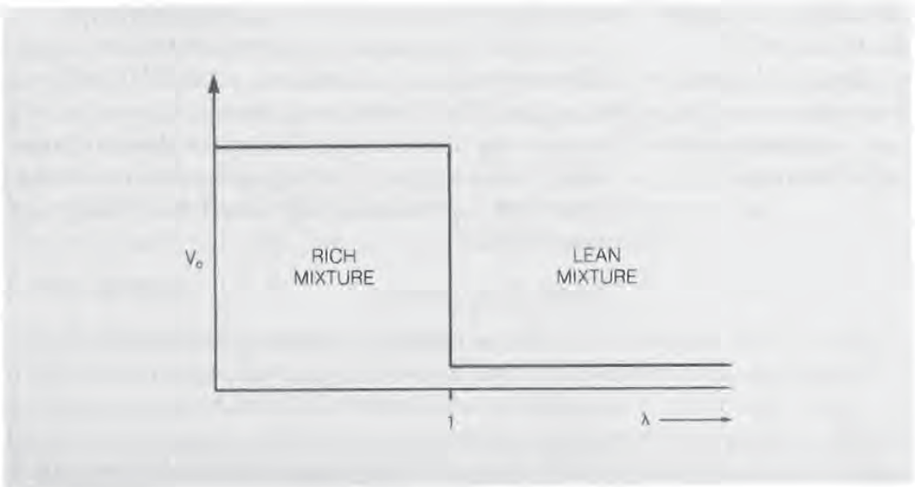
1. Abrupt change in voltage at stoichiometry
2. Rapid switching of output voltage in response to exhaust gas oxygen changes
3. Large difference in sensor output voltage between rich and lean mixture conditions
4. Stable voltages with respect to exhaust temperature

Switching Characteristics

The switching time for the EGO sensor also must be considered in control applications. An ideal characteristic for a limit-cycle controller is shown in Figure 6.20. The actual characteristics of a new EGO sensor are shown in Figure 6.21. This data was obtained by slowly varying air/fuel ratios across stoichiometry. The arrow pointing down indicates the change in V_o as the air/fuel ratio was varied from rich to lean. The up arrow indicates the change in V_o as the air/fuel ratio was varied from lean to rich. Note that the sensor output doesn't change at exactly the same point for increasing air/fuel ratio as for decreasing air/fuel ratio. This phenomenon is called *hysteresis*.

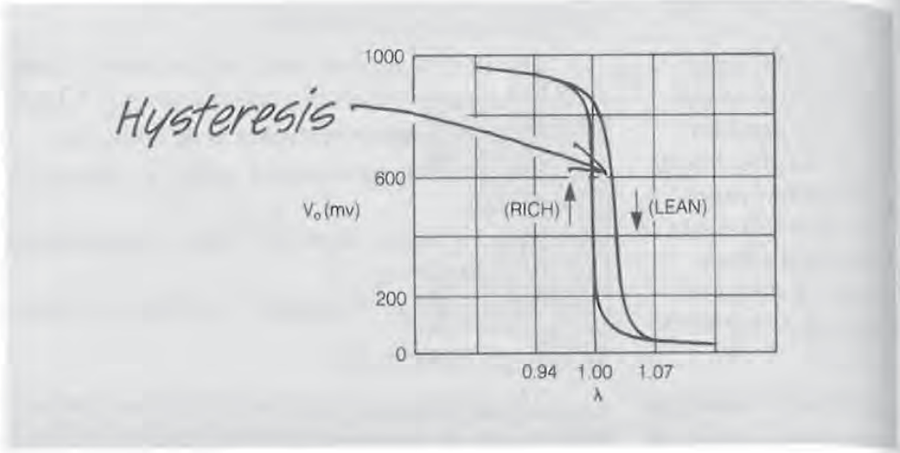
Temperature affects switching times and output voltage. Switching times at two temperatures are shown in Figure 6.22. Note that the time per division is twice as much for the display at 350°C as at 800°C. This means that the switching times are roughly 0.1 second at 350°C, whereas at 800°C they are

Figure 6.20 Ideal EGO Switching Characteristics



PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Figure 6.21
Typical EGO Sensor Characteristics



about 0.05 second. This is a 2:1 change in switching times due to changing temperature.

The temperature dependence of the EGO sensor output voltage is very important. The graph in Figure 6.23 shows the temperature dependence of an EGO sensor output voltage for lean and rich mixtures and for two different load resistances—5 megohms (5 million ohms) and 0.83 megohm. The EGO sensor output voltage for a rich mixture is in the range of about 0.80 to 1.0 volt for an exhaust temperature range of 350°C to 800°C. For a lean mixture, this voltage is roughly in the range of 0.05 to 0.07 volt for the same temperature range.

EGO sensors are not used for control when exhaust gas temperature falls below 300°C because the voltage difference between rich and lean conditions is minimal in this range.

Under certain conditions, the fuel control using an EGO sensor will be operated in open-loop mode and for other conditions it will be operated in closed-loop mode (as will be explained in Chapter 7). The EGO sensor should not be used for control at temperatures below about 300°C because the difference between rich and lean voltages decreases rapidly with temperature in this region. This important property of the sensor is partly responsible for the requirement to operate the fuel control system in the open-loop mode at low exhaust temperature. Closed-loop operation with the EGO output voltage used as the error input cannot begin until the EGO sensor temperature exceeds about 300°C.

Heated EGO Sensors

The increasingly stringent exhaust emission requirements for automobiles in the 1990s have forced automakers to shorten the time from engine start to the point at which the EGO sensor is at operating temperature. This requirement has led to the development of the heated exhaust gas oxygen (HEGO) sensor. This sensor is electrically heated from start-up until it yields an output signal of sufficient magnitude to be useful in closed-loop control.

VW EX1019 (Part 2 of 2)
U.S. Patent No. 6,581,565

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

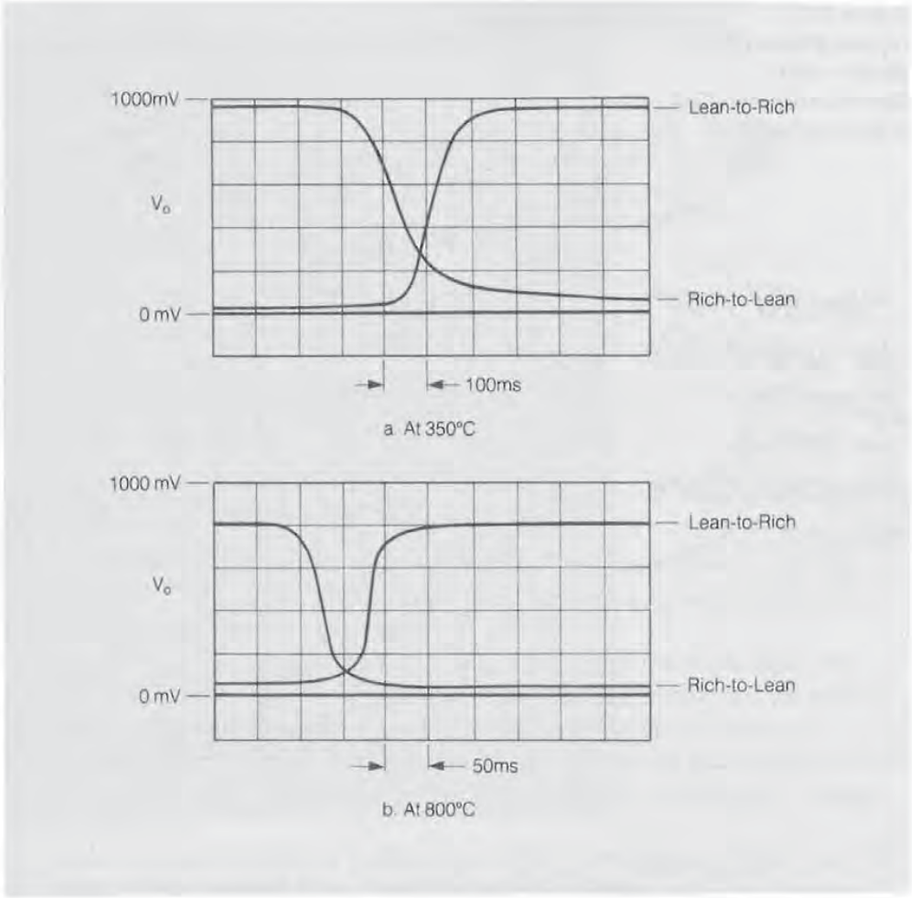


Figure 6.22 Typical Voltage Switching Characteristics of EGO Sensor

The HEGO sensor includes a section of resistance material. Electrical power from the car battery is applied at start-up, which quickly warms the sensor to usable temperatures. This heating potentially shortens the time interval until closed-loop operation is possible, thereby minimizing the time during warm-up that air/fuel ratio deviates from stoichiometry and correspondingly reducing undesirable exhaust gas emissions.

Knock Sensors

Another sensor having applications in closed-loop engine control is the so-called knock sensor. As explained in Chapter 7, this sensor is employed in closed-loop ignition timing to prevent undesirable knock. Although a more detailed explanation of knock is given in Chapter 7, for the purposes of this chapter it can be described generally as a rapid rise in cylinder pressure during combustion. It does not occur normally, but only under special conditions. It

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

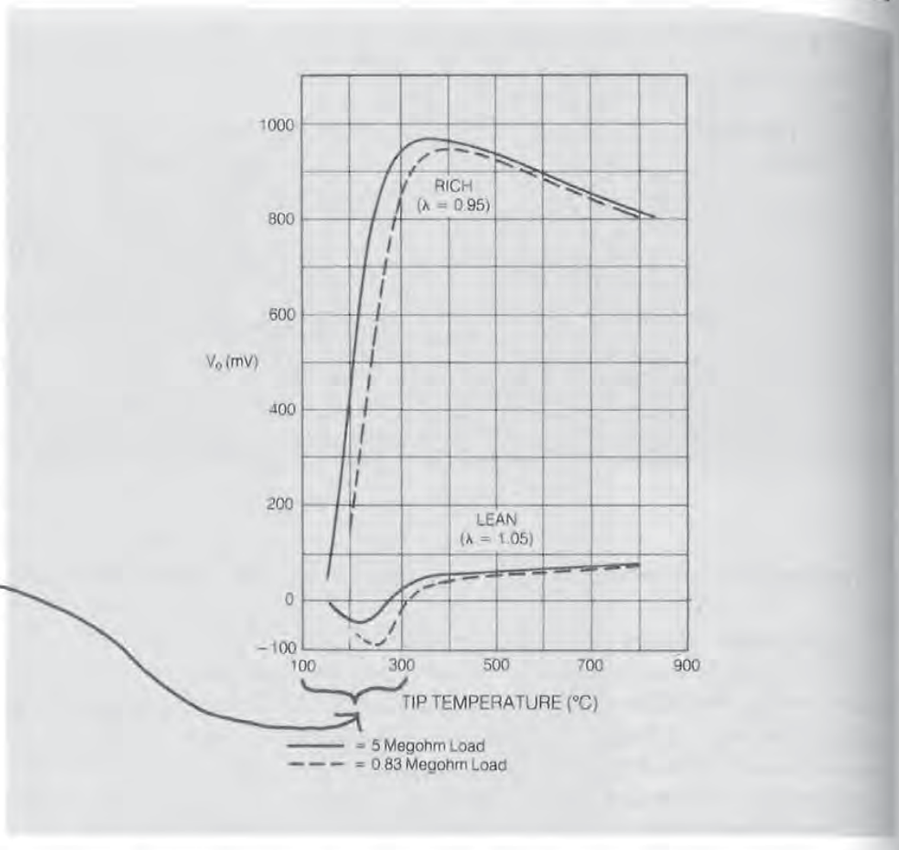


Figure 6.23
Typical Influence of Mixture and Temperature on EGO Output Voltage

Should not be used for control in this temperature range.

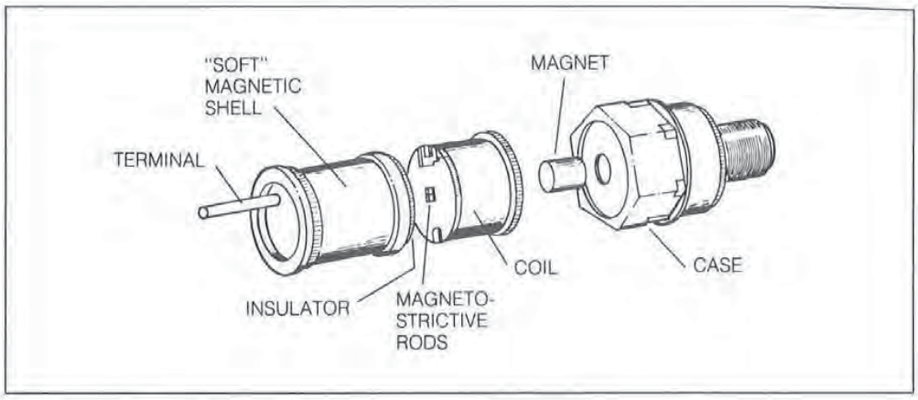
occurs most commonly with high manifold pressure and excessive spark advance. It is important to detect knock and avoid excessive knock; otherwise, there may be damage to the engine.

Some engine knock sensors use rods within a magnetic field to detect the presence of knock. Other use vibration-sensitive crystals or semiconductors.

One way of controlling knocking is to sense when knocking begins and then retard the ignition until the knocking stops. A key to the control loop for this method is a knock sensor. A knock sensor using magnetostrictive techniques is shown in Figure 6.24. *Magnetostriction* is a phenomenon whereby the magnetic properties of a material depend on stress (due to an applied force). When sensing knock, the magnetostrictive rods, which are in a magnetic field, change the flux field in the coil due to knock-induced forces. This change in flux produces a voltage change in the coil. This voltage is used to sense excessive knock (see Chapter 7). Other sensors use piezoelectric crystals or the piezoresistance of a doped silicon semiconductor. Whichever type of sensor is used, it forms a closed-loop system that retards the ignition to reduce the knock detected at the cylinders. Systems using knock sensors are explained in Chapter 7. The problem of detecting knock is complicated by the presence of other vibrations and noises in the engine.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Figure 6.24
Knock Sensor



AUTOMOTIVE ENGINE CONTROL ACTUATORS

In addition to the set of sensors, electronic engine control is critically dependent on a set of actuators to control air/fuel ratio, ignition, and EGR. Each of these devices will be discussed separately.

In general, an actuator is a device that receives an electrical input (e.g., from the engine controller) and produces a mechanical or thermal (or other) output. Examples of actuators include: various types of electric motors, solenoids, and piezoelectric force generators. In automotive electronic systems the solenoid is the most commonly used device because it is relatively simple and inexpensive.

The solenoid is used in applications ranging from precise fuel control to mundane applications such as electric door locks. A solenoid is in essence a powerful electromagnet having a configuration generally similar to that illustrated in Figure 6.25. The solenoid consists of a fixed steel (i.e., ferromagnetic) frame with a movable steel element. A spring holds the movable element in position such that there is a gap between the end of the movable element and the opening in the frame. A coil is wound around the steel frame, forming a powerful electromagnet.

When a current passes through the coil, a magnetic field is created that tends to pull the movable element toward the steel frame. When the magnetic field, which is proportional to the current, is sufficient to overcome the force at the spring holding the movable element, then it begins to move toward the frame. As this element moves, the size of the gap is reduced, causing an increase in the strength of the magnetic field. This increase causes the movable element to accelerate toward the frame until it reaches the stop.

This abrupt motion of the movable element is essentially in the form of a mechanical switching action such that the solenoid tends to be either in its rest position (as held by the spring) or against the mechanical stop. The movable

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

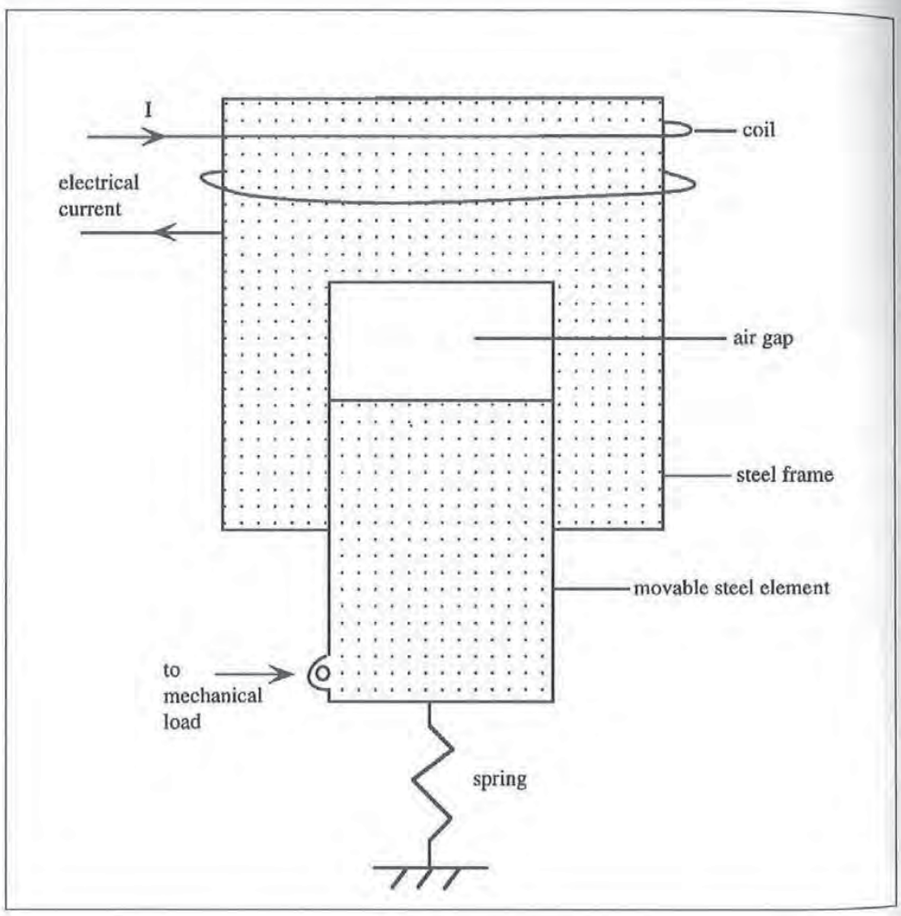
element is typically connected to a mechanism that is correspondingly moved by the snap action of this element. Applications of solenoids in automotive electronics include fuel injectors and EGR valves.

Fuel Injection

A fuel injector is (in essence) a solenoid-operated valve. The valve opens or closes to permit or block fuel flow to the engine. The valve is attached to the movable element of the solenoid and is switched by the solenoid activation (Figure 6.25).

In a fuel injector with no current flowing, the solenoid movable element is held down against the stop, covering the aperture or nozzle. Fuel is thereby blocked from flowing from the pressurized fuel chamber into the aperture. When current flows through the solenoid coil, the movable element is switched

Figure 6.25 Schematic Drawing of a Solenoid



PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

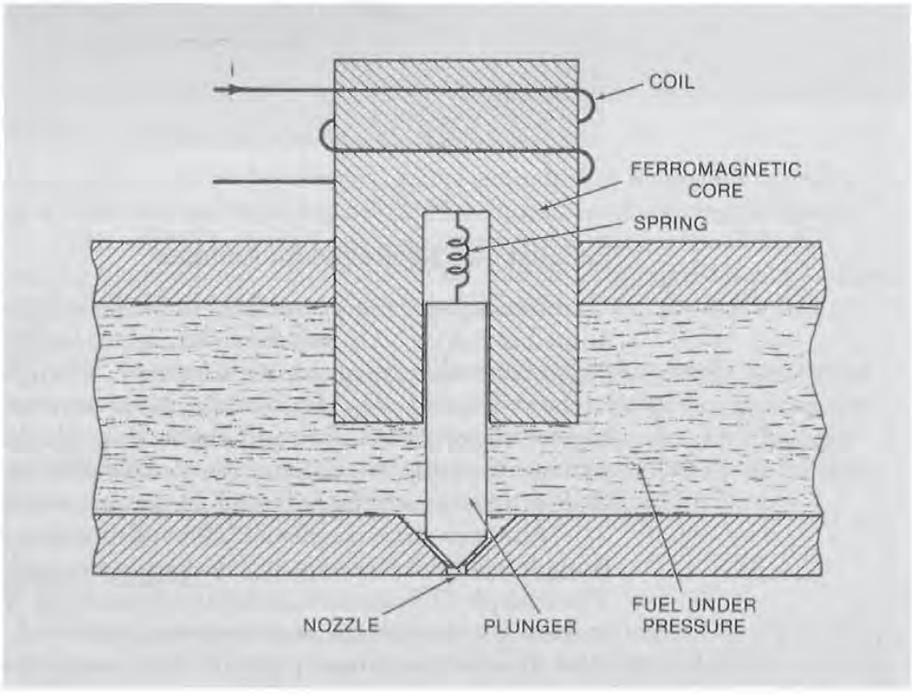
upward, the aperture is exposed, and fuel (under pressure) sprays through this aperture.

The fuel flow rate through the nozzle is constant for a given regulated fuel pressure and nozzle geometry; therefore, the quantity of fuel injected into the air stream is proportional to the time the valve is open. The control current that operates the fuel injector is pulsed on and off to deliver precise quantities of fuel.

Fuel Injector Signal

Consider an idealized fuel injector as shown in Figure 6.26, in which the injector is open when the applied voltage is on and is closed when the applied voltage is off. In this idealization, the control voltage operating the fuel injector is a binary pulse train (i.e., either on or off). For a pulse train signal, the ratio of on time t to the period of the pulse T (on time plus off time) is called the *duty cycle*. This is shown in Figure 6.27. The fuel injector is energized for time t to allow fuel to spray from the nozzle into the air stream going to the intake manifold. The injector is deenergized for the remainder of the period. Therefore, a low duty cycle, as seen in Figure 6.27a, is used for a high air/fuel ratio (lean mixture), and a high duty cycle (Figure 6.27b) is used for a low air/fuel ratio (rich mixture).

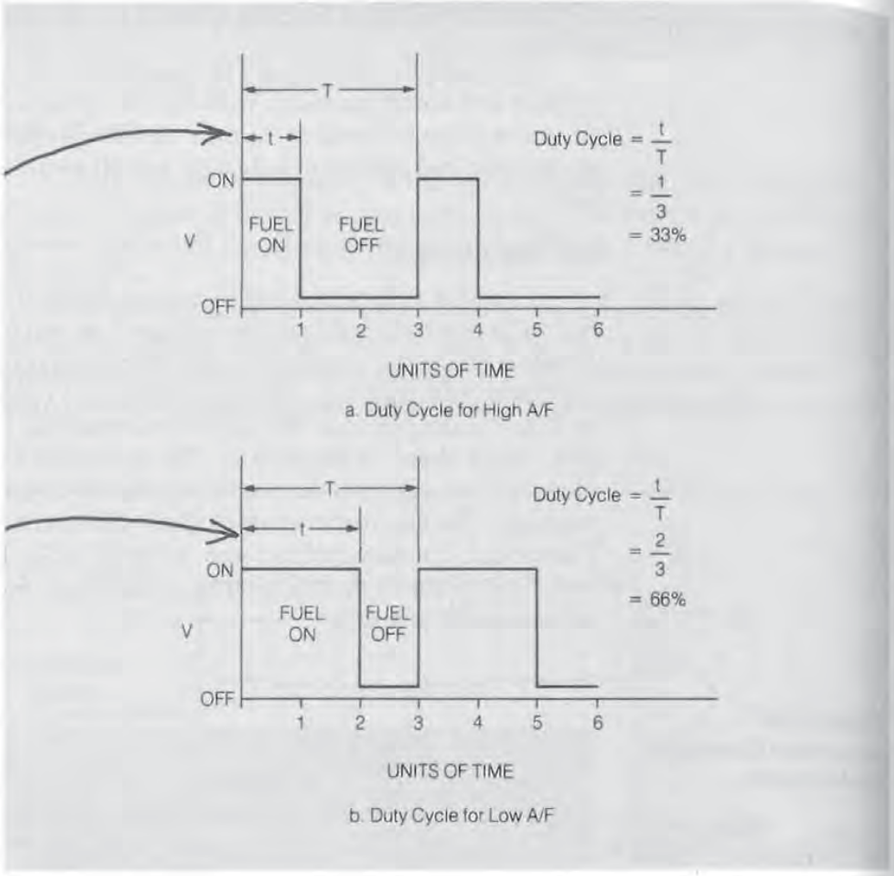
Figure 6.26
Schematic Drawing of Fuel Injector



PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Figure 6.27
Pulse Mode Fuel Control Signal to Fuel Injector

High air-to-fuel ratio.



Low air-to-fuel ratio.

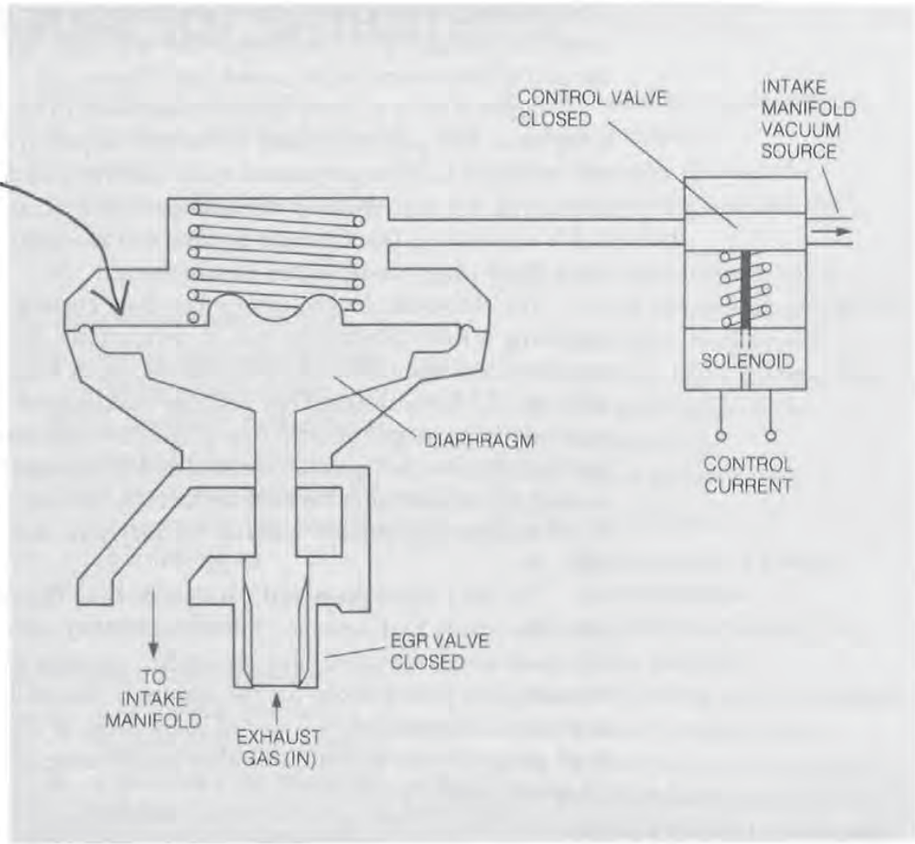
Exhaust Gas Recirculation Actuator

In Chapter 5 it was explained that exhaust gas recirculation (EGR) is utilized to reduce NO_x emissions. The amount of EGR is regulated by the engine controller, as explained in Chapter 7. When the correct amount of EGR has been determined by the controller based on measurements from the various engine control sensors, the controller sends an electrical signal to the EGR actuator. Typically, this actuator is a variable-position valve that regulates the EGR as a function of intake manifold pressure and exhaust gas pressure.

Although there are many EGR configurations, only one representative example will be discussed to explain the basic operation of this type of actuator. The example EGR actuator is shown schematically in Figure 6.28. This actuator is a vacuum-operated diaphragm valve with a spring that holds the valve closed if no vacuum is applied. The vacuum that operates the diaphragm

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Figure 6.28
EGR Actuator Control



One kind of EGR actuator consists of a vacuum-operated valve with the vacuum supply controlled by a solenoid. When the EGR valve is open, exhaust gas flows into the intake manifold.

is supplied by the intake manifold and is controlled by a solenoid-operated valve. This solenoid valve is controlled by the output of the control system.

This solenoid operates essentially the same as that explained in the discussion on fuel injectors. Whenever the solenoid is energized (i.e., by current supplied by the control system flowing through the coil), the EGR valve is opened by the applied vacuum.

The amount of valve opening is determined by the average pressure on the vacuum side of the diaphragm. This pressure is regulated by pulsing the solenoid with a variable-duty-cycle electrical control current. The duty cycle (see discussion on fuel injectors) of this pulsing current controls the average pressure in the chamber that affects the diaphragm deflection, thereby regulating the amount of EGR.

Ignition System

The equivalent of an actuator for the ignition system on an engine is the combination of the spark plug, the ignition coil, and driver electronic circuits.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

This is the subsystem that receives the electrical signal from the engine controller and delivers as its output the spark that ignites the mixture during the end of the compression stroke (see Chapter 1).

Figure 6.29 is a block diagram schematic drawing illustrating this subsystem. The primary circuit of the coil (depicted as the left portion P of the coil in Figure 6.29) is connected to the battery and through a power transistor to ground. For convenience, the collector, emitter, and base are denoted c, e, and b respectively (see Chapter 3). The coil secondary S is connected to one or more spark plugs, as explained in Chapter 7.

The electronic controller supplies base current to the power transistor, rendering it fully conductive (i.e., in saturation). When it is conducting, the transistor acts essentially like a closed switch. A relatively large current (denoted I_p) flows through the primary windings of the coil (P), creating a relatively large magnetic field that is linked to the secondary coil. At the appropriate time for ignition the controller switches off the base current, causing the transistor to be nonconducting. At this instant the primary current drops to zero very quickly, causing the magnetic field strength to drop rapidly also.

The very rapid drop in the magnetic field (linked to the secondary S) generates a very high voltage (30,000 to 50,000 volts), which, in turn, creates the spark across the spark plug electrodes, igniting the mixture and, finally, initiating the power stroke for the engine. It should be noted that the coil secondary is connected to a pair of spark plugs in Figure 6.29. Firing a pair of spark plugs on two separate cylinders has become commonplace today (see Chapters 1 and 7).

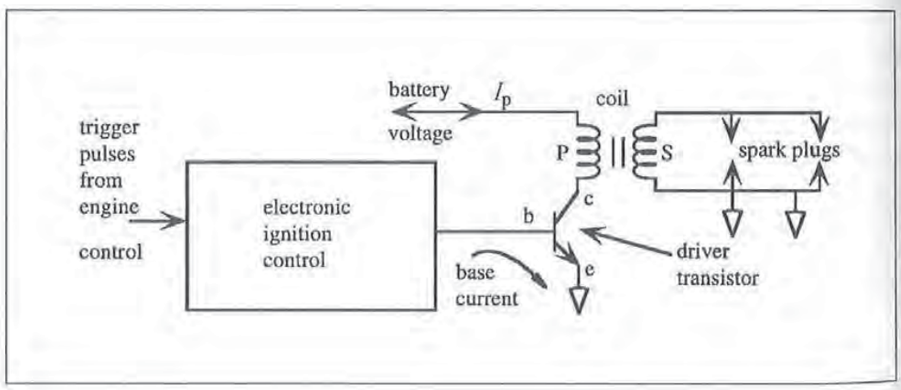


Figure 6.29
Electronic Ignition Subsystem

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Quiz for Chapter 6

1. What does a sensor do?
   - **a.** it selects transmission gear ratio
   - **b.** it measures some variable
   - **c.** it is an output device
   - **d.** it sends signals to the driver
2. What does an actuator do?
   - **a.** it is an input device for an engine control system
   - **b.** it provides a mathematical model for an engine
   - **c.** it causes an action to be performed in response to an electrical signal
   - **d.** it indicates the results of a measurement
3. What is a MAP sensor?
   - **a.** a sensor that measures manifold absolute pressure
   - **b.** a vacation route planning scheme
   - **c.** a measurement of fluctuations in manifold air
   - **d.** an acronym for mean atmospheric pressure
4. What is an EGO sensor?
   - **a.** a measure of the self-centeredness of the driver
   - **b.** a device for measuring the oxygen concentration in the exhaust of an engine
   - **c.** a spark advance mechanism
   - **d.** a measure of crankshaft acceleration
5. The crankshaft angular position sensor measures
   - **a.** the angle between the connecting rods and the crankshaft
   - **b.** the angle between a line drawn through the crankshaft axis and a mark on the flywheel and a reference line
   - **c.** the pitch angle of the crankshaft
   - **d.** the oil pressure angle
6. The Hall effect is
   - **a.** the resonance of a long, narrow corridor
   - **b.** the flow of air through the intake manifold
   - **c.** zero crossing error in camshaft position measurements
   - **d.** a phenomenon occurring in semiconductor materials in which a voltage is generated that is proportional to the strength of a magnetic field
7. A mass air flow sensor measures
   - **a.** the density of atmospheric air
   - **b.** the composition of air
   - **c.** the rate at which air is flowing into an engine measured in terms of its mass
   - **d.** the flow of exhaust out of the engine

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

8. A thermistor is
   - **a.** a semiconductor temperature sensor
   - **b.** a device for regulating engine temperature
   - **c.** a temperature control system for the passenger
   - **d.** a new type of transistor

9. Piezoresistivity is
   - **a.** a property of certain semiconductors in which resistivity varies with strain
   - **b.** a resistance property of insulators
   - **c.** metal bonding pads
   - **d.** an Italian resistor

10. Reluctance is
    - **a.** the reciprocal of permeability
    - **b.** a property of a magnetic circuit that is analogous to resistance in an electrical circuit
    - **c.** a line of constant magnetic flux
    - **d.** none of the above

11. An optical crankshaft position sensor
    - **a.** senses crankshaft angular position
    - **b.** operates by alternately passing or stopping a beam of light from a source to an optical detector
    - **c.** operates in a pulsed mode
    - **d.** all of the above

12. The resistance of a thermistor
    - **a.** varies inversely with temperature
    - **b.** varies directly with temperature
    - **c.** is always 100,000 ohms
    - **d.** none of the above

13. Duty cycle in a fuel injector actuator refers to the ratio of
    - **a.** fuel on time to fuel off time
    - **b.** fuel off time to fuel on time
    - **c.** fuel on time to fuel on time plus fuel off time
    - **d.** none of the above

14. An EGO sensor is
    - **a.** a perfectly linear sensor
    - **b.** a sensor having two different output levels depending on air/fuel ratio
    - **c.** unaffected by exhaust oxygen levels
    - **d.** unaffected by temperature

15. A potentiometer is
    - **a.** a variable-resistance circuit component
    - **b.** sometimes used to sense air flow
    - **c.** usable in a throttle angle sensor
    - **d.** all of the above

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Digital Engine Control System

Chapter 5 discussed some of the fundamental issues involved in electronic engine control. This chapter explores some practical digital control systems. There is, of course, considerable variation in the configuration and control concept from one manufacturer to another. However, this chapter describes representative control systems that are not necessarily based on the system of any given manufacturer, thereby giving the reader an understanding of the configuration and operating principles of a generic representative system. As such, the systems in this discussion are a compilation of the features used by several manufacturers.

In Chapter 5, engine control was discussed with respect to continuous-time representation. In fact, most modern engine control systems, such as discussed in this chapter, are digital. A typical engine control system incorporates a microprocessor and is essentially a special-purpose computer.

Electronic engine control has evolved from a relatively rudimentary fuel control system employing discrete analog components to the highly precise fuel and ignition control through 32-bit microprocessor-based integrated digital electronic power train control. The motivation for development of the more sophisticated digital control systems has been the increasingly stringent exhaust emission and fuel economy regulations. It has proven to be cost effective to implement the power train controller as a multimode computer-based system to satisfy these requirements.

A multimode controller operates in one of many possible modes, and, among other tasks, changes the various calibration parameters as operating conditions change in order to optimize performance. To implement multimode control in analog electronics it would be necessary to change hardware parameters (for example, via switching systems) to accommodate various operating conditions. In a computer-based controller, however, the control law and system parameters are changed via program (i.e., software) control. The hardware remains fixed but the software are reconfigured in accordance with operating conditions as determined by sensor measurements and switch inputs to the controller.

This chapter will explain how the microcontroller under program control is responsible for generating the electrical signals that operate the fuel injectors and trigger the ignition pulses. This chapter also discusses secondary functions (including management of secondary air that must be provided to the catalytic converter EGR regulation and evaporative emission control) that have not been discussed in detail before.

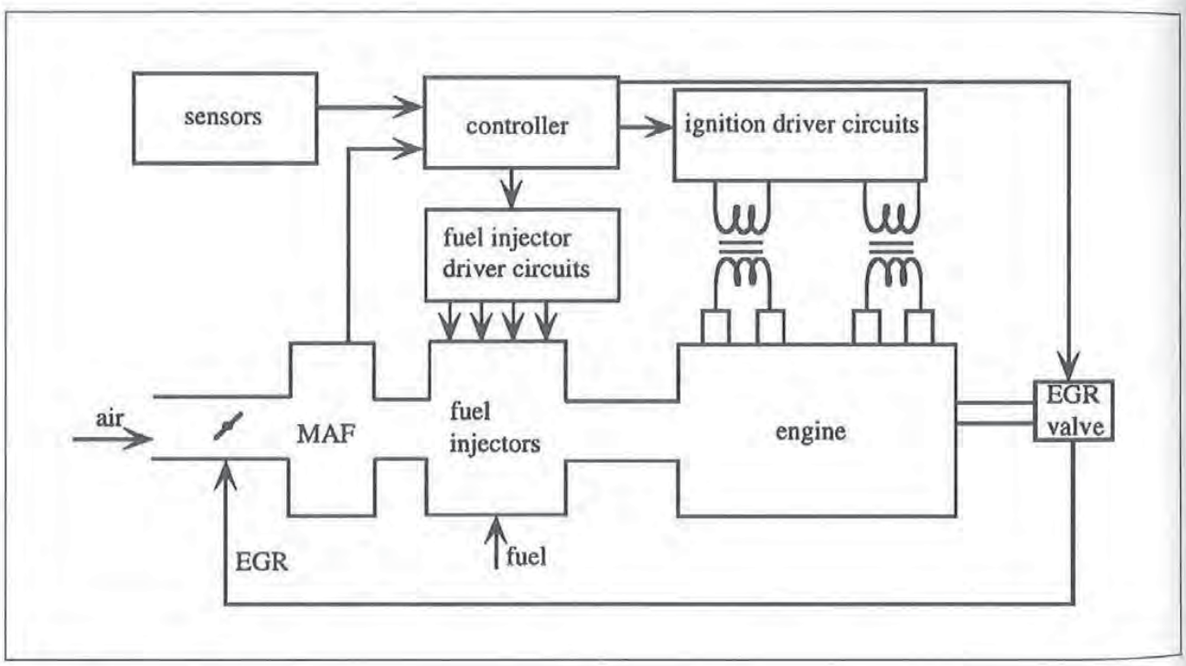
PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

DIGITAL ENGINE CONTROL FEATURES

Recall from Chapter 5 that the primary purpose of the electronic engine control system is to regulate the mixture (i.e., air–fuel), the ignition timing, and EGR. Virtually all major manufacturers of cars sold in the United States (both foreign and domestic) use the three-way catalyst for meeting exhaust emission constraints. For such cars, the air/fuel ratio is held as closely as possible to the stoichiometric value of about 14.7 for as much of the time as possible. Ignition timing and EGR are controlled separately to optimize performance and fuel economy.

Figure 7.1 illustrates the primary components of an electronic engine control system. In this figure, the engine control system is a microcontroller, typically implemented with a specially designed microprocessor and operating under program control. Typically, the controller incorporates hardware multiply and ROM (see Chapter 4). The hardware multiply greatly speeds up the multiplication operation required at several stages of engine control relative to software multiplication routines, which are generally cumbersome and slow. The associated ROM contains the program for each mode as well as calibration parameters and

Figure 7.1
Components of an Electronically Controlled Engine



PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

lookup tables. The earliest such systems incorporated 8-bit microprocessors, although the trend is toward implementation with 32-bit microprocessors. The microcontroller under program control generates output electrical signals to operate the fuel injectors so as to maintain stoichiometric mixture and ignition to optimize performance. The correct stoichiometric mixture is obtained by regulating the quantity of fuel delivered into each cylinder during the intake stroke in accordance with the air mass, as explained in Chapter 5.

In determining the correct fuel flow, the controller obtains a measurement or estimate of the mass air flow rate into the cylinder. As explained in Chapter 5, the measurement is obtained using a mass air flow sensor (MAF). Alternatively, the mass air flow rate is estimated (calculated) using the speed-density method, also explained in Chapter 5. This estimate can be found from measurement of the intake manifold absolute pressure (MAP), the RPM, and the inlet air temperature.

Using this measurement or estimate, the quantity of fuel to be delivered is determined by the controller in accordance with the instantaneous control mode. The quantity of fuel delivered by the fuel injector is determined by the operation of the fuel injector. As explained in Chapter 6, a fuel injector is essentially a solenoid-operated valve. Fuel that is supplied to each injector from the fuel pump is supplied to each fuel injector at a regulated fuel pressure. When the injector valve is opened, fuel flows at a rate R_f (in gal/sec) that is determined by the (constant) regulated pressure and by the geometry of the fuel injector valve. The quantity of fuel F delivered to any cylinder is proportional to the time T that this valve is opened:

$$F = R_f T$$

The engine control system, then, determines the correct quantity of fuel to be delivered to each cylinder (for a stoichiometric mixture) via measurement of mass air flow rate. The controller then generates an electrical signal that opens the fuel injector valve for the appropriate time interval T to deliver this desired fuel quantity to the cylinder such that a stoichiometric air/fuel ratio is maintained.

The controller also determines the correct time for fuel delivery to correspond to the intake stroke for the relevant cylinder. This timing is determined by measurements of crankshaft and camshaft position using sensors such as those described in Chapter 6.

CONTROL MODES FOR FUEL CONTROL

The engine control system is responsible for controlling fuel and ignition for all possible engine operating conditions. However, there are a number of distinct categories of engine operation, each of which corresponds to a separate and distinct operating mode for the engine control system. The differences between these operating modes are sufficiently great that different software is

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

used for each. The control system must determine the operating mode from the existing sensor data and call the particular corresponding software routine.

Engines have different modes of operation as the operating conditions change. Seven different modes of operation commonly affect fuel control.

For a typical engine there are seven different engine operating modes that affect fuel control: engine crank, engine warm-up, open-loop control, closed-loop control, hard acceleration, deceleration, and idle. The program for mode control logic determines the engine operating mode from sensor data and timers.

In the earliest versions of electronic fuel control systems, the fuel metering actuator typically consisted of one or two fuel injectors mounted near the throttle plate so as to deliver fuel into the throttle body. These throttle body fuel injectors (TBFI) were in effect an electromechanical replacement for the carburetor. Requirements for the TBFI were such that they only had to deliver fuel at the correct average flow rate for any given mass air flow. Mixing of the fuel and air, as well as distribution to the individual cylinders, took place in the intake manifold system.

The more stringent exhaust emissions regulations of the late 1980s and the 1990s have demanded more precise fuel delivery than can normally be achieved by TBFI. These regulations and the need for improved performance have led to timed sequential port fuel injection (TSPFI). In such a system there is a fuel injector for each cylinder that is mounted so as to spray fuel directly into the intake of the associated cylinder. Fuel delivery is timed to occur during the intake stroke for that cylinder.

The digital engine control system requires sensors for measuring the engine variables and parameters discussed in Chapter 5. Referring to Figure 7.1, the set of sensors may include, for example, mass air flow (MAF), exhaust gas oxygen concentration (EGO), and crankshaft angular position (CPS), as well as RPM, camshaft position (possibly a single reference point for each engine cycle), coolant temperature (CT), throttle plate angular position (TPS), intake air temperature, and exhaust pressure ratio (EPR) for EGR control.

During engine crank and engine warm-up modes, the controller holds the air/fuel ratio to a purposely low value (a rich fuel mixture).

In the example configuration of Figure 7.1, fuel delivery is assumed to be TSPFI (i.e., via individual fuel injectors located so as to spray fuel directly into the intake port and timed to coincide with the intake stroke). Air flow measurement is via an MAF sensor. In addition to MAF, sensors are available for the measurement of exhaust gas oxygen (EGO) concentration, RPM, inlet air and coolant temperatures, throttle position, crankshaft (and possibly camshaft) position, and exhaust differential pressure (for EGR calculation). Some engine controllers involve vehicle speed sensors and various switches to identify brake on/off and the transmission gear, depending on the particular control strategy employed.

When the ignition key is switched on initially, the mode control logic automatically selects an engine start control scheme that provides the low air/fuel ratio required for starting the engine. Once the engine RPM rises above the cranking value, the controller identifies the "engine started" mode and passes control to the program for the engine warm-up mode. This operating mode keeps the air/fuel ratio low to prevent engine stall during cool weather until the

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

engine coolant temperature rises above some minimum value. The particular value for the minimum coolant temperature is specific to any given engine and, in particular, to the fuel metering system. (Alternatively, the low air/fuel ratio may be maintained for a fixed time interval following start, depending on start-up engine temperature.)

After warm-up, the controller switches to open-loop control until accurate readings can be obtained from the EGO sensor. The controller then changes to, and remains in, closed-loop mode under ordinary driving conditions.

When the coolant temperature rises sufficiently, the mode control logic directs the system to operate in the open-loop control mode until the EGO sensor warms up enough to provide accurate readings. This condition is detected by monitoring the EGO sensor's output for voltage readings above a certain minimum rich air/fuel mixture voltage set point. When the sensor has indicated rich at least once and after the engine has been in open loop for a specific time, the control mode selection logic selects the closed-loop mode for the system. (Note: other criteria may also be used.) The engine remains in the closed-loop mode until either the EGO sensor cools and fails to read a rich mixture for a certain length of time or a hard acceleration or deceleration occurs. If the sensor cools, the control mode logic selects the open-loop mode again.

During conditions of hard acceleration or deceleration, the controller adjusts the air/fuel ratio as needed. During idle periods, the controller adjusts engine speed to reduce engine roughness and stalling.

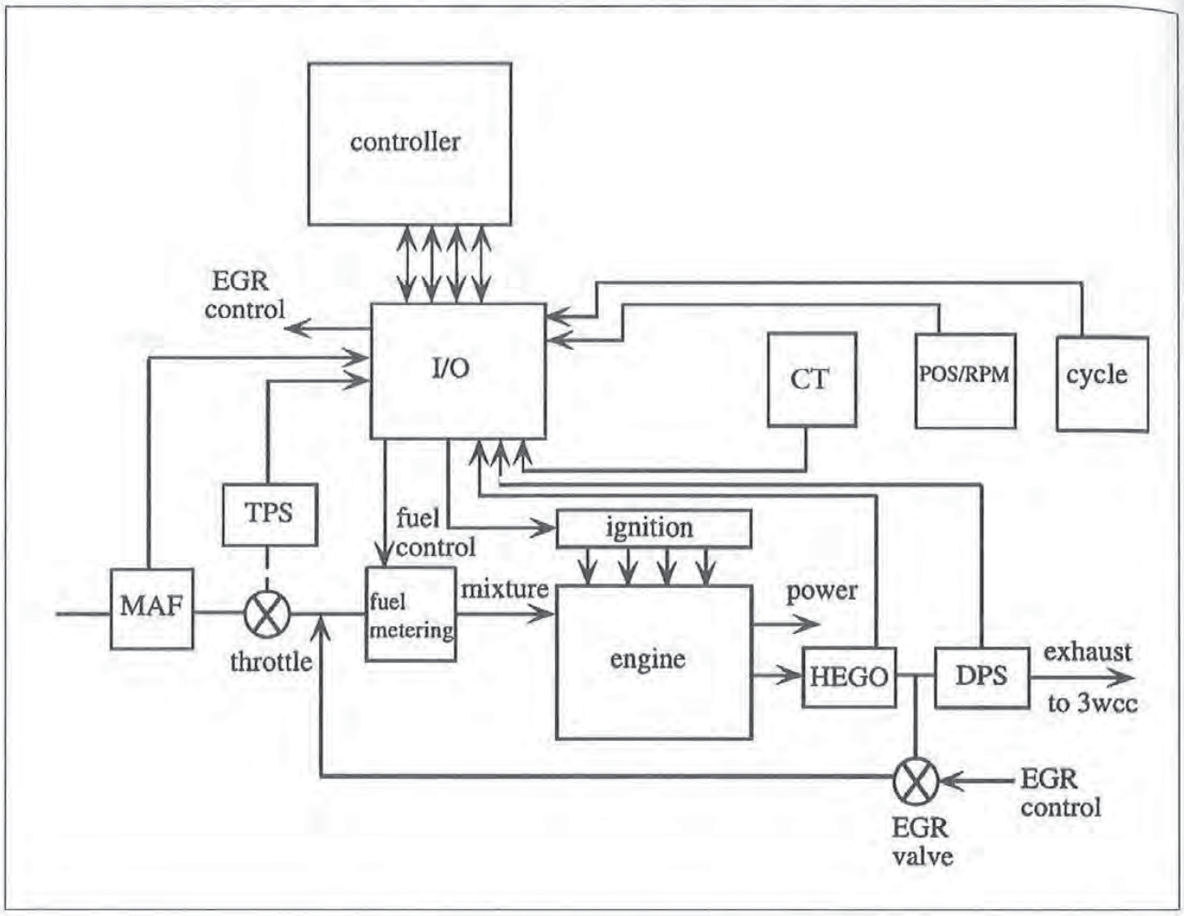
During hard acceleration or heavy engine load, the control mode selection logic chooses a scheme that provides a rich air/fuel mixture for the duration of the acceleration or heavy load. This scheme provides maximum torque but relatively poor emissions control and poor fuel economy regulation as compared with a stoichiometric air/fuel ratio. After the need for enrichment has passed, control is returned to either open-loop or closed-loop mode, depending on the control mode logic selection conditions that exist at that time.

During periods of deceleration, the air/fuel ratio is increased to reduce emissions of HC and CO due to unburned excess fuel. When idle conditions are present, control mode logic passes system control to the idle speed control mode. In this mode, the engine speed is controlled to reduce engine roughness and stalling that might occur because the idle load has changed due to air conditioner compressor operation, alternator operation, or gearshift positioning from park/neutral to drive, although stoichiometric mixture is used if the engine is warm.

In modern engine control systems, the controller is a special-purpose digital computer built around a microprocessor. A block diagram of a typical modern digital engine control system is depicted in Figure 7.2. The controller also includes ROM containing the main program (of several thousand lines of code) as well as RAM for temporary storage of data during computation. The sensor signals are connected to the controller via an input/output (I/O) subsystem. Similarly, the I/O subsystem provides the output signals to drive the fuel injectors (shown as the fuel metering block of Figure 7.2) as well as to trigger pulses to the ignition system (described later in this chapter). In addition this solid-state control system includes hardware for sampling and analog-to-digital conversion such that all sensor measurements are in a format suitable for reading by the microprocessor. (Note: see Chapter 4 for a detailed discussion of these components.)

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Figure 7.2
Digital Engine Control System Diagram



The sensors that measure various engine variables for control are as follows:

MAF	Mass air flow sensor
CT	Engine temperature as represented by coolant temperature
HEGO	(One or two) heated exhaust gas oxygen sensor(s)
POS/RPM	Crankshaft angular positon and RPM sensor cycle Camshaft position sensor for determining start of each engine cycle
TPS	Throttle position sensor
DPS	Differential pressure sensor (exhaust to intake) for EGR control

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

The control system selects an operating mode based on the instantaneous operating condition as determined from the sensor measurements. Within any given operating mode the desired air/fuel ratio $(A/F)_d$ is selected. The controller then determines the quantity of fuel to be injected into each cylinder during each engine cycle. This quantity of fuel depends on the particular engine operating condition as well as the controller mode of operation, as will presently be explained.

Engine Crank

During engine crank, the controller compares the value from the coolant temperature sensor with values stored in a lookup table to determine the correct air/fuel ratio at that temperature.

While the engine is being cranked, the fuel control system must provide an intake air/fuel ratio of anywhere from 2:1 to 12:1, depending on engine temperature. The correct air/fuel ratio (i.e., $[A/F]_d$) is selected from a ROM lookup table as a function of coolant temperature. Low temperatures affect the ability of the fuel metering system to atomize or mix the incoming air and fuel. At low temperatures, the fuel tends to form into large droplets in the air, which do not burn as efficiently as tiny droplets. The larger fuel droplets tend to increase the apparent air/fuel ratio, because the amount of usable fuel (on the surface of the droplets) in the air is reduced; therefore, the fuel metering system must provide a decreased air/fuel ratio to provide the engine with a more combustible air/fuel mixture. During engine crank the primary issue is to achieve engine start as rapidly as possible. Once the engine is started the controller switches to an engine warm-up mode.

Engine Warm-Up

The controller selects a warm-up time from a lookup table based on the temperature of the coolant. During engine warm-up the air/fuel ratio is still rich, but it is changed by the controller as the coolant temperature increases.

While the engine is warming up, an enriched air/fuel ratio is still needed to keep it running smoothly, but the required air/fuel ratio changes as the temperature increases. Therefore, the fuel control system stays in the open-loop mode, but the air/fuel ratio commands continue to be altered due to the temperature changes. The emphasis in this control mode is on rapid and smooth engine warm-up. Fuel economy and emission control are still a secondary concern.

A diagram illustrating the lookup table selection of desired air/fuel ratios is shown in Figure 7.3. Essentially, the measured coolant temperature (CT) is converted to an address for the lookup table. This address is supplied to the ROM table via the system address bus (A/B). The data stored at this address in the ROM is the desired air/fuel ratio $(A/F)_d$ for that temperature. This data is sent to the controller via the system data bus (D/B).

There is always the possibility of a coolant temperature failure. Such a failure could result in excessively rich or lean mixtures, which can seriously degrade the performance of both the engine and the three-way catalytic converter (3wcc). One scheme that can circumvent a temperature sensor failure involves having a time function to limit the duration of the engine warm-up mode. The nominal time to warm the engine from cold soak at various temperatures is known. The controller is configured to switch from engine

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

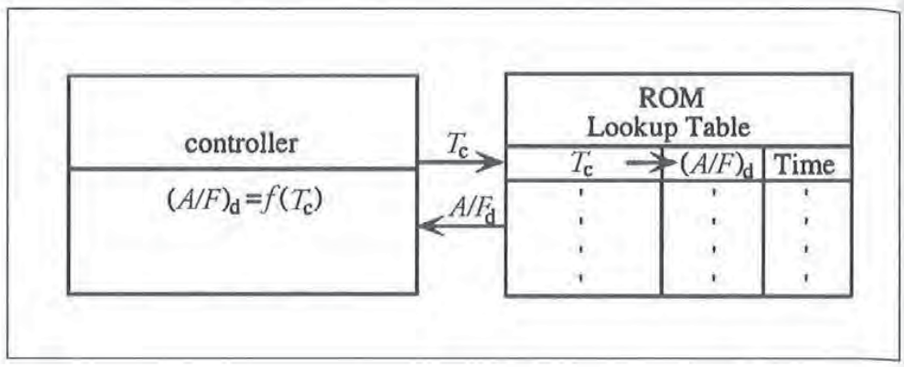


Figure 7.3 Illustration of Lookup Table for Desired Air/Fuel Ratio

warm-up mode to an open-loop (warmed-up engine) mode after a sufficient time by means of an internal timer.

It is worthwhile at this point to explain how the quantity of fuel to be injected is determined. This method is implemented in essentially all operating modes and is described here as a generic method, even though each engine control scheme may vary somewhat from the following. The quantity of fuel to be injected during the intake stroke of any given cylinder (which we call F) is determined by the mass of air (A) drawn into that cylinder (i.e., the air charge) during that intake stroke. That quantity of fuel is given by the air charge divided by the desired air/fuel ratio:

$$F = \frac{A}{(A/F)_d}$$

The quantity of air drawn into the cylinder, A, is computed from the mass air flow rate and the RPM. The mass air flow rate (MAF) will be given in kg/sec. If the engine speed in revolutions/minute is RPM, then the number of revolutions/second (which we call r) is

$$r = \frac{\text{RPM}}{60}$$

Then, the mass air flow is distributed approximately uniformly to half the cylinders during each revolution. If the number of cylinders is N then the air charge (mass) in each cylinder during one revolution is

$$A = \frac{\text{MAF}}{r(N/2)}$$

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

In this case, the mass of fuel delivered to each cylinder is

$$F = \frac{\text{MAF}}{r(N/2)(A/F)_d}$$

This computation is carried out by the controller continuously so that the fuel quantity can be varied quickly to accommodate rapid changes in engine operating condition. The fuel injector pulse duration T corresponding to this fuel quantity is computed using the known fuel injector delivery rate R_f:

$$T = \frac{F}{R_f}$$

This pulse width is known as the *base pulse width*. The actual pulse width used is modified from this according to the mode of operation at any time, as will presently be explained.

Open-Loop Control

After engine warm-up, open-loop control is used. The most popular method uses the mass density equation to calculate the amount of air entering the intake manifold.

For a warmed-up engine, the controller will operate in an open loop if the closed-loop mode is not available for any reason. For example, the engine may be warmed sufficiently but the EGO sensor may not provide a usable signal. In any event, as soon as possible it is important to have a stoichiometric mixture to minimize exhaust emissions. The base pulse width T_b is computed as described above, except that the desired air/fuel ratio $(A/F)_d$ is 14.7 (stoichiometry):

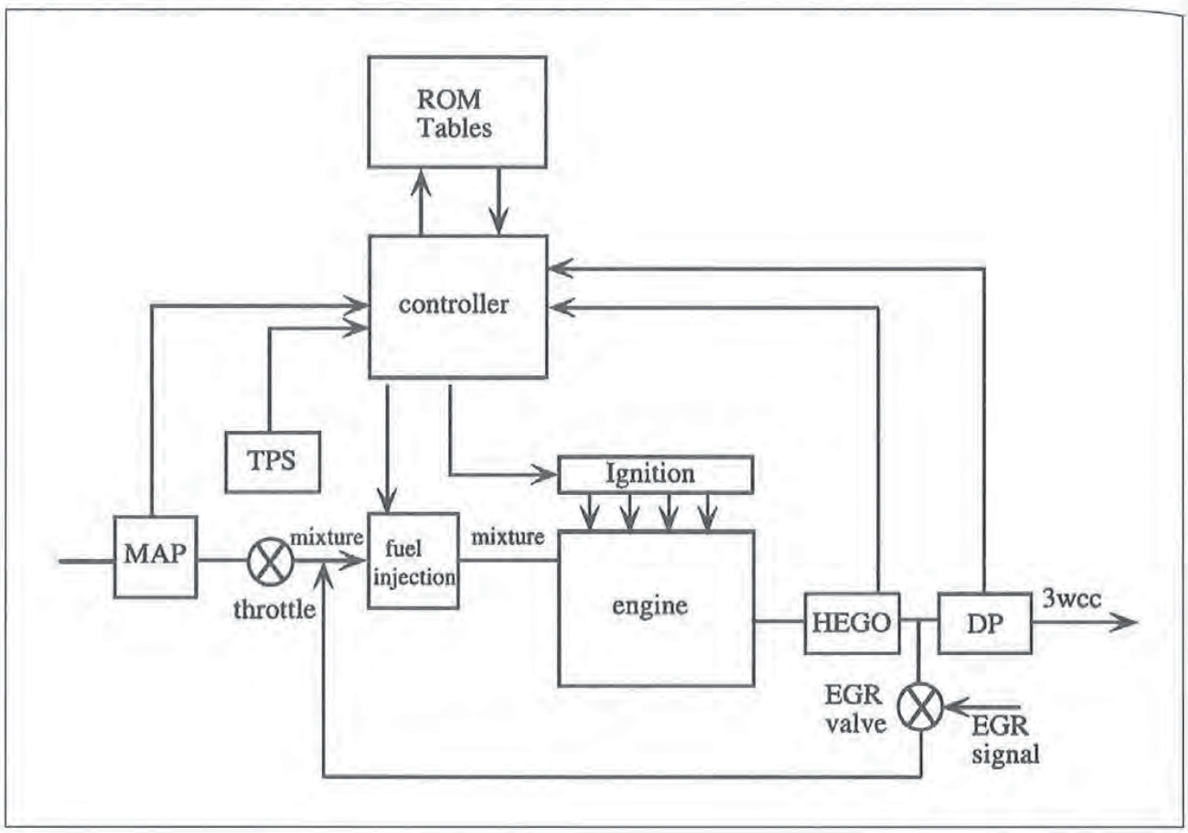
$$T_b = \frac{\text{MAF}}{r(N/s)(14.7)R_f} \qquad \text{base pulse width}$$

Corrections of the base pulse width occur whenever anything affects the accuracy of the fuel delivery. For example, low battery voltage might affect the pressure in the fuel rail that delivers fuel to the fuel injectors. Corrections to the base pulse width are then made using the actual battery voltage.

As explained in Chapter 5, an alternate method of computing mass air flow rate is the speed-density method. Although the speed-density method has essentially been replaced by direct mass air flow measurements, there will continue to be a number of cars employing this method for years to come, so it is arguably worthwhile to include a brief discussion in this chapter. This method, which is illustrated in Figure 7.4, is based on measurements of manifold absolute pressure (MAP), RPM, and intake air temperature T_i. The

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Figure 7.4
Engine Control System Using the Speed-Density Method

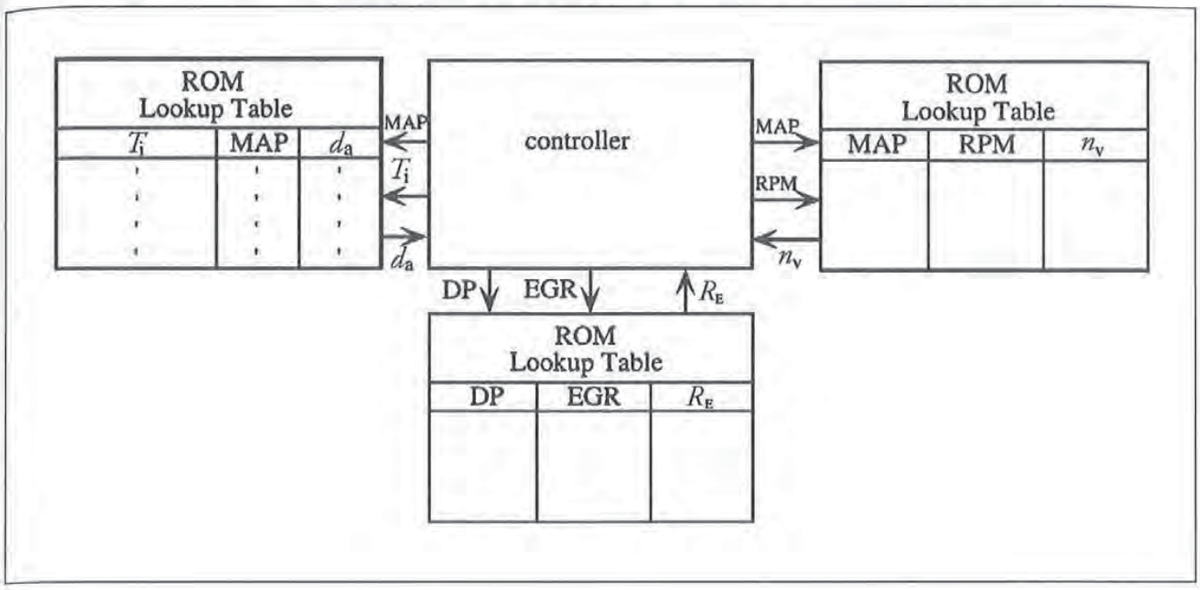


air density d_a is computed from MAP and T_i, and the volume flow rate R_v of combined air and EGR is computed from RPM and volumetric efficiency, the latter being a function of MAP and RPM. The volume rate for air is found by subtracting the EGR volume flow rate from the combined air and EGR. Finally, the mass air flow rate is computed as the product of the volume flow rate for air and the intake air density. Given the complexity of the speed-density method it is easy to see why automobile manufacturers would choose the direct mass air flow measurement once a cost-effective mass air flow sensor became available.

The speed-density method can be implemented either by computation in the engine control computer or via lookup tables. Figure 7.5 is an illustration of the lookup table implementation. In this figure, three variables need to be determined: volumetric efficiency (n_v), intake density (d_a), and EGR volume

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Figure 7.5
Lookup Table Determination of d_a, R_E, and n_v



flow rate (R_E). The volumetric efficiency is read from ROM with an address determined from RPM and MAP measurements. The intake air density is read from another section of ROM with an address determined from MAP and T_i measurements. The EGR volume flow rate is read from still another section of ROM with an address determined from differential pressure (DP) and EGR valve position. These variables are combined to yield the mass air flow rate:

$$\text{MAF} = d_a\left[\left(\frac{\text{RPM}}{60}\right)\left(\frac{D}{2}\right)n_v - R_E\right]$$

where D is the engine displacement.

Closed-Loop Control

Perhaps the most important adjustment to the fuel injector pulse duration comes when the control is in the closed-loop mode. In the open-loop mode the accuracy of the fuel delivery is dependent on the accuracy of the measurements of the important variables. However, any physical system is susceptible to changes with either operating conditions (e.g., temperature) or with time (aging or wear of components).

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

In any closed-loop control system a measurement of the output variables is compared with the desired value for those variables. In the case of fuel control, the variables being regulated are exhaust gas concentrations of HC, CO, and NO_x, as explained in Chapter 5. Although direct measurement of these exhaust gases is not feasible in production automobiles, it is sufficient for fuel control purposes to measure the exhaust gas oxygen concentration. Recall from Chapter 5 that these regulated gases can be optimally controlled with a stoichiometric mixture. Recall further from Chapter 6 that the EGO sensor is, in essence, a switching sensor that changes output voltage abruptly as the input mixture crosses the stoichiometric mixture of 14.7.

The closed-loop mode can only be activated when the EGO (or HEGO) sensor is sufficiently warmed. Recall from Chapter 6 that the output voltage of the sensor is high (approximately 1 volt) when the exhaust oxygen concentration is low (i.e., for a rich mixture relative to stoichiometry). The EGO sensor voltage is low (approximately .1 volt) whenever the exhaust oxygen concentration is high (i.e., for a mixture that is lean relative to stoichiometry).

The time-average EGO sensor output voltage provides the feedback signal for fuel control in the closed-loop mode. The instantaneous EGO sensor voltage fluctuates rapidly from high to low values, but the average value is a good indication of the mixture.

As explained earlier, fuel delivery is regulated by the engine control system by controlling the pulse duration (T) for each fuel injector. The engine controller continuously adjusts the pulse duration for varying operating conditions and for operating parameters. A representative algorithm for fuel injector pulse duration for a given injector during the nth computation cycle, $T(n)$, is given by

$$T(n) = T_b(n) \times [1 + C_L(n)]$$

where

$T_b(n)$ is the base pulse width as determined from measurements of mass air flow rate and the desired air/fuel ratio

$C_L(n)$ is the closed-loop correction factor

For open-loop operation, $C_L(n)$ equals 0; for closed-loop operation, C_L is given by

$$C_L(n) = \alpha I(n) + \beta P(n)$$

where

$I(n)$ is the integral part of the closed-loop correction

$P(n)$ is the proportional part of the closed-loop correction

α and β are constants

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

These latter variables are determined from the output of the exhaust gas oxygen (EGO) sensor as described in Chapter 6.

Whenever the EGO sensor indicates a rich mixture (i.e., EGO sensor voltage is high), then the integral term is reduced by the controller for the next cycle,

$$I(n+1) = I(n) - 1$$

for a rich mixture.

Whenever the EGO sensor indicates a lean mixture (i.e., low output voltage), the controller increments $I(n)$ for the next cycle,

$$I(n+1) = I(n) + 1$$

for a lean mixture. The integral part of C_L continues to increase or decrease in a limit-cycle operation, as explained in Chapter 5 for continuous-time operation.

The computation of the closed-loop correction factor continues at a rate determined within the controller. This rate is normally high enough to permit rapid adjustment of the fuel injector pulse width during rapid throttle changes at high engine speed. The period between successive computations is the computation cycle described above.

In addition to the integral component of the closed-loop correction to pulse duration is the proportional term. This term, $P(n)$, is proportional to the deviation of the average EGO sensor signal from its mid-range value (corresponding to stoichiometry). The combined terms change with computation cycle as depicted in Figure 7.6. In this figure the regions of lean and rich (relative to stoichiometry) are depicted. During relatively lean periods the closed-loop correction term increases for each computation cycle, whereas during relatively rich intervals this term decreases.

Once the computation of the closed-loop correction factor is completed, the value is stored in a specific memory location (RAM) in the controller. At the appropriate time for fuel injector activation (during the intake stroke), the instantaneous closed-loop correction factor is read from its location in RAM and an actual pulse of the corrected duration is generated by the engine control.

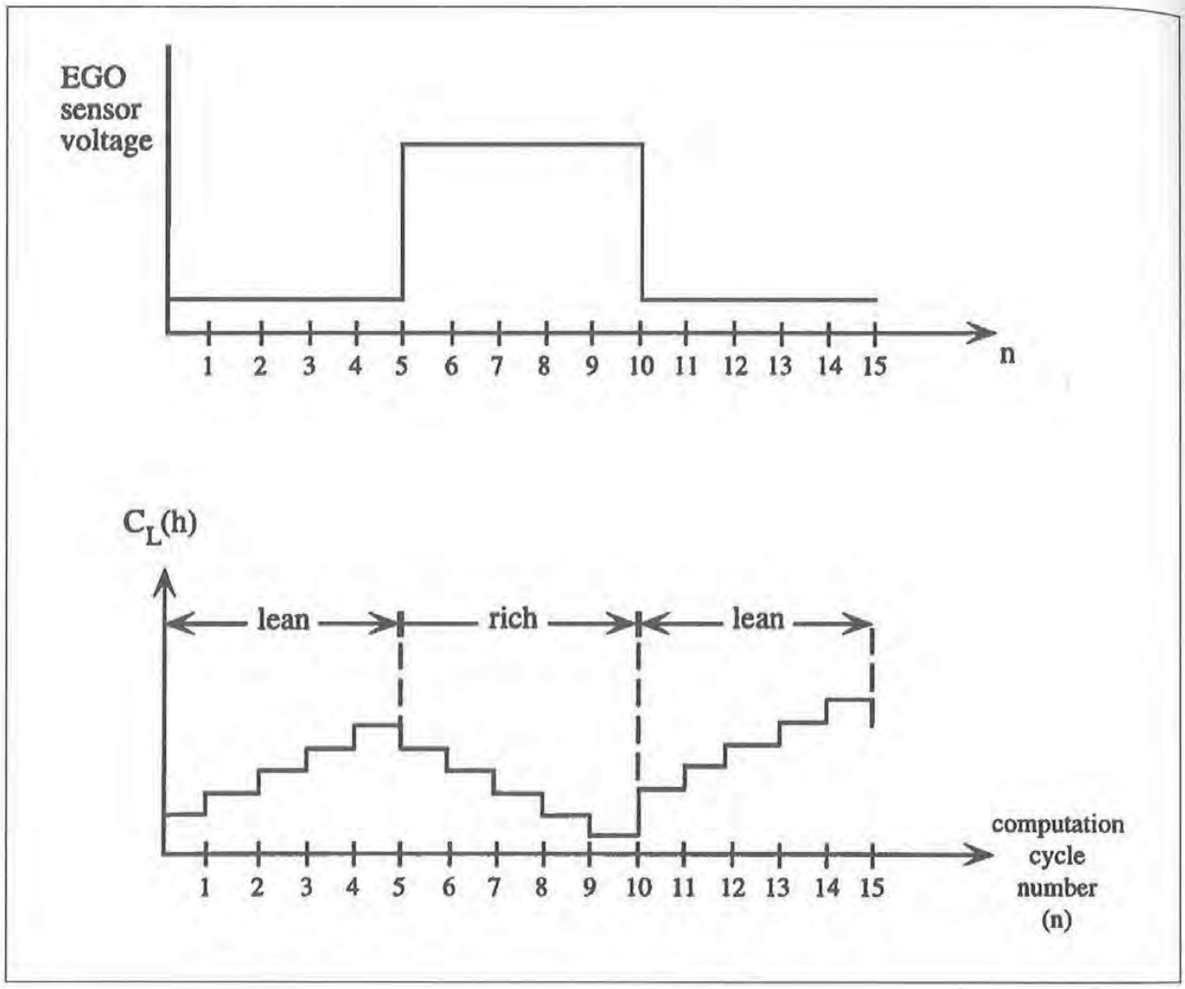
Acceleration Enrichment

The mixture is enriched to maximize torque during very heavy load (for example, a wide open throttle).

During periods of heavy engine load such as during hard acceleration, fuel control is adjusted to provide an enriched air/fuel ratio to maximize engine torque and neglect fuel economy and emissions. This condition of enrichment is permitted within the regulations of the EPA as it is only a temporary condition. It is well recognized that hard acceleration is occasionally required for maneuvering in certain situations and is, in fact, related at times to safety.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Figure 7.6
Closed-Loop Correction Factor



The computer detects this condition by reading the throttle angle sensor voltage. High throttle angle corresponds to heavy engine load and is an indication that heavy acceleration is called for by the driver. In some vehicles a switch is provided to detect wide open throttle. The fuel system controller responds by increasing the pulse duration of the fuel injector signal for the duration of the heavy load. This enrichment enables the engine to operate with a torque greater than that allowed when emissions and fuel

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

economy are controlled. Enrichment of the air/fuel ratio to about 12:1 is sometimes used.

Deceleration Leaning

Fuel flow is reduced during deceleration with closed throttle.

During periods of light engine load and high RPM such as during coasting or hard deceleration, the engine operates with a very lean air/fuel ratio to reduce excess emissions of HC and CO. Deceleration is indicated by a sudden decrease in throttle angle or by closure of a switch when the throttle is closed (depending on the particular vehicle configuration). When these conditions are detected by the control computer, it computes a decrease in the pulse duration of the fuel injector signal. The fuel may even be turned off completely for very heavy deceleration.

Idle Speed Control

When the throttle angle reaches its closed position and engine RPM falls below a preset value, the controller switches to idle speed control. A stepping motor opens a valve, allowing a limited amount of air to bypass the closed throttle plate.

Idle speed control is used by some manufacturers to prevent engine stall during idle. The goal is to allow the engine to idle at as low an RPM as possible, yet keep the engine from running rough and stalling when power-consuming accessories, such as air conditioning compressors and alternators, turn on.

The control mode selection logic switches to idle speed control when the throttle angle reaches its zero (completely closed) position and engine RPM falls below a minimum value, and when the vehicle is stationary. Idle speed is controlled by using an electronically controlled throttle bypass valve (Figure 7.7a) that allows air to flow around the throttle plate and produces the same effect as if the throttle had been slightly opened.

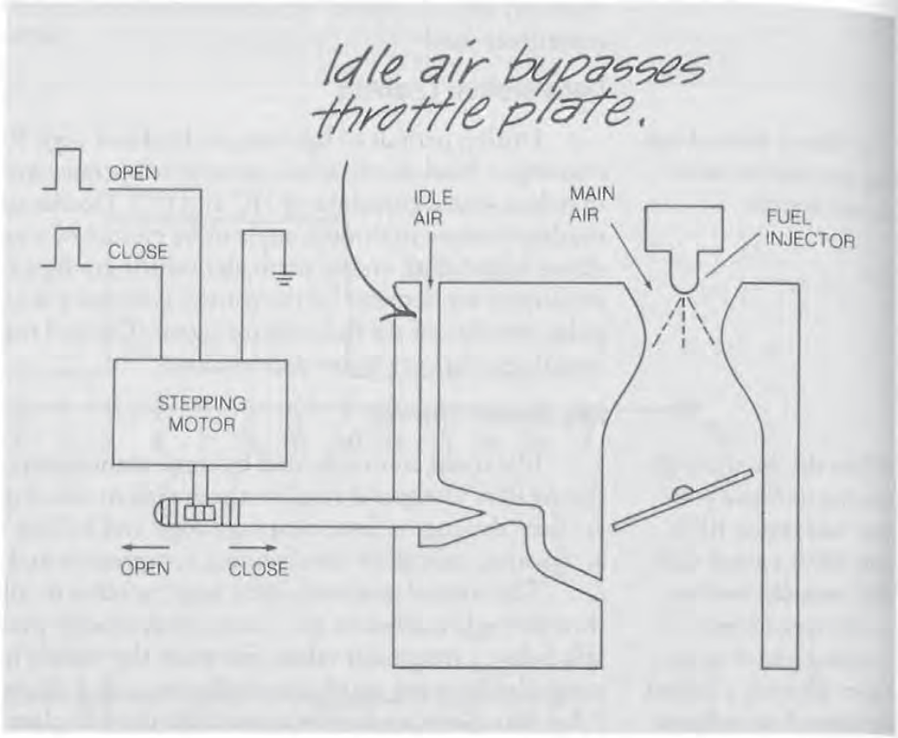
There are various schemes for operating a valve to introduce bypass air for idle control. One relatively common method for controlling the idle speed bypass air uses a special type of motor called a *stepper motor.* A stepper motor moves in fixed angular increments when activated by pulses on its two sets of windings (i.e., open or close). Such a motor can be operated in either direction by supplying pulses in the proper phase to the windings. This is advantageous for idle speed control since the controller can very precisely position the idle bypass valve by sending the proper number of pulses of the correct phasing.

The engine control computer can know precisely the position of the valve in a number of ways. In one way the computer can send sufficient pulses to completely close the valve when the ignition is first switched on. Then it can send open pulses (phased to open the valve) to a specified (known) position.

A block diagram of a simplified idle speed control system is shown in Figure 7.7b. Idle speed is detected by the RPM sensor, and the speed is adjusted to maintain a constant idle RPM. The computer receives digital on/off status inputs from several power-consuming devices attached to the engine, such as the air conditioner clutch switch, park–neutral switch, and the battery charge indicator. These inputs indicate the load that is applied to the engine during idle.

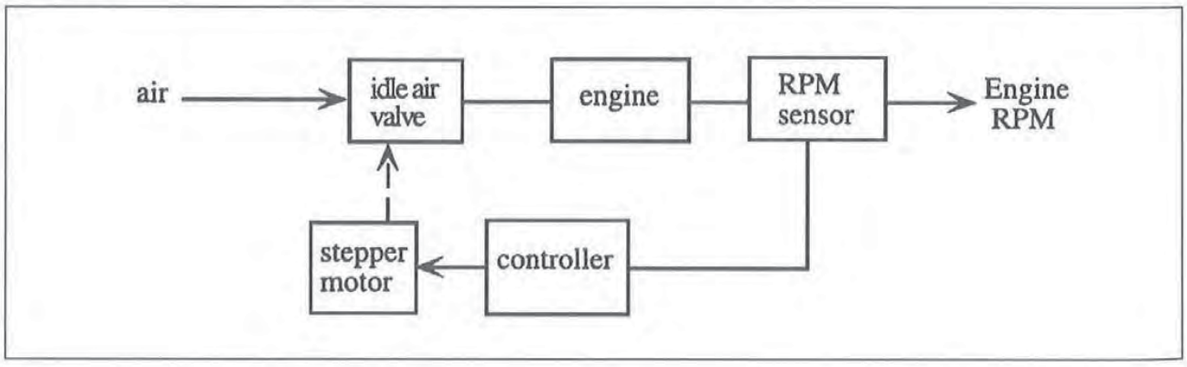
PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Figure 7.7a
Idle Air Control



When the engine is not idling, the idle speed control valve may be completely closed so that the throttle plate has total control of intake air. During periods of deceleration leaning, the idle speed valve may be opened to provide extra air to increase the air/fuel ratio in order to reduce HC emissions.

Figure 7.7b
Idle Air Control



PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

EGR CONTROL

A second electronic engine control subsystem is the control of exhaust gas that is recirculated back to the intake manifold. Under normal operating conditions, engine cylinder temperatures can reach more than 3000°F. The higher the temperature, the more chance the exhaust will have NO_x emissions. As explained in Chapter 5, a small amount of exhaust gas is introduced into the cylinder to replace normal intake air. This results in lower combustion temperatures, which reduces NO_x emissions.

The engine controller also must determine when the EGR valve should be opened or closed.

The control mode selection logic determines when EGR is turned off or on. EGR is turned off during cranking, cold engine temperature (engine warm-up), idling, acceleration, or other conditions demanding high torque.

Since exhaust gas recirculation was first introduced as a concept for reducing NO_x exhaust emissions, its implementation has gone through considerable change. There are in fact many schemes and configurations for EGR realization. We discuss here one method of EGR implementation that incorporates enough features to be representative of all schemes in use today and in the near future.

Fundamental to all EGR schemes is a passageway or port connecting the exhaust and intake manifolds. A valve is positioned along this passageway whose position regulates EGR from zero to some maximum value. Typically the valve is operated by a diaphragm connected to a variable vacuum source, as explained in Chapter 6. The controller operates a solenoid in a periodic variable-duty-cycle mode. The average level of vacuum on the diaphragm (see Chapter 6) varies with the duty cycle. By varying this duty cycle, the control system has proportional control over the EGR valve opening and thereby over the amount of EGR.

In many EGR control systems the controller monitors the differential pressure between the exhaust and intake manifold via a differential pressure sensor (DPS). With the signal from this sensor the controller can calculate the valve opening for the desired EGR level. The amount of EGR required is a predetermined function of the load on the engine (i.e., power produced).

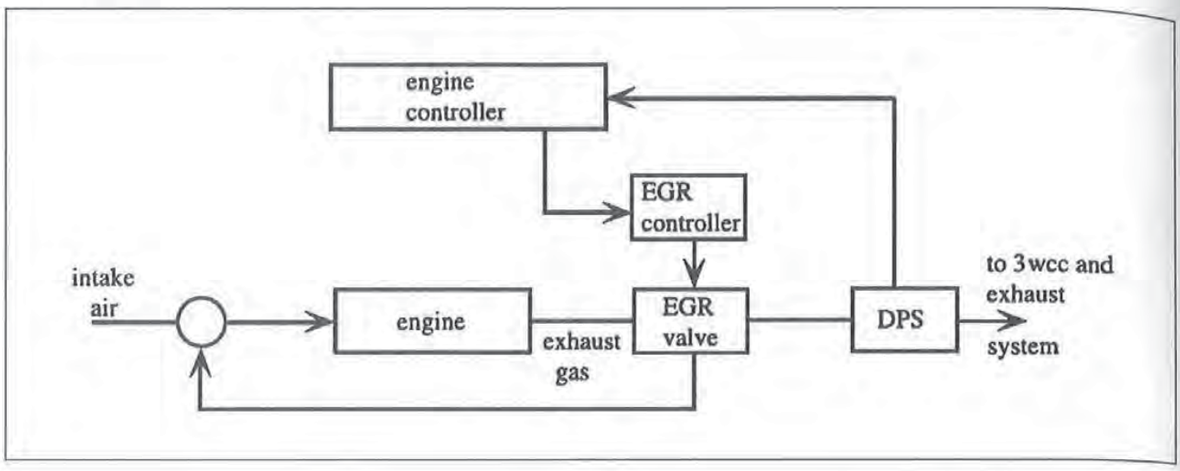
A simplified block diagram for an EGR control system is depicted in Figure 7.8. In this figure the EGR valve is operated by a solenoid-regulated vacuum actuator (coming from the intake). An explanation of this proportional actuator is given in Chapter 6. The engine controller determines the required amount of EGR based on the engine operating condition and the signal from the differential pressure sensor (DPS) between intake and exhaust manifolds. The controller then commands the correct EGR valve position to achieve the desired amount of EGR.

ELECTRONIC IGNITION CONTROL

As we have seen in Chapter 1, an engine must be provided with fuel and air in correct proportions, and the means to ignite this mixture in the form of

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Figure 7.8
EGR Control



an electric spark. Before the development of electronic ignition the traditional ignition system included spark plugs, a distributor, and a high-voltage ignition coil (see Chapter 1). The distributor would sequentially connect the coil output high voltage to the correct spark plug. In addition, it would cause the coil to generate the spark by interrupting the primary current (ignition points) in the desired coil, thereby generating the required spark. The time of occurrence of this spark (i.e., the ignition timing) in relation of the piston to TDC influences the torque generated.

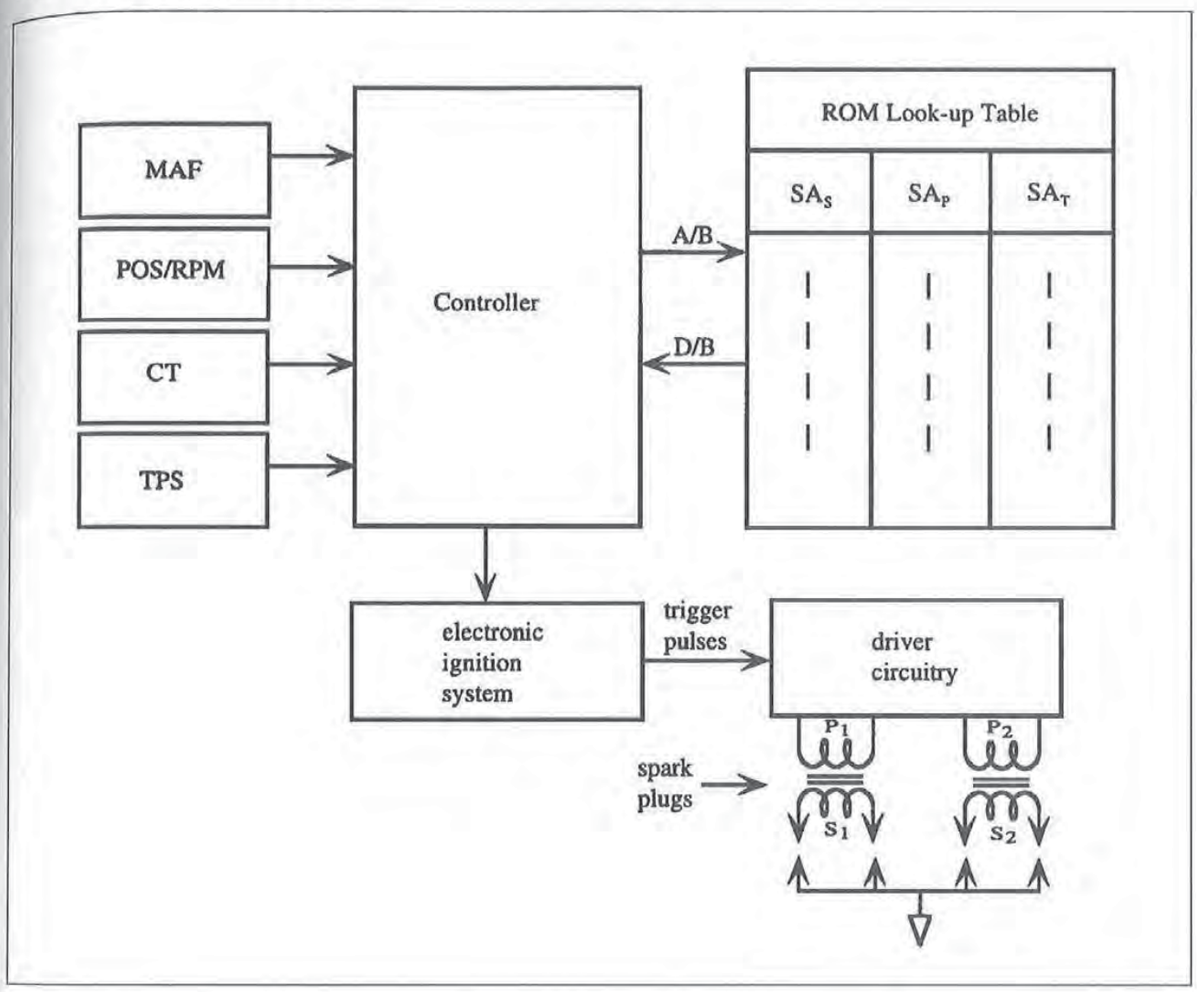
In most present-day electronically controlled engines the distributor has been replaced by multiple coils. Each coil supplies the spark to either one or two cylinders. In such a system the controller selects the appropriate coil and delivers a trigger pulse to ignition control circuitry at the correct time for each cylinder. (Note: In some cases the coil is on the spark plug as an integral unit.)

Figure 7.9a illustrates such a system for an example 4-cylinder engine. In this example a pair of coils provides the spark for firing two cylinders for each coil. Cylinder pairs are selected such that one cylinder is on its compression stroke while the other is on exhaust. The cylinder on compression is the cylinder to be fired (at a time somewhat before it reaches TDC). The other cylinder is on exhaust.

The coil fires the spark plugs for these two cylinders simultaneously. For the former cylinder, the mixture is ignited and combustion begins for the power stroke that follows. For the other cylinder (on exhaust stroke), the combustion has already taken place and the spark has no effect.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

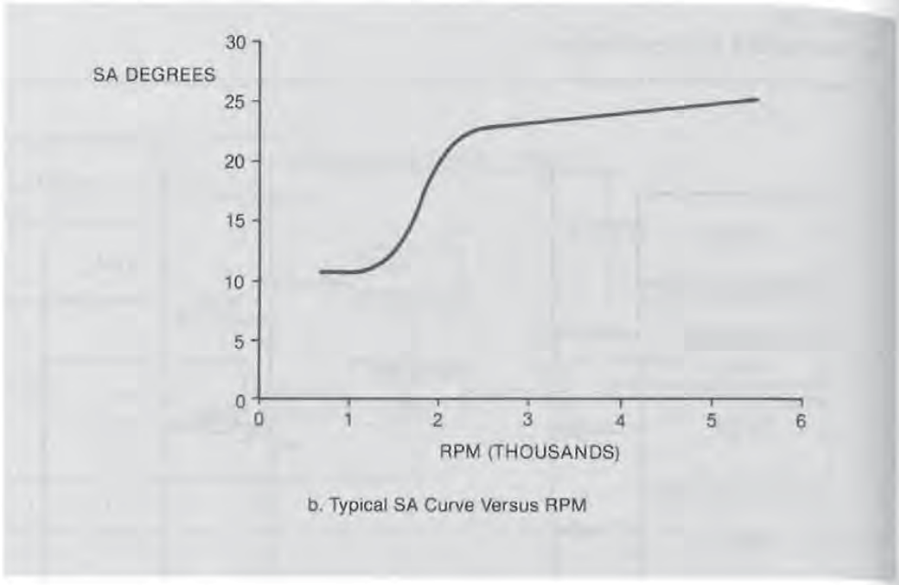
Figure 7.9a
Distributorless Ignition System



Although the mixture for modern emission-regulated engines is constrained to stoichiometry, the spark timing can be varied in order to achieve optimum performance within the mixture constraint. For example, the ignition timing can be chosen to produce the best possible engine torque for any given operating condition. This optimum ignition timing is known for any given engine configuration from studies of engine performance as measured on an engine dynamometer. More will be said about this topic when we discuss closed-loop ignition timing later in this chapter.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Figure 7.9b Distributorless Ignition System



b. Typical SA Curve Versus RPM

Ignition timing can be adjusted to maximize engine performance within emission constraints. The engine control system calculates spark advance from several variables, including MAP and RPM.

The variables that influence the optimum spark timing at any operating condition include RPM, manifold pressure (or mass air flow), barometric pressure, and coolant temperature. The correct ignition timing for each value of these variables is stored in a ROM lookup table. For example, the variation of spark advance (SA) with RPM for a representative engine is shown in Figure 7.9b. The engine control system obtains readings from the various sensors and generates an address to the lookup table (ROM). After reading the data from the lookup tables, the control system computes the correct spark advance. An output signal is generated at the appropriate time to activate the spark.

Figure 7.9a is a schematic of a representative electronic ignition system. In this example configuration the spark advance value is computed in the main engine control (i.e., the controller that regulates fuel). This system receives data from the various sensors (as described above with respect to fuel control) and determines the correct spark advance for the instantaneous operating condition.

In the configuration depicted in Figure 7.9a, the electronic ignition is implemented in a stand-alone ignition module. This solid-state module receives the correct spark advance data and generates electrical signals that operate the coil driver circuitry. These signals are produced in response to timing inputs coming from crankshaft and camshaft signals (POS/RPM).

The coil driver circuits generate the primary current in windings P_1 and P_2 of the coil packs depicted in Figure 7.9a. These primary currents build up during the so-called *dwell period* before the spark is to occur. At the correct time the driver circuits interrupt the primary currents via a solid-state switch. This

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

interruption of the primary current causes the magnetic field in the coil pack to drop rapidly, inducing a very high voltage (20,000–40,000 volts) that causes a spark. In the example depicted in Figure 7.9a, a pair of coil packs, each firing two spark plugs, is shown. Such a configuration would be appropriate for a 4-cylinder engine. Normally there would be one coil pack for each pair of cylinders.

The ignition system described above is known as a *distributorless ignition system* (DIS) since it uses no distributor (see Chapter 1). There are a number of older car models on the road that utilize a distributor. However, the electronic ignition system is the same as that shown in Figure 7.9a, up to the coil packs. In distributor-equipped engines there is only one coil, and its secondary is connected to the rotary switch (or distributor) as described in Chapter 1.

In a typical electronic ignition control system, the total spark advance, SA (in degrees before TDC), is made up of several components that are added together:

$$SA = SA_S + SA_P + SA_T$$

The first component, SA_S, is the basic spark advance, which is a tabulated function of RPM and MAP. The control system reads RPM and MAP, and calculates the address in ROM of the SA_S that corresponds to these values. Typically, the advance of RPM from idle to about 1200 RPM is relatively slow. Then, from about 1200 to about 2300 RPM the increase in RPM is relatively quick. Beyond 2300 RPM, the increase in RPM is again relatively slow. Each engine configuration has its own spark advance characteristic, which is normally a compromise between a number of conflicting factors (the details of which are beyond the scope of this book).

The second component, SA_P, is the contribution to spark advance due to manifold pressure. This value is obtained from ROM lookup tables. Generally speaking, the SA is reduced as pressure increases.

The final component, SA_T, is the contribution to spark advance due to temperature. Temperature effects on spark advance are relatively complex, including such effects as cold cranking, cold start, warm-up, and fully warmed-up conditions and are beyond the scope of this book.

Closed-Loop Ignition Timing

The ignition system described in the foregoing is an open-loop system. The major disadvantage of open-loop control is that it cannot automatically compensate for mechanical changes in the system. Closed-loop control of ignition timing is desirable from the standpoint of improving engine performance and maintaining that performance in spite of system changes.

For best performance, spark is advanced until excessive knock occurs.

One scheme for closed-loop ignition timing is based on the improvement in performance that is achieved by advancing the ignition timing relative to TDC. For a given RPM and manifold pressure, the variation in torque with spark advance is as depicted in Figure 7.10. One can see that

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

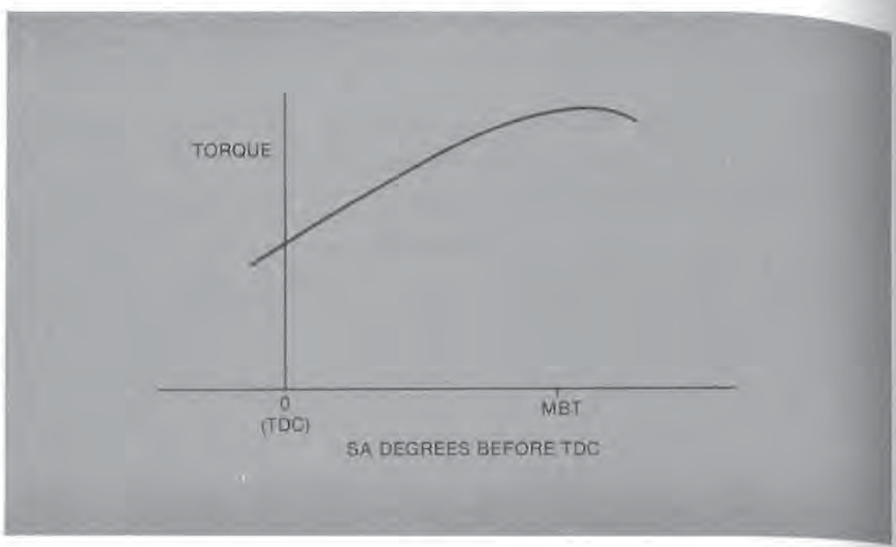


Figure 7.10
Torque versus SA for Typical Engine

advancing the spark relative to TDC increases the torque until a point is reached at which best torque is produced. This spark advance is known as *mean best torque*, or MBT.

When the spark is advanced too far, an abnormal combustion phenomenon occurs that is known as *knocking*. Although the details of what causes knocking are beyond the scope of this book, it is generally a result of a portion of the air–fuel mixture autoigniting, as opposed to being normally ignited by the advancing flame front that occurs in normal combustion following spark ignition. Roughly speaking, the amplitude of knock is proportional to the fraction of the total air and fuel mixture that autoignites. It is characterized by an abnormally rapid rise in cylinder pressure during combustion, followed by very rapid oscillations in cylinder pressure. The frequency of these oscillations is specific to a given engine configuration and is typically in the range of a few kilohertz. Figure 7.11 is a graph of a typical cylinder pressure versus time under knocking conditions. A relatively low level of knock is arguably beneficial to performance, although excessive knock is unquestionably damaging to the engine and must be avoided.

One control strategy for spark advance under closed-loop control is to advance the spark timing until the knock level becomes unacceptable. At this point, the control system reduces the spark advance (retarded spark) until acceptable levels of knock are achieved. Of course, a spark advance control scheme based on limiting the levels of knocking requires a knock sensor such as that explained in Chapter 6. This sensor responds to the acoustical energy in the spectrum of the rapid cylinder pressure oscillations, as shown in Figure 7.11.

Figure 7.12 is a diagram of the instrumentation for measuring knock intensity. Output voltage V_E of the knock sensor is proportional to the

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

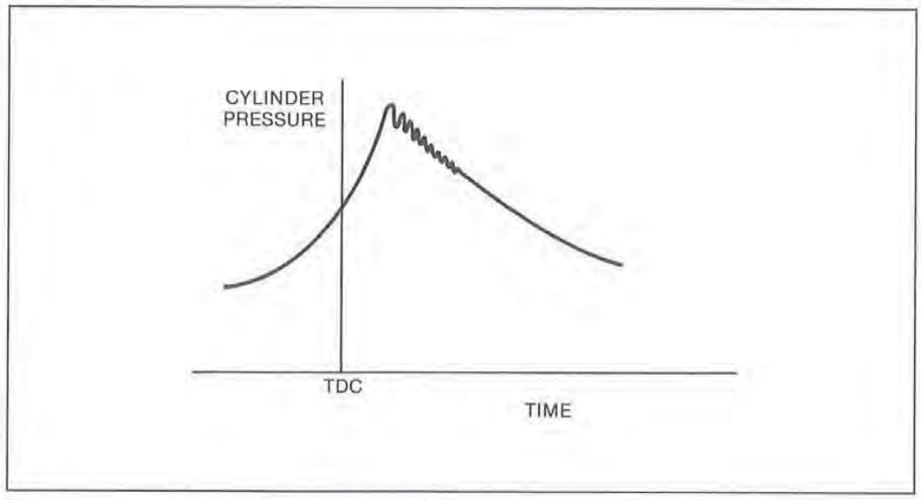


Figure 7.11
Cylinder Pressure (Knocking Condition)

acoustical energy in the engine block at the sensor mounting point. This voltage is sent to a narrow bandpass filter that is tuned to the knock frequency. The filter output voltage V_F is proportional to the amplitude of the knock oscillations, and is thus a "knock signal." The envelope voltage of these oscillations, V_d, is obtained with a detector circuit. This voltage is sent to the controller, where it is compared with a level corresponding to the knock intensity threshold. Whenever the knock level is less than the threshold, the spark is advanced. Whenever it exceeds the threshold, the spark is retarded.

Following the detector in the circuit of Figure 7.12 is an electronic gate that examines the knock sensor output at the time for which the knock amplitude is largest (i.e., shortly after TDC). The gate is, in essence, an electronic switch that is normally open, but is closed for a short interval (from 0 to T) following TDC. It is during this interval that the knock signal is largest in relationship to engine noise. The probability of successfully detecting the knock signal is greatest during this interval. Similarly, the possibility of mistaking engine noise for true knock signal is smallest during this interval.

The final stage in the knock-measuring instrumentation is integration with respect to time; this can be accomplished using an operational amplifier. For example, the circuit of Figure 7.13 could be used to integrate the gate output. The electronic gate actually controls switches S_1 and S_2. The output voltage V_K at the end of the gate interval T is given by:

$$V_K = -(1/RC)\int_0^T V_d(t)\,dt$$

This voltage increases sharply (negative), reaching a maximum amplitude at the end of the gate interval, as shown in Figure 7.13, provided that knock occurs. However, if there is no knock, V_K remains near zero.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

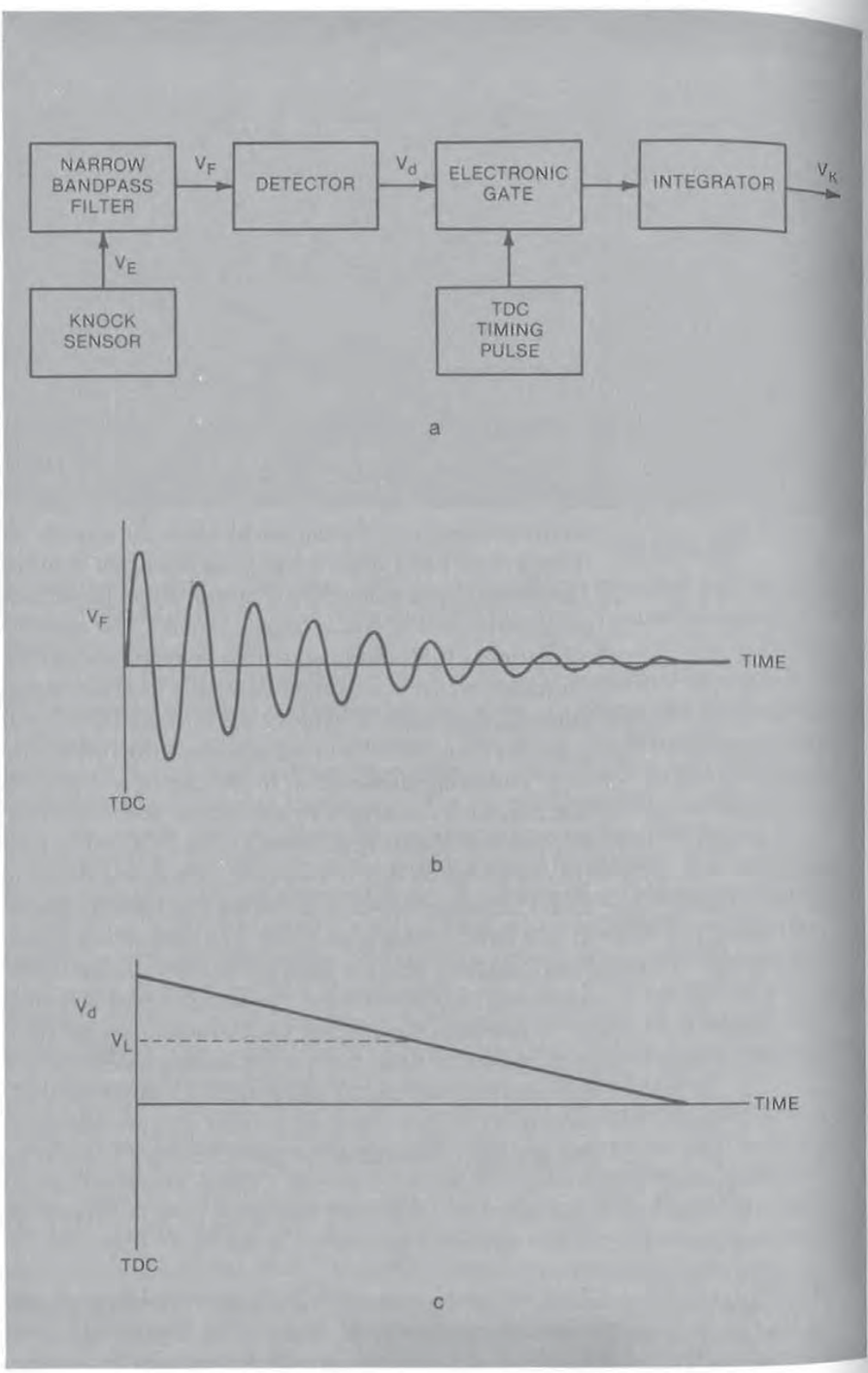
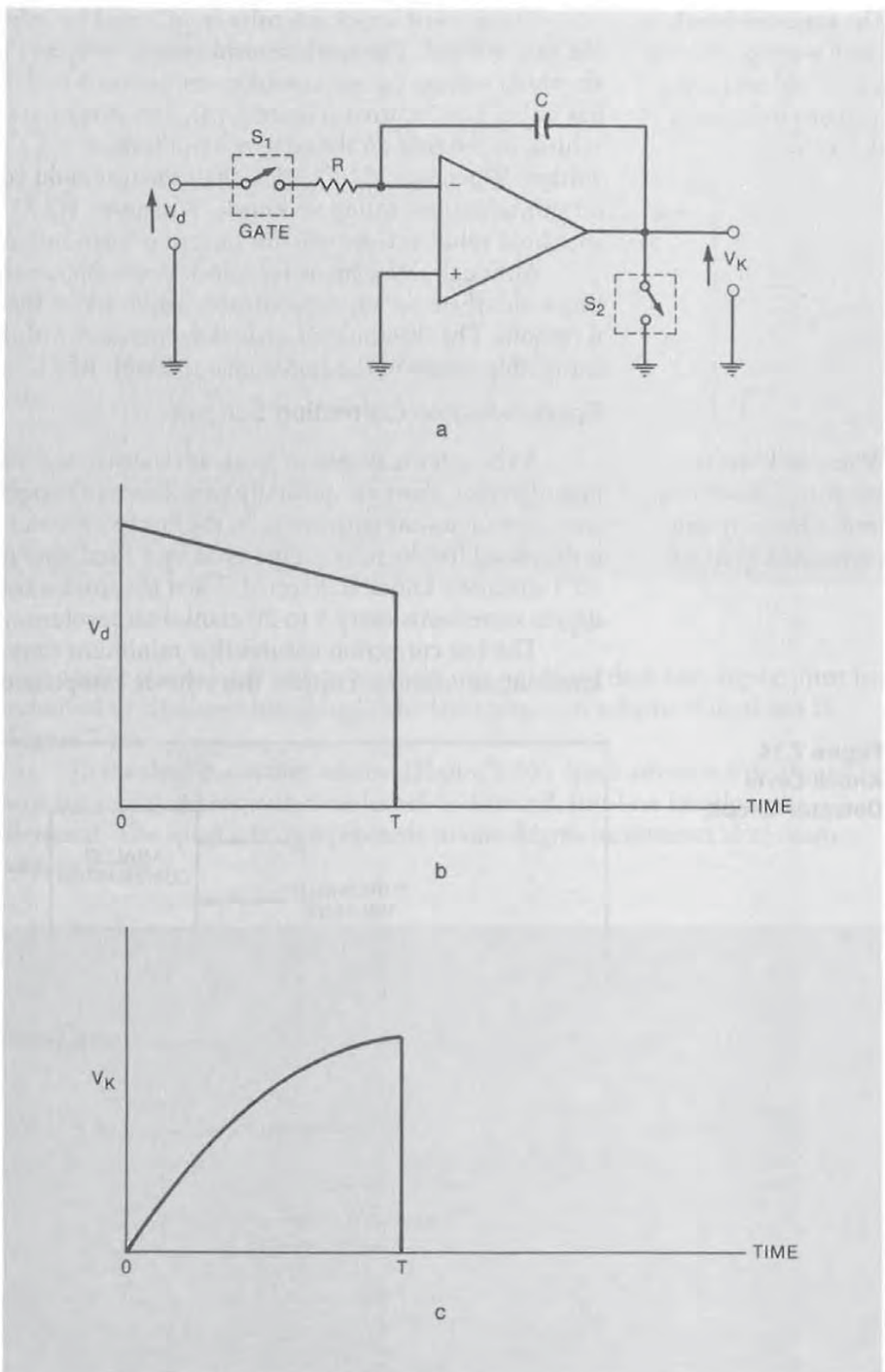


Figure 7.12 Instrumentation and Waveforms for Closed-Loop Ignition Control

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Figure 7.13
Example Integrator Circuit Diagram



PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

The acoustical knock signal is compared with a threshold level corresponding to unacceptable knock.

The level of knock intensity is indicated by voltage $V_K(T)$ at the end of the gate interval. The spark control system compares this voltage with a threshold voltage (using an analog comparator) to determine whether knock has or has not occurred (Figure 7.14). The comparator output voltage is binary valued, depending on the relative amplitude of $V_K(T)$ and the threshold voltage. Whenever $V_K(T)$ is less than the threshold voltage, the comparator output is low, indicating no knock. Whenever $V_K(T)$ is greater than the threshold value, the comparator output is high, indicating knock.

Although this scheme for knock detection has shown a constant threshold, there are some production applications that have a variable threshold. The threshold in such cases increases with RPM because the competing noises in the engine increase with RPM.

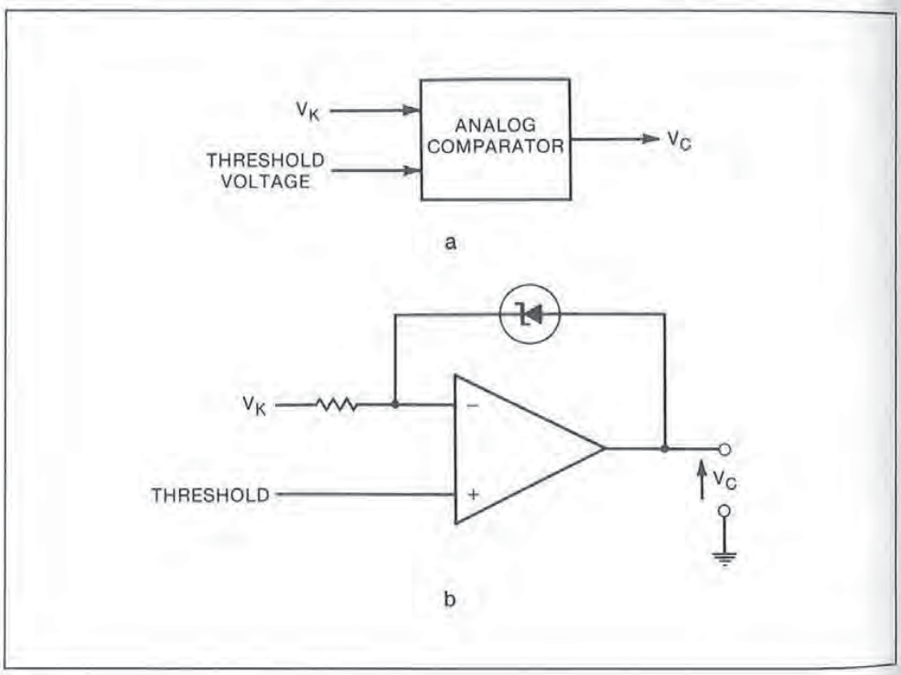
Spark Advance Correction Scheme

Whenever knock is excessive, a closed-loop spark advance system causes spark to retard.

Although the details of spark advance control vary from manufacturer to manufacturer, there are generally two classes of correction that are used: fast correction and slow correction. In the fast correction scheme, the spark advance is decreased for the next engine cycle by a fixed amount (typically from 5° to 10°) whenever knock is detected. Then the spark advance is advanced in one-degree increments every 5 to 20 crankshaft revolutions.

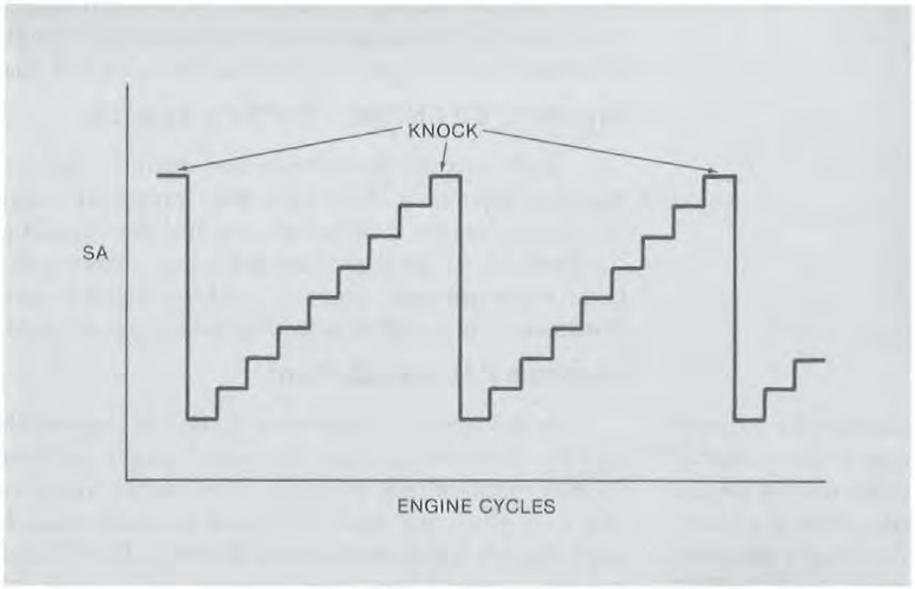
The fast correction ensures that minimum time is spent under heavy knocking conditions. Further, this scheme compensates for hysteresis (i.e., for

Figure 7.14 Knock Level Detector Circuit



PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

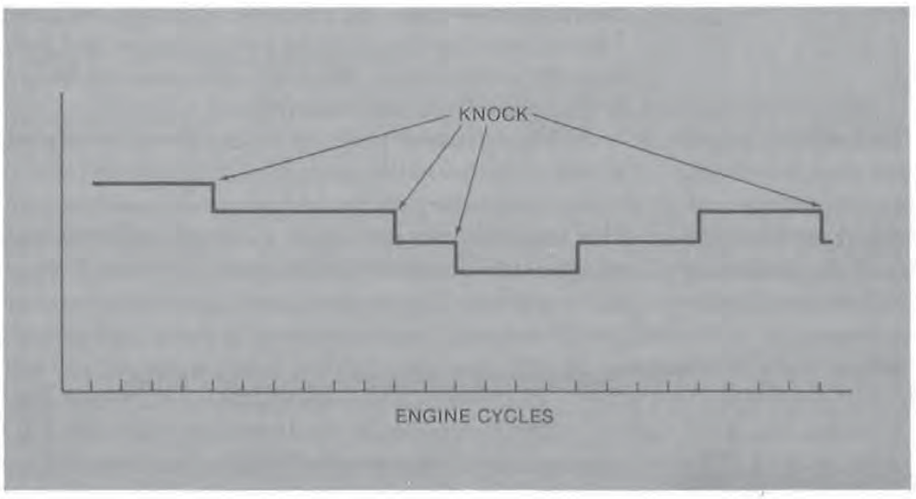
Figure 7.15
Fast Correction
Spark Advance



one degree of spark advance to cause knocking, more than one degree must be removed to eliminate knocking). The fast correction scheme is depicted in Figure 7.15.

In the slow correction scheme (Figure 7.16), spark advance is decreased by one (or more) degree each time knock is detected, until no knocking is detected. The spark advance proceeds in one-degree increments after many engine cycles.

Figure 7.16
Slow Correction
Spark Advance



PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

The slow correction scheme is more of an adaptive closed-loop control than is the fast correction scheme. It is primarily employed to compensate for relatively slow changes in engine condition or fuel quality (i.e., octane rating).

INTEGRATED ENGINE CONTROL SYSTEM

Each control subsystem for fuel control, spark control, and EGR has been discussed separately. However, a fully integrated electronic engine control system can include these subsystems and provide additional functions. (Usually the flexibility of the digital control system allows such expansion quite easily because the computer program can be changed to accomplish the expanded functions.) Several of these additional functions are discussed in the following.

Secondary Air Management

Secondary air management is used to improve performance of the catalytic converter. During engine warm-up, secondary air is routed to the exhaust manifold to speed warm-up of the converter.

Secondary air management is used to improve the performance of the catalytic converter by providing extra (oxygen-rich) air to either the converter itself or to the exhaust manifold. The catalyst temperature must be above about 200°C to efficiently oxidize HC and CO and reduce NO_x. During engine warm-up when the catalytic converter is cold, HC and CO are oxidized in the exhaust manifold by routing secondary air to the manifold. This creates extra heat to speed warm-up of the converter and EGO sensor, enabling the fuel controller to go to the closed-loop mode more quickly.

The converter can be damaged if too much heat is applied to it. This can occur if large amounts of HC and CO are oxidized in the manifold during periods of heavy loads, which call for fuel enrichment, or during severe deceleration. In such cases, the secondary air is directed to the air cleaner, where it has no effect on exhaust temperatures.

After warm-up, the main use of secondary air is to provide an oxygen-rich atmosphere in the second chamber of the three-way catalyst, dual-chamber converter system. In a dual-chamber converter, the first chamber contains rhodium, palladium, and platinum to reduce NO_x and to oxidize HC and CO. The second chamber contains only platinum and palladium. The extra oxygen from the secondary air improves the converter's ability to oxidize HC and CO in the second converter chamber.

The computer controls secondary air by using two solenoid-operated valves that route air to the air cleaner, exhaust manifold, or directly to the converter.

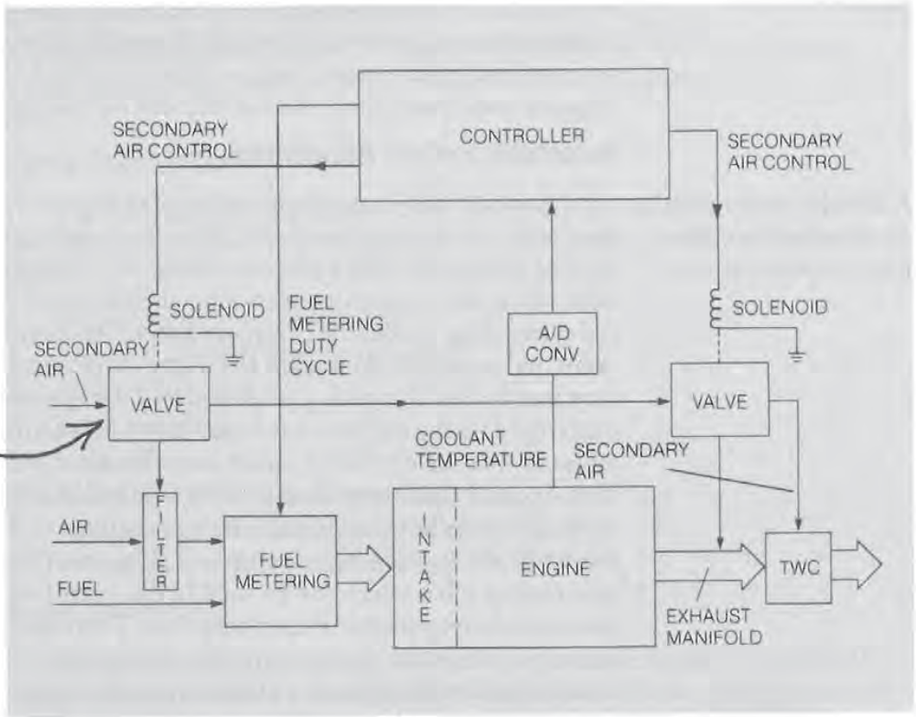
The computer program for the control mode selection logic can be modified to include the conditions for controlling secondary air. The computer controls secondary air by using two solenoid valves similar to the EGR valve. One valve switches air flow to the air cleaner or to the exhaust system. The other valve switches air flow to the exhaust manifold or to the converter. The air routing is based on engine coolant temperature and air/fuel ratio. The control system diagram for secondary air is shown in Figure 7.17.

Evaporative Emissions Canister Purge

During engine-off conditions, the fuel stored in the fuel system tends to evaporate into the atmosphere. To reduce these HC emissions, they are

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Figure 7.17
Secondary Air
Control System



secondary air either to intake, exhaust, or converter.

collected by a charcoal filter in a canister. The collected fuel is released into the intake through a solenoid valve controlled by the computer. This is done during closed-loop operation to reduce fuel calculation complications in the open-loop mode.

Torque Converter Lock-up Control

Automatic transmissions use a hydraulic or fluid coupling to transmit engine power to the wheels. Because of slip, the fluid coupling is less efficient than the nonslip coupling of a pressure-plate manual clutch used with a manual transmission. Thus, fuel economy is usually lower with an automatic transmission than with a standard transmission. This problem has been partially remedied by placing a clutch functionally similar to a standard pressure-plate clutch inside the torque converter of the automatic transmission and engaging it during periods of steady cruise. This enables the automatic transmission to provide fuel economy near that of a manual transmission and still retain the automatic shifting convenience.

Here is a good example of the ease of adding a function to the electronic engine control system. The torque converter locking clutch (TCC) is activated

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

by a lock-up solenoid controlled by the engine control system computer. The computer determines when a period of steady cruise exists from throttle position and vehicle speed changes. It pulls in the locking clutch and keeps it engaged until it senses conditions that call for disengagement.

Automatic System Adjustment

A digital control system can actually "learn" from previous performances.

Another important feature of microcomputer engine control systems is their ability to be programmed to learn from their past experiences. Many control systems use this feature to enable the computer to learn new lookup table values for computing open-loop air/fuel ratios. While the computer is in the closed-loop mode, the computer checks its open-loop calculated air/fuel ratios and compares them with the closed-loop average limit-cycle values. If they match closely, nothing is learned and the open-loop lookup tables are unchanged. If the difference is large, the system controller corrects the lookup tables so that the open-loop values more closely match the closed-loop values. This updated open-loop lookup table is stored in separate memory (RAM), which is always powered directly by a car battery so that the new values are not lost while the ignition key is turned off. The next time the engine is started, the new lookup table values will be used in the open-loop mode and will provide more accurate control of the air/fuel ratio. This feature is very important because it allows the system controller to adjust to long-term changes in engine and fuel system conditions. This feature can be applied in individual subsystem control systems or in the fully integrated control system. If not available initially, it may be added to the system by modifying its control program.

System Diagnosis

Another important feature of microcomputer engine control systems is their ability to diagnose failures in their control systems and alert the operator. Sensor and actuator failures or misadjustments can be easily detected by the computer. For instance, the computer will detect a malfunctioning MAF sensor if the sensor's output goes above or below certain specified limits, or fails to change for long periods of time. A prime example is the automatic adjustment system just discussed. If the open-loop calculations consistently come up wrong, the engine control computer may determine that one of the many sensors used in the open-loop calculations has failed.

Abnormal responses from sensors or actuators can be detected by microcomputer engine control systems.

If the computer detects the loss of a primary control sensor or actuator, it may choose to operate in a different mode until the problem is repaired. The operator is notified of a failure by blinking lights or some other indicator on the instrument panel. Because of the flexibility of the microcomputer engine control system, additional diagnostic programs might be added to accommodate different engine models that contain more or fewer sensors. Keeping the system totally integrated gives the microcomputer controller access to more sensor inputs so they can be checked. Chapter 10 discusses system diagnosis more fully.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

SUMMARY OF CONTROL MODES

Now that a typical electronic engine control system has been discussed, let's summarize what happens in an integrated system operating in the various modes.

Engine Crank (Start)

The following list is a summary of the engine operation in the engine crank (starting) mode. Here, the primary control concern is reliable engine start.

1. Engine RPM at cranking speed.
2. Engine coolant at low temperature.
3. Air/fuel ratio low.
4. Spark retarded.
5. EGR off.
6. Secondary air to exhaust manifold.
7. Fuel economy not closely controlled.
8. Emissions not closely controlled.

Engine Warm-Up

While the engine is warming up, the engine temperature is rising to its normal operating value. Here, the primary control concern is rapid and smooth engine warm-up. A summary of the engine operations during this period follows:

1. Engine RPM above cranking speed at command of driver.
2. Engine coolant temperature rises to minimum threshold.
3. Air/fuel ratio low.
4. Spark timing set by controller.
5. EGR off.
6. Secondary air to exhaust manifold.
7. Fuel economy not closely controlled.
8. Emissions not closely controlled.

Open-Loop Control

The following list summarizes the engine operations when the engine is being controlled with an open-loop system. This is before the EGO sensor has reached the correct temperature for closed-loop operation. Fuel economy and emissions are closely controlled.

1. Engine RPM at command of driver.
2. Engine temperature above warm-up threshold.
3. Air/fuel ratio controlled by an open-loop system to 14.7.
4. EGO sensor temperature less than minimum threshold.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

5. Spark timing set by controller.
6. EGR controlled.
7. Secondary air to catalytic converter.
8. Fuel economy controlled.
9. Emissions controlled.

Closed-Loop Control

For the closest control of emissions and fuel economy under various driving conditions, the electronic engine control system is in a closed loop. Fuel economy and emissions are controlled very tightly. The following is a summary of the engine operation during this period:

1. Engine RPM at command of driver.
2. Engine temperature in normal range (above warm-up threshold).
3. Average air/fuel ratio controlled to 14.7, ±0.05.
4. EGO sensor's temperature above minimum threshold detected by a sensor output voltage indicating a rich mixture of air and fuel for a minimum amount of time.
5. System returns to open loop if EGO sensor cools below minimum threshold or fails to indicate rich mixture for given length of time.
6. EGR controlled.
7. Secondary air to catalytic converter.
8. Fuel economy tightly controlled.
9. Emissions tightly controlled.

Hard Acceleration

When the engine must be accelerated quickly or if the engine is under heavy load, it is in a special mode. Now, the engine controller is primarily concerned with providing maximum performance. Here is a summary of the operation under these conditions:

1. Driver asking for sharp increase in RPM or in engine power, demanding maximum torque.
2. Engine temperature in normal range.
3. Air/fuel ratio rich mixture.
4. EGO not in loop.
5. EGR off.
6. Secondary air to intake.
7. Relatively poor fuel economy.
8. Relatively poor emissions control.

Deceleration and Idle

Slowing down, stopping, and idling are combined in another special mode. The engine controller is primarily concerned with reducing excess

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

emissions during deceleration, and keeping idle fuel consumption at a minimum. This engine operation is summarized in the following list.

1. RPM decreasing rapidly due to driver command or else held constant at idle.
2. Engine temperature in normal range.
3. Air/fuel ratio lean mixture.
4. Special mode in deceleration to reduce emissions.
5. Special mode in idle to keep RPM constant at idle as load varies due to air conditioner, automatic transmission engagement, etc.
6. EGR on.
7. Secondary air to intake.
8. Good fuel economy during deceleration.
9. Poor fuel economy during idle, but fuel consumption kept to minimum possible.

IMPROVEMENTS IN ELECTRONIC ENGINE CONTROL

Although major improvements have been made in electronic engine control, the fuel strategy continues to maintain stoichiometry.

The digital engine control system in this chapter has been made possible by a rapid evolution of the state of technology. Some of this technology has been briefly mentioned in this chapter. It is worthwhile to review some of the technological improvements that have occurred in digital engine control in greater detail to fully appreciate the capabilities of modern digital engine control.

Integrated Engine Control System

One of the developments that has occurred since the introduction of digital engine control technology is the integration of the various functions into a single control unit. Whereas the earlier systems in many cases had separate control systems for fuel and ignition control, the trend is toward integrated control. This trend has been made possible, in part, by improvements in digital hardware and in computational algorithms and software. For example, one of the hardware improvements that has been achieved is the operation of the microprocessor (MPU) at higher clock frequencies. This higher frequency results in a reduction of the time for any given MPU computation, thereby permitting greater computational capability. This increased computational capability has made it possible, in turn, to have more precise control of fuel delivery during rapid transient engine operation.

Except for long steady cruise while driving on certain rural roads or freeways, the automobile engine is operated under changing load and RPM conditions. The limitations in the computational capability of early engine control systems restricted the ability of the controller to continuously maintain the air/fuel ratio at stoichiometry under such changing operating conditions. The newer, more capable digital engine control systems are more precise than the earlier versions at maintaining stoichiometry and therefore

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

operate more of the time within the optimum window for the three-way catalytic converter.

Moreover, since the control of fuel and ignition requires, in some cases, data from the same sensor set, it is advantageous to have a single integrated system for fuel and ignition timing control. The newer engine controllers have the capability to maintain stoichiometry and simultaneously optimize ignition timing.

Oxygen Sensor Improvements

Improvements have also been made in the exhaust gas oxygen sensor, which remains today as the primary sensor for closed-loop operation in cars equipped with the three-way catalyst. As we have seen, the signal from the oxygen sensor is not useful for closed-loop control until the sensor has reached a temperature of about 300°C. Typically, the temperature of the sensor is too low during the starting and engine warm-up phase, but it can also be too low during relatively long periods of deceleration. It is desirable to return to closed-loop operation in as short a time as possible. Thus the oxygen sensor must reach its minimum operating temperature in the shortest possible time.

An improved exhaust gas oxygen sensor has been developed that incorporates an electric heating element inside the sensor, as shown in Figure 7.18. This EGO sensor is known as the heated exhaust gas oxygen, or HEGO, sensor. The heat current is automatically switched on and off depending on the engine operating condition. The operating regions in which heating is applied are determined by the engine control system as derived from engine RPM and MAP sensors. The heating element is made from resistive material and derives heat from the power dissipated in the associated resistance. The HEGO sensor

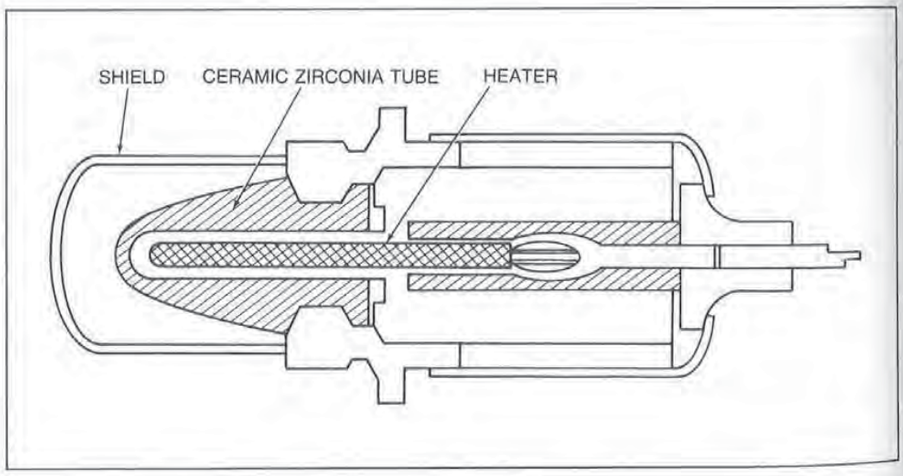


Figure 7.18
Heated Exhaust Gas Oxygen Sensor

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

is packaged in such a way that this heat is largely maintained within the sensor housing, thereby leading to a relatively rapid temperature rise.

Normally, the heating element need only be turned on for cold-start operations. Shortly after engine start the exhaust gas has sufficient heat to maintain the EGO sensor at a suitable temperature.

Fuel Injection Timing

Earlier in this chapter, the fuel control methods and algorithms were explained for a sequential multipoint fuel injection system. In such a fuel control system, it was shown that a separate fuel injector is provided for each cylinder. The fuel injector for each cylinder is typically mounted in the intake manifold such that fuel is sprayed directly into the intake port of the corresponding cylinder during the intake stroke.

During the intake stroke, the intake valve is opened and the piston is moving down from top dead center (TDC). Figure 7.19 illustrates the timing for the fuel injectors for a 4-cylinder engine. It can be seen that in two complete engine revolutions (as indicated by the No. 1 cylinder position), all four injectors have been switched on for a time $T(n)$. This pulse duration results in delivery of the desired quantity of fuel for the nth engine cycle. This system provides for highly uniform fueling of all the cylinders and is superior in performance to either carburetors or throttle body fuel injectors.

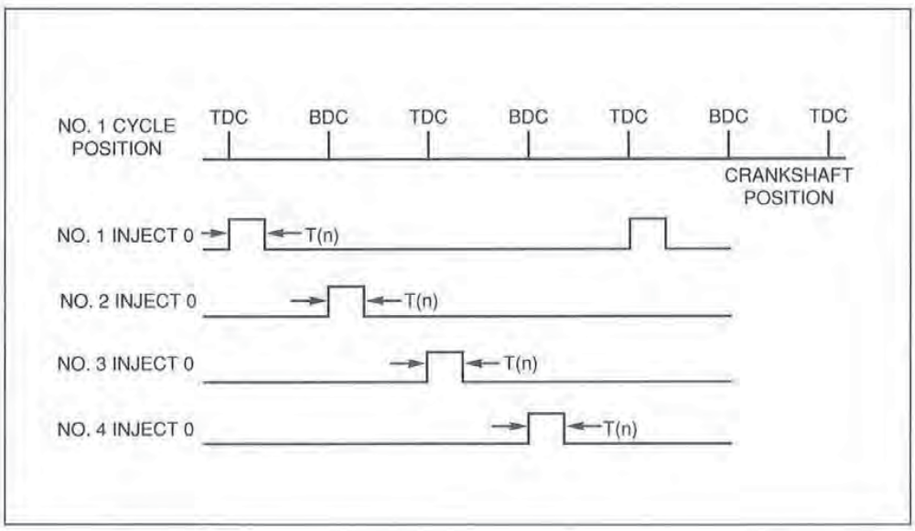


Figure 7.19
Injector Timing for 4-Cylinder Engine

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Quiz for Chapter 7

1. A typical fuel control system may include the following components
   - **a.** MAF sensor
   - **b.** fuel injector
   - **c.** EGO sensor
   - **d.** all of the above
2. A fuel control system
   - **a.** has many operating modes
   - **b.** is never operated in open-loop mode
   - **c.** does not control air/fuel ratio during warm-up
   - **d.** none of the above
3. During hard deceleration the engine requires
   - **a.** very rich mixture
   - **b.** very lean mixture
   - **c.** stoichiometric mixture
   - **d.** none of the above
4. Electronic control system for ignition can perform
   - **a.** timing for maximum torque
   - **b.** correct timing calculation with respect to RPM
   - **c.** correct timing calculation with respect to MAP
   - **d.** all of the above
5. The controller discussed in this chapter is what type of controller?
   - **a.** analog
   - **b.** digital
   - **c.** both analog and digital
6. A low air/fuel ratio is what type of fuel mixture?
   - **a.** lean
   - **b.** rich
   - **c.** poor
   - **d.** fat
7. Open- and closed-loop fuel control systems control air/fuel ratio near which of the following?
   - **a.** rich
   - **b.** lean
   - **c.** stoichiometry
   - **d.** rich and lean
8. Acceleration enrichment is used for what purpose?
   - **a.** reduce fuel consumption
   - **b.** reduce exhaust emissions
   - **c.** provide maximum torque
   - **d.** provide minimum fuel economy
9. Idle speed control is used for what reason?
   - **a.** maximum idle speed
   - **b.** minimum idle fuel consumption
   - **c.** deceleration leaning
   - **d.** maintaining desired idle speeds
10. Under closed-loop ignition timing control, spark advance is limited by
    - **a.** the distributor rotation
    - **b.** knock
    - **c.** MBT
    - **d.** coolant temperature

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

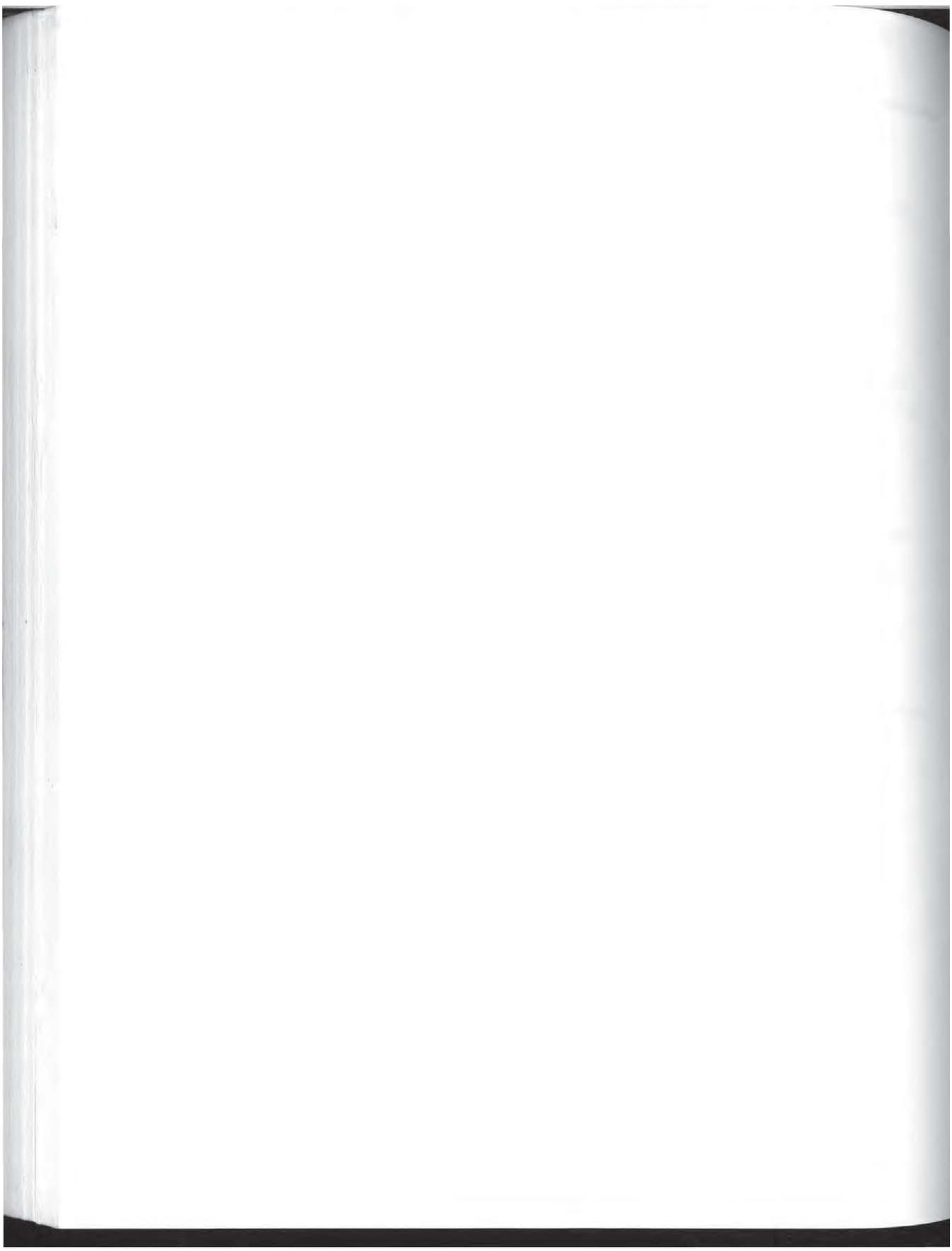
11. The secondary air management system is used
- **a.** to control EGR
- **b.** to avoid knock
- **c.** with low-octane fuels
- **d.** to improve performance of the catalytic converter

12. When knock is detected in a closed-loop ignition system, spark timing is
- **a.** initially advanced then retarded slowly
- **b.** always advanced to BDC
- **c.** retarded then advanced
- **d.** none of the above

13. Secondary functions of a digital engine control system may include
- **a.** evaporative emissions canister purge
- **b.** torque converter lockup
- **c.** secondary air management
- **d.** all of the above

14. In a direct electronic ignition control system
- **a.** the distributor is not required
- **b.** spark plugs are not needed
- **c.** the coil is not needed
- **d.** none of the above

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565



Vehicle Motion Control

Electronic controls can automate some driver functions that were previously performed manually.

A cruise control is a closed-loop system that uses feedback of vehicle speed to adjust throttle position.

The previous chapter discussed the application of digital electronics to engine control. This chapter discusses the application of electronics to vehicle motion control systems such as cruise control, tire slip control, ride control, antilock braking, and electronic power steering control.

TYPICAL CRUISE CONTROL SYSTEM

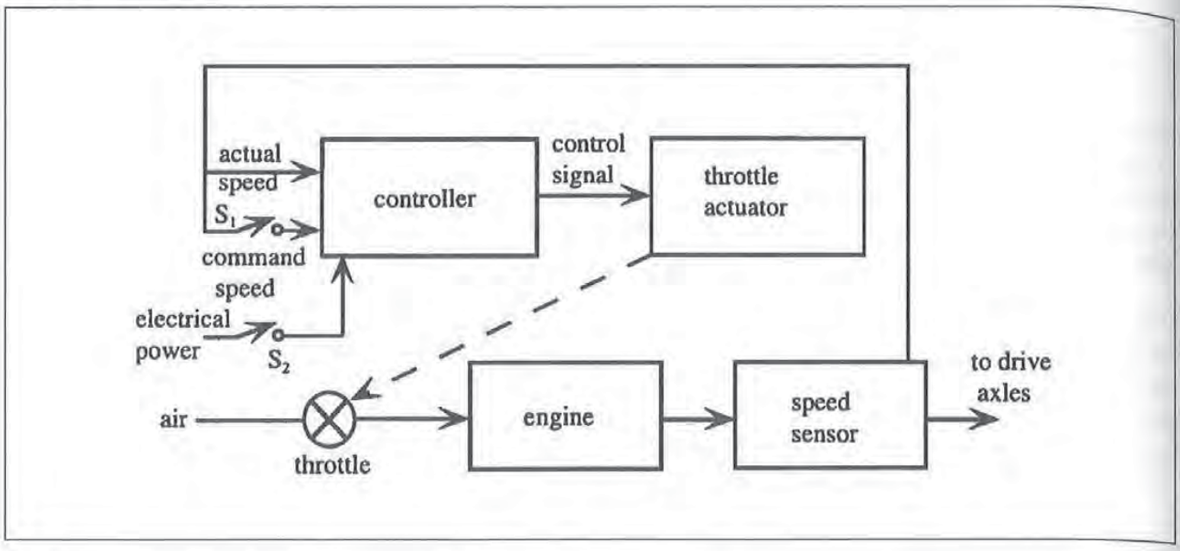
Automotive cruise control is an excellent example of the type of electronic feedback control system that was discussed in general terms in Chapter 2. Recall that the components of a control system include the plant, or system being controlled, and a sensor for measuring the plant variable being regulated. It also includes an electronic control system that receives inputs in the form of the desired value of the regulated variable and the measured value of that variable from the sensor. The control system generates an error signal constituting the difference between the desired and actual values of this variable. It then generates an output from this error signal that drives an electromechanical actuator. The actuator controls the input to the plant in such a way that the regulated plant variable is moved toward the desired value.

In the case of a cruise control, the variable being regulated is the vehicle speed. The driver manually sets the car speed at the desired value via the accelerator pedal. Upon reaching the desired speed the driver activates a momentary contact switch that sets that speed as the command input to the control system. From that point on, the cruise control system maintains the desired speed automatically by operating the throttle via a throttle actuator. The plant being controlled consists of the power train (i.e., engine and drivetrain), which drives the vehicle through the drive axles and wheels. The load on this plant includes friction and aerodynamic drag as well as a portion of the vehicle weight when the car is going up and down hills.

The configuration for a typical automotive cruise control is shown in Figure 8.1. The momentary contact (push-button) switch that sets the command speed is denoted S_1 in Figure 8.1. Also shown in this figure is a disable switch that completely disengages the cruise control system from the power supply such that throttle control reverts back to the accelerator pedal. This switch is denoted S_2 in Figure 8.1 and is a safety feature. In an actual cruise control system the disable function can be activated in a variety of ways, including the master power switch for the cruise control system, and a brake pedal–activated switch that disables the cruise control any time that the brake pedal is moved from its rest position. The throttle actuator opens and closes the throttle in response to the error between the desired and actual speed.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Figure 8.1
Cruise Control Configuration



Whenever the actual speed is less than the desired speed the throttle opening is increased by the actuator, which increases vehicle speed until the error is zero, at which point the throttle opening remains fixed until either a disturbance occurs or the driver calls for a new desired speed.

A block diagram of a cruise control system is shown in Figure 8.2. In the cruise control depicted in this figure, a proportional integral (PI) control strategy has been assumed. However, there are many cruise control systems still on the road today with proportional (P) controllers. Nevertheless, the PI controller is representative of good design for such a control system since it can reduce speed errors due to disturbances (such as hills) to zero (as explained in Chapter 2). In this strategy an error e is formed by subtracting (electronically) the actual speed V_a from the desired speed V_d:

$$e = V_d - V_a$$

The controller then electronically generates the actuator signal by combining a term proportional to the error ($K_P e$) and a term proportional to the integral of the error (that is, $K_I \int e\,dt$). The actuator signal u is a combination of these two terms:

$$u = K_P e + K_I \int e\,dt$$

The throttle opening is proportional to the value of this actuator signal.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

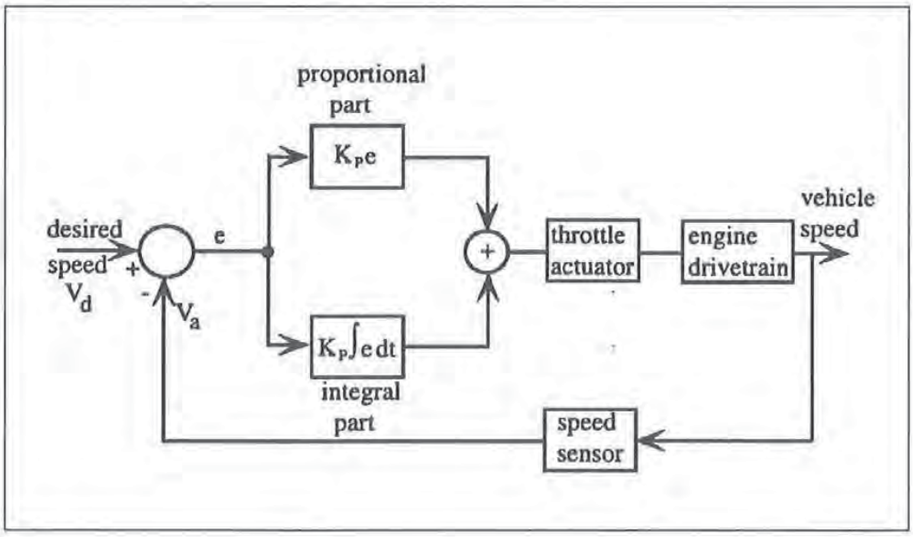


Figure 8.2
Cruise Control Block Diagram

Operation of the system can be understood by first considering the operation of a proportional controller (that is, imagine that the integral term is not present for the sake of this preliminary discussion). We assume that the driver has reached the desired speed (say, 60 mph) and activated the speed set switch. If the car is traveling on a level road at the desired speed, then the error is zero and the throttle remains at a fixed position.

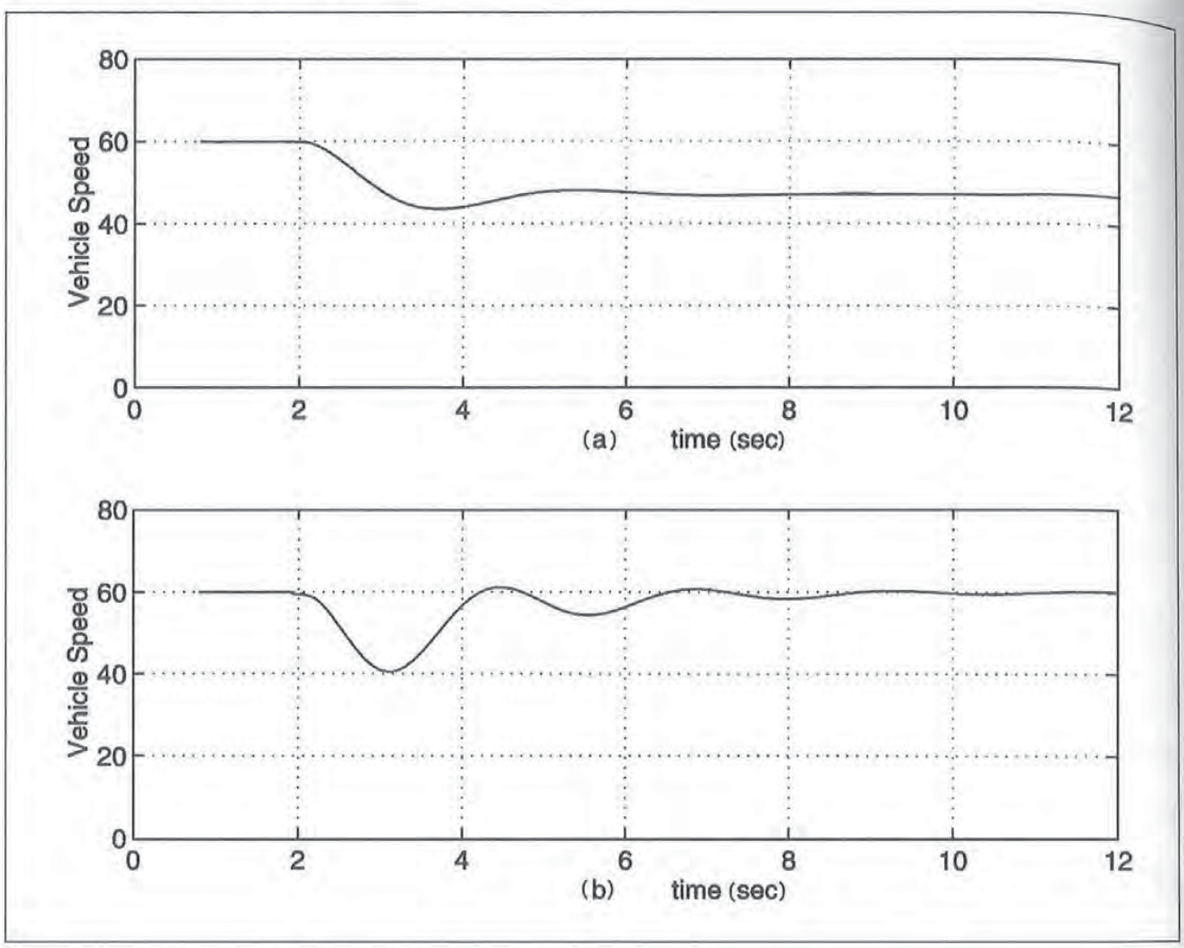
If the car were then to enter a long hill with a steady positive slope (i.e., a hill going up) while the throttle is set at the cruise position for level road, the engine will produce less power than required to maintain that speed on the hill. The hill represents a disturbance to the cruise control system. The vehicle speed will decrease, thereby introducing an error to the control system. This error, in turn, results in an increase in the signal to the actuator, causing an increase in engine power. This increased power results in an increase in speed. However, in a proportional control system the speed error is not reduced to zero since a nonzero error is required so that the engine will produce enough power to balance the increased load of the disturbance (i.e., the hill).

The speed response to the disturbance is shown in Figure 8.3a. When the disturbance occurs, the speed drops off and the control system reacts immediately to increase power. However, a certain amount of time is required for the car to accelerate toward the desired speed. As time progresses, the speed reaches a steady value that is less than the desired speed, thereby accounting for the steady error (e_s) depicted in Figure 8.3a (i.e., the final speed is less than the starting 60 mph).

If we now consider a PI control system, we will see that the steady error when integrated produces an ever-increasing output from the integrator. This increasing output causes the actuator to increase further, with a resulting speed

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Figure 8.3
Cruise Control Speed Performance

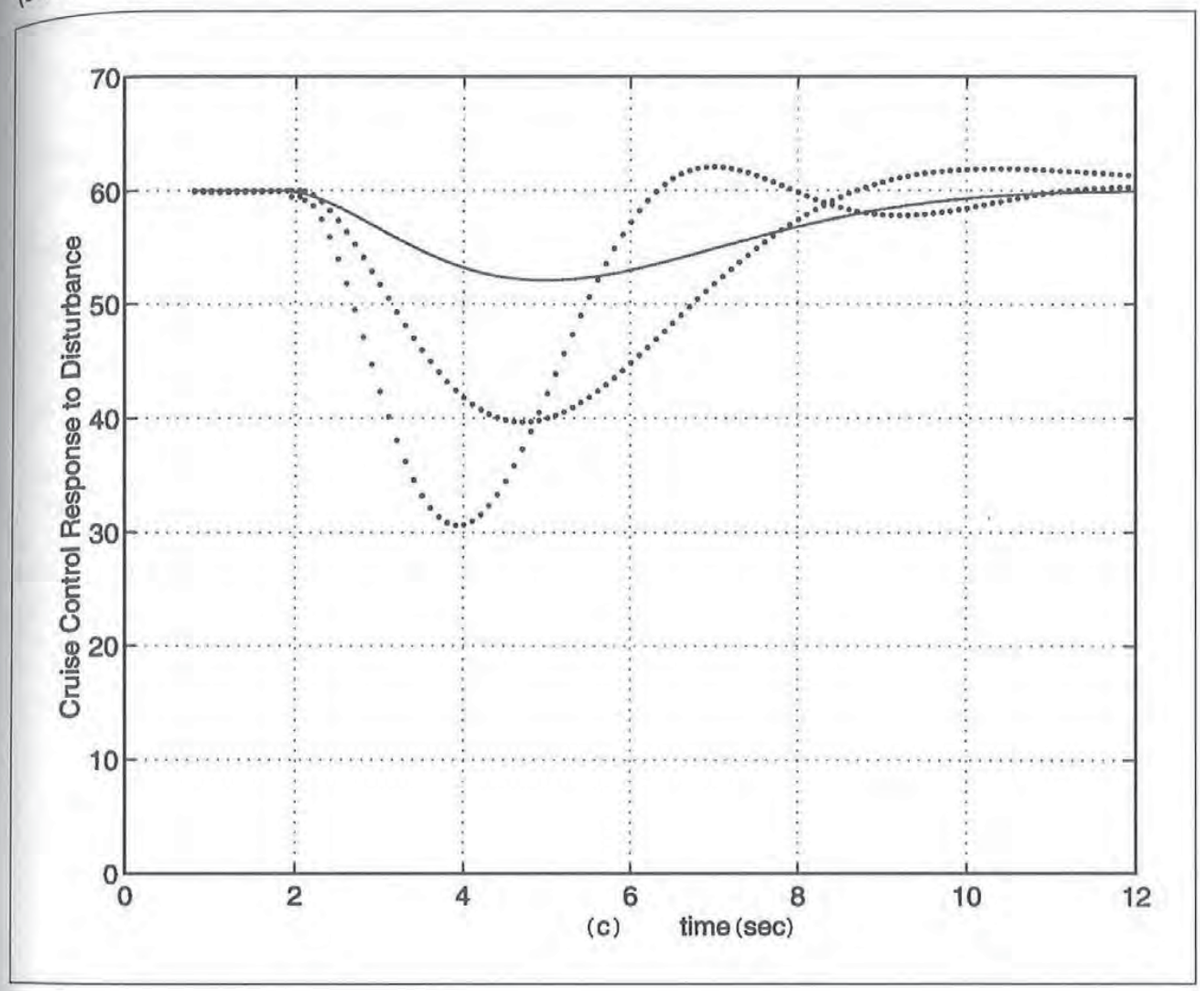


increase. In this case the actuator output will increase until the error is reduced to zero. The response of the cruise control with PI control is shown in Figure 8.3b.

The response characteristics of a PI controller depend strongly on the choice of the gain parameters K_P and K_I. It is possible to select values for these parameters to increase the speed of the system response to disturbance. If the speed increases too rapidly, however, overshoot will occur and the actual speed will oscillate around the desired speed. The amplitude of oscillations decreases by an amount determined by a parameter called the *damping ratio*. The damping ratio that produces the fastest response without overshoot is called *critical damping*. A damping ratio less than critically damped is said to be *underdamped*, and one greater than critically damped is said to be *overdamped*.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Figure 8.3
(continued)



Speed Response Curves

When a new speed is requested, the time required for the vehicle to reach that speed is affected by the control system's damping coefficient.

The curves of Figure 8.3c show the response of a cruise control system with a PI control strategy to a sudden disturbance. These curves are all for the same car cruising initially at 60 mph along a level road and encountering an upsloping hill. The only difference in the response of these curves is the controller gain parameters.

Consider, first, the curve that initially drops to about 30 mph and then increases, overshooting the desired speed and oscillating above and

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

below the desired speed until it eventually decays to the desired 60 mph. This curve has a relatively low damping ratio as determined by the controller parameters K_p and K_I and takes more time to come to the final steady value.

Next, consider the curve that drops initially to about 40 mph, then increases with a small overshoot and decays to the desired speed. The numerical value for this damping ratio (see Chapter 2) is about .7, whereas the first curve had a damping ratio of about .4. Finally, consider the solid curve of Figure 8.3c. This curve corresponds to critical damping. This situation involves the most rapid response of the car to a disturbance, with no overshoot.

The importance of these performance curves is that they demonstrate how the performance of a cruise control system is affected by the controller gains. These gains are simply parameters that are contained in the control system. They determine the relationship between the error, the integral of the error, and the actuator control signal.

Usually a control system designer attempts to balance the proportional and integral control gains so that the system is optimally damped. However, because of system characteristics, in many cases it is impossible, impractical, or inefficient to achieve the optimal time response and therefore another response is chosen. The control system should make the engine drive force react quickly and accurately to the command speed, but should not overtax the engine in the process. Therefore, the system designer chooses the control electronics that provide the following system qualities:

1. Quick response
2. Relative stability
3. Small steady-state error
4. Optimization of the control effort required

Digital Cruise Control

The explanation of the operation of cruise control thus far has been based on a continuous-time formulation of the problem. This formulation correctly describes the concept for cruise control regardless of whether the implementation is by analog or digital electronics. Cruise control is now mostly implemented digitally using a microprocessor-based computer. For such a system, proportional and integral control computations are performed numerically in the computer. A block diagram for a typical digital cruise control is shown in Figure 8.4. The vehicle speed sensor (described later in this chapter) is digital. When the car reaches the desired speed, S_d, the driver activates the speed set switch. At this time, the output of the vehicle speed sensor is transferred to a storage register.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

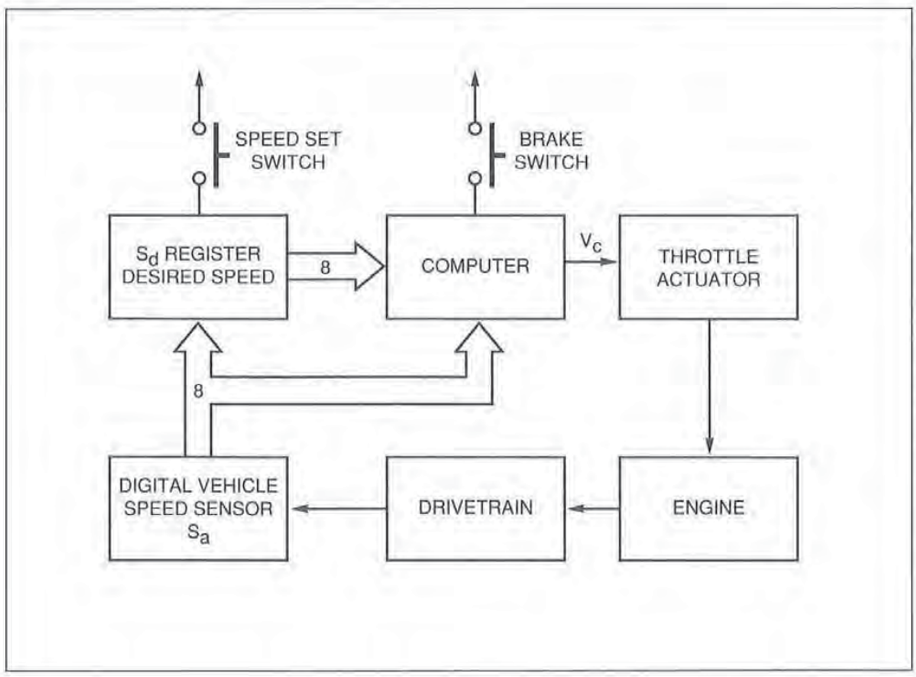


Figure 8.4 Digital Cruise Control System

The computer continuously reads the actual vehicle speed, S_a, and generates an error, e_n, at the sample time, t_n (n is an integer). $e_n = S_d - S_a$ at time t_n. A control signal, d, is computed that has the following form:

$$d = K_P e_n + K_I \sum_{m=1}^{M} e_{n-m}$$

(Note: the symbol Σ in this equation means to add the M previously calculated errors to the present error.) This sum, which is computed in the cruise control computer, is then multiplied by the integral gain K_I and added to the most recent error multiplied by the proportional gain K_P to form the control signal.

This control signal is actually the duty cycle of a square wave (V_c) that is applied to the throttle actuator (as explained later). The throttle opening increases or decreases as d increases or decreases due to the action of the throttle actuator.

The operation of the cruise control system can be further understood by examining the vehicle speed sensor and the actuator in detail. Figure 8.5a is a sketch of a sensor suitable for vehicle speed measurement.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Figure 8.5a Digital Speed Sensor

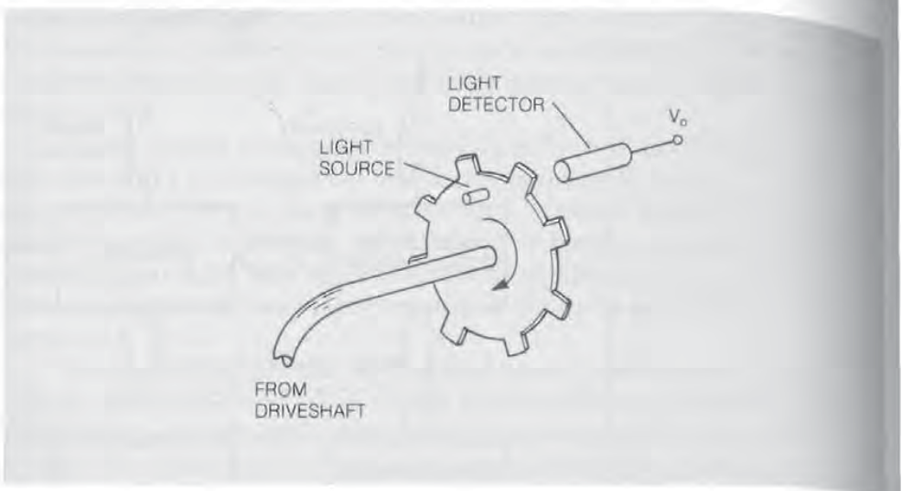
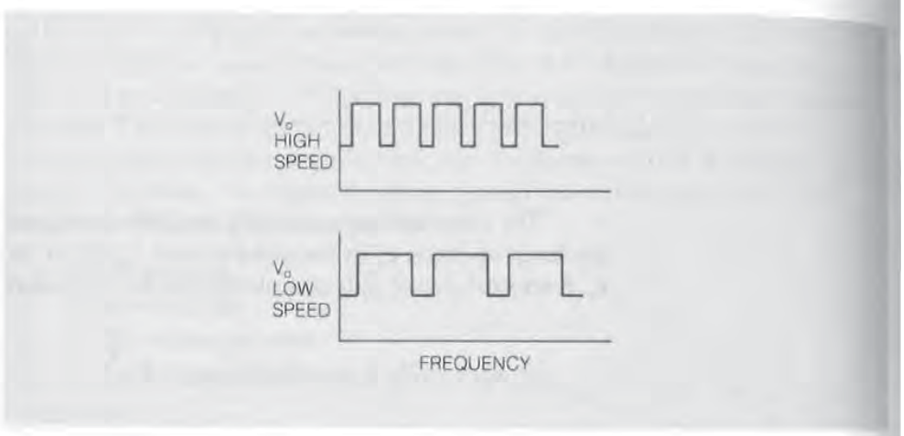


Figure 8.5b Digital Speed Signal



In a typical vehicle speed measurement system, the vehicle speed information is mechanically coupled to the speed sensor by a flexible cable coming from the driveshaft, which rotates at an angular speed proportional to vehicle speed. A speed sensor driven by this cable generates a pulsed electrical signal (Figure 8.5b) that is processed by the computer to obtain a digital measurement of speed.

A speed sensor can be implemented magnetically or optically. The magnetic speed sensor was discussed in Chapter 6, so we hypothesize an optical sensor for the purposes of this discussion. For the hypothetical optical sensor, a flexible cable drives a slotted disk that rotates between a light source and a light detector. The placement of the source, disk, and detector is such that the slotted disk interrupts or passes the light from source to detector, depending on

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

whether a slot is in the line of sight from source to detector. The light detector produces an output voltage whenever a pulse of light from the light source passes through a slot to the detector. The number of pulses generated per second is proportional to the number of slots in the disk and the vehicle speed:

$$f = NSK$$

where,

f is the frequency in pulses per second
N is the number of slots in the sensor disk
S is the vehicle speed
K is the proportionality constant that accounts for differential gear ratio and wheel size

It should be noted that either a magnetic or optical speed sensor generates a pulse train such as described here.

The output pulses are passed through a sample gate to a digital counter (Figure 8.6). The gate is an electronic switch that either passes the pulses to the counter or does not pass them depending on whether the switch is closed or open. The time interval during which the gate is closed is precisely controlled by the computer. The digital counter counts the number of pulses from the light detector during time t that the gate is open. The number of pulses P that is counted by the digital counter is given by:

$$P = tNSK$$

That is, the number P is proportional to vehicle speed S. The electrical signal in the binary counter is in a digital format that is suitable for reading by the cruise control computer.

Throttle Actuator

The throttle actuator is an electromechanical device that, in response to an electrical input from the controller, moves the throttle through some appropriate mechanical linkage. Two relatively common throttle actuators

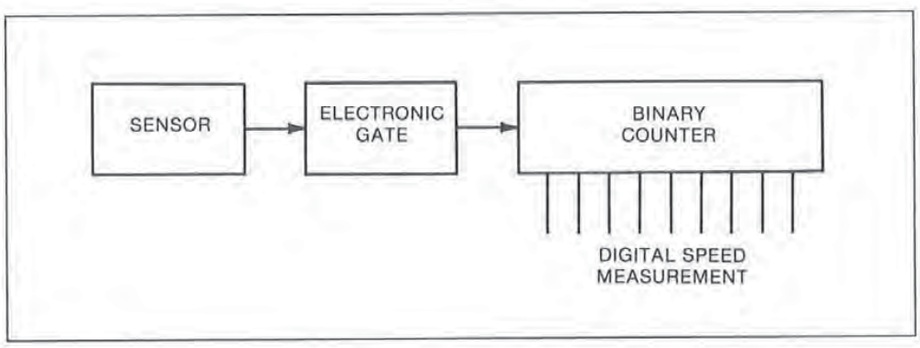


Figure 8.6 Digital Speed Measurement System

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

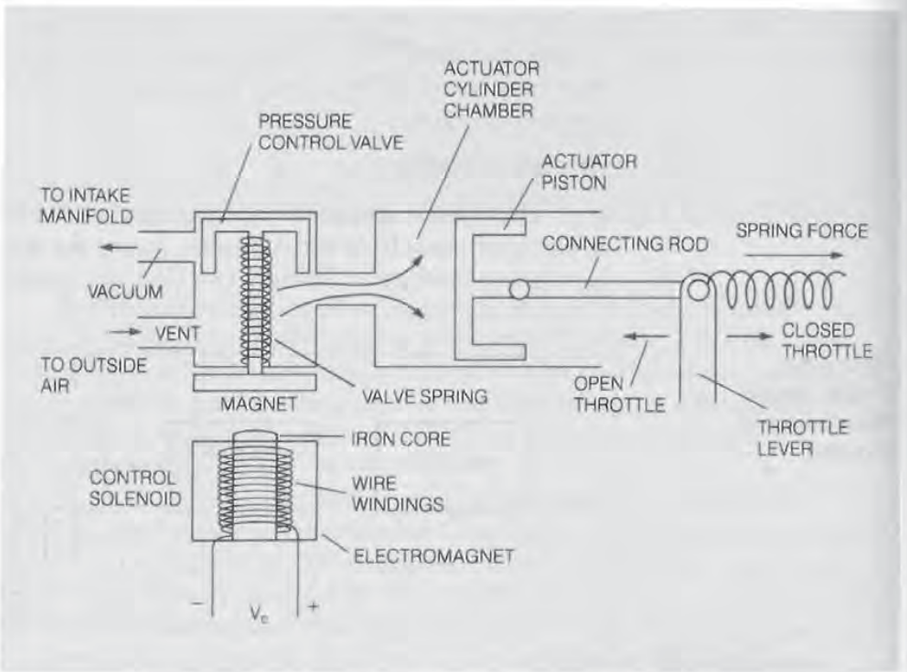
operate either from manifold vacuum or with a stepper motor. The stepper motor implementation operates similarly to the idle speed control actuator described in Chapter 7. The throttle opening is either increased or decreased by the stepper motor in response to the sequences of pulses sent to the two windings depending on the relative phase of the two sets of pulses.

The throttle actuator that is operated by manifold vacuum through a solenoid valve is similar to that used for the EGR valve described in Chapter 7. During cruise control operation the throttle position is set automatically by the throttle actuator in response to the actuator signal generated in the control system. This type of manifold-vacuum-operated actuator is illustrated in Figure 8.7.

Throttle actuators use manifold vacuum to pull a piston that is mechanically linked to the throttle. The amount of vacuum provided is controlled by a solenoid valve that is turned on and off rapidly.

A pneumatic piston arrangement is driven from the intake manifold vacuum. The piston-connecting rod assembly is attached to the throttle lever. There is also a spring attached to the lever. If there is no force applied by the piston, the spring pulls the throttle closed. When an actuator input signal energizes the electromagnet in the control solenoid, the pressure control valve is pulled down and changes the actuator cylinder pressure by providing a path to manifold pressure. Manifold pressure is lower than atmospheric pressure, so the actuator cylinder pressure quickly drops, causing the piston to pull against the throttle lever to open the throttle.

Figure 8.7 Vacuum-Operated Throttle Actuator



PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

A switching, duty-cycle type of signal is applied to the solenoid coil. By varying the duty cycle, the amount of vacuum, and hence the corresponding throttle angle, is varied.

The force exerted by the piston is varied by changing the average pressure in the cylinder chamber. This is done by rapidly switching the pressure control valve between the outside air port, which provides atmospheric pressure, and the manifold pressure port, the pressure of which is lower than atmospheric pressure. In one implementation of a throttle actuator, the actuator control signal V_c is a variable-duty-cycle type of signal like that discussed for the fuel injector actuator. A high V_c signal energizes the electromagnet; a low V_c signal deenergizes the electromagnet. Switching back and forth between the two pressure sources causes the average pressure in the chamber to be somewhere between the low manifold pressure and outside atmospheric pressure. This average pressure and, consequently, the piston force are proportional to the duty cycle of the valve control signal V_c. The duty cycle is in turn proportional to the control signal d (explained above) that is computed from the sampled error signal e_n.

This type of duty-cycle-controlled throttle actuator is ideally suited for use in digital control systems. If used in an analog control system, the analog control signal must first be converted to a duty-cycle control signal. The same frequency response considerations apply to the throttle actuator as to the speed sensor. In fact, with both in the closed-loop control system, each contributes to the total system phase shift and gain.

CRUISE CONTROL ELECTRONICS

In an analog cruise control system, an error amplifier compares actual speed and desired (command) speed. The error signal output is fed to a proportional amplifier and an integral amplifier. The resultant outputs are combined by a summing amplifier.

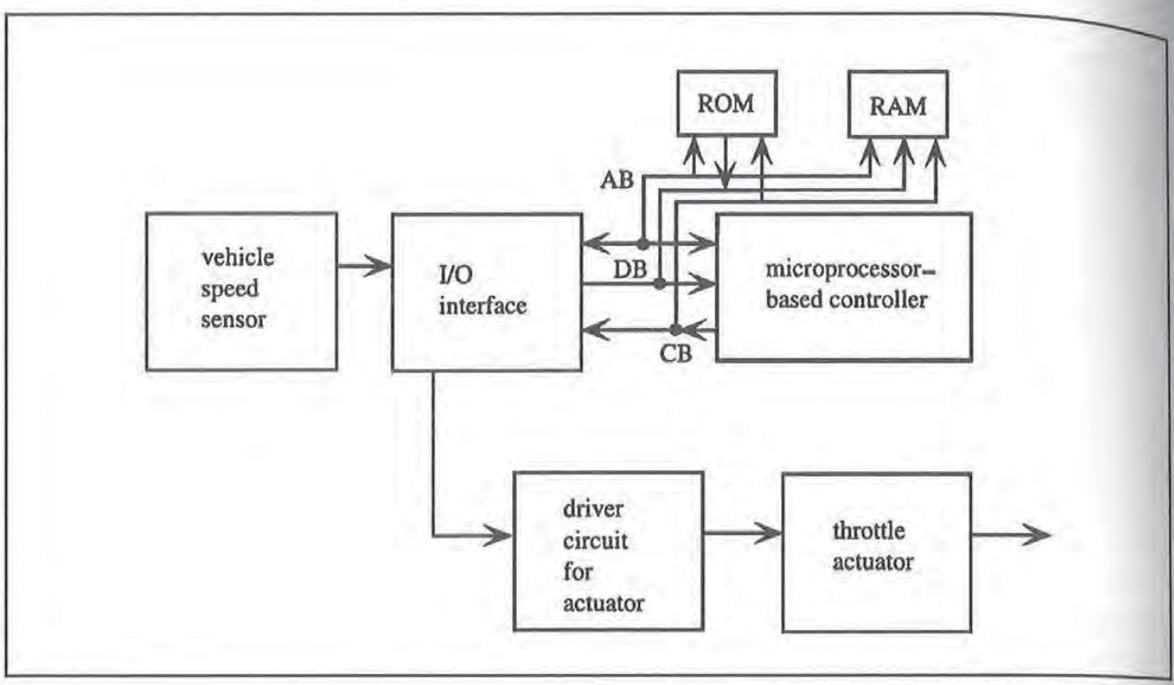
Cruise control can be implemented electronically in various ways, including with a microcontroller with special-purpose digital electronics or with analog electronics. It can also be implemented (in proportional control strategy alone) with an electromechanical speed governor.

The physical configuration for a digital, microprocessor-based cruise control is depicted in Figure 8.8. A system such as is depicted in Figure 8.8 is often called a *microcontroller* since it is implemented with a microprocessor operating under program control. The actual program that causes the various calculations to be performed is stored in read-only memory (ROM). Typically the ROM also stores parameters that are critical to the correct calculations. Normally a relatively small-capacity RAM memory is provided to store the command speed and to store any temporary calculation results. Input from the speed sensor and output to the throttle actuator are handled by the I/O interface (normally an integrated circuit that is a companion to the microprocessor). The output from the controller (i.e., the control signal) is sent via the I/O (on one of its output ports) to so-called driver electronics. The latter electronics receives this control signal and generates a signal of the correct format and power level to operate the actuator (as explained below).

A microprocessor-based cruise control system performs all of the required control law computations digitally under program control. For example, a PI control strategy is implemented as explained above, with a proportional term

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Figure 8.8
Digital Cruise Control Configuration



and an integral term that is formed by a summation. In performing this task the controller continuously receives samples of the speed error e_n, and where n is a counting index ($n = 1, 2, 3, 4, \ldots$). This sampling occurs at a sufficiently high rate to be able to adjust the control signal to the actuator in time to compensate for changes in operating condition or to disturbances. At each sample the controller reads the most recent error. As explained earlier, that error is multiplied by a constant K_P that is called the proportional gain, yielding the proportional term in the control law. It also computes the sum of a number of previous error samples (the exact sum is chosen by the control system designer in accordance with the desired steady-state error). Then this sum is multiplied by a constant K_I and added to the proportional term, yielding the control signal.

The control signal at this point is simply a number that is stored in a memory location in the digital controller. The use of this number by the electronic circuitry that drives the throttle actuator to regulate vehicle speed depends on the configuration of the particular control system and on the actuator used by that system.

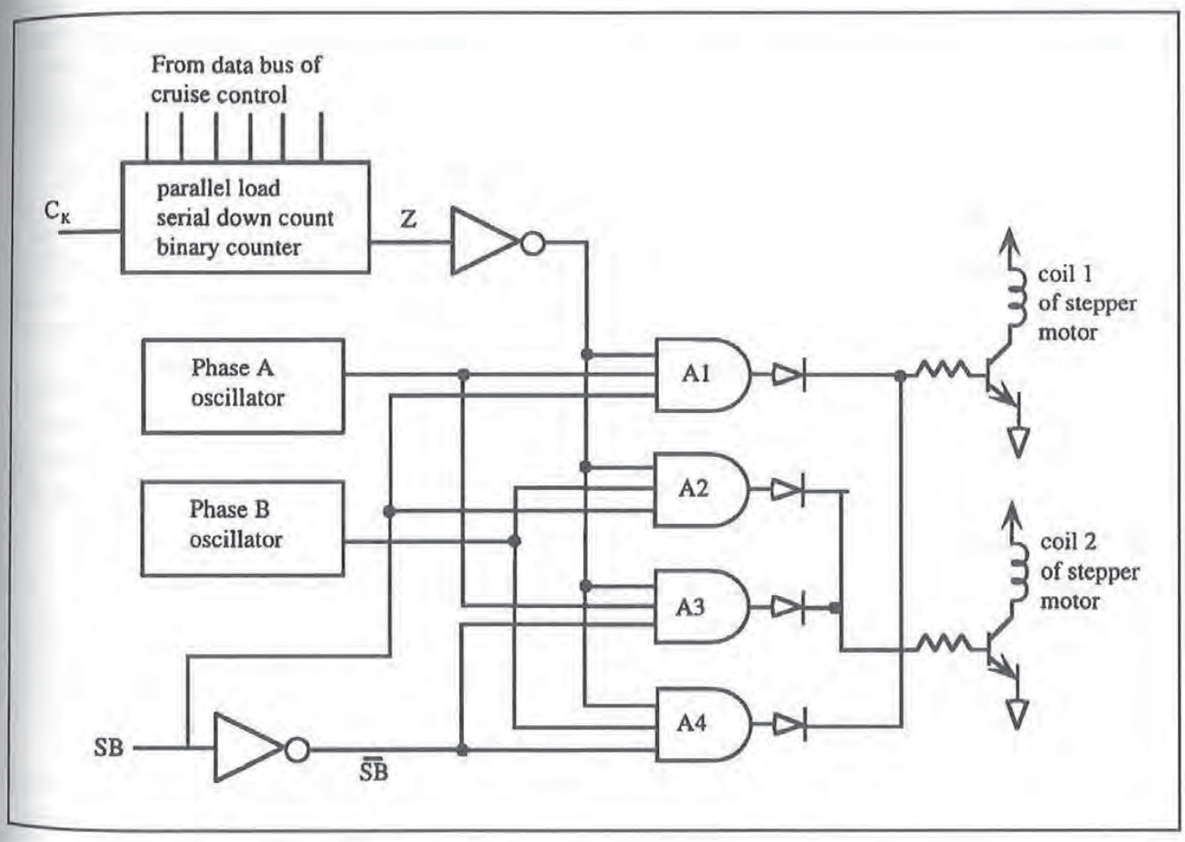
PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Stepper Motor-Based Actuator

For example, in the case of a stepper motor actuator, the actuator driver electronics reads this number and then generates a sequence of pulses to the pair of windings on the stepper motor (with the correct relative phasing) to cause the stepper motor to either advance or retard the throttle setting as required to bring the error toward zero.

An illustrative example of driver circuitry for a stepper motor actuator is shown in Figure 8.9.The basic idea for this circuitry is to continuously drive the stepper motor to advance or retard the throttle in accordance with the control signal that is stored in memory. Just as the controller periodically updates the actuator control signal, the stepper motor driver electronics continually adjusts the throttle by an amount determined by the actuator signal.

Figure 8.9
Stepper Motor Actuator for Cruise Control



PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

This signal is, in effect, a signed number (i.e., a positive or negative numerical value). A sign bit indicates the direction of the throttle movement (advance or retard). The numerical value determines the amount of advance or retard.

The magnitude of the actuator signal (in binary format) is loaded into a parallel load serial down-count binary counter. The direction of movement is in the form of the sign bit (SB of Figure 8.9). The stepper motor is activated by a pair of quadrature phase signals (i.e., signals that are a quarter of a cycle out of phase) coming from a pair of oscillators. To advance the throttle, phase A signal is applied to coil 1 and phase B to coil 2. To retard the throttle these phases are each switched to the opposite coil. The amount of movement in either direction is determined by the number of cycles of A and B, one step for each cycle.

The number of cycles of these two phases is controlled by a logical signal (Z in Figure 8.9). This logical signal is switched high, enabling a pair of AND gates (from the set A1, A2, A3, A4). The length of time that it is switched high determines the number of cycles and corresponds to the number of steps of the motor.

The logical variable Z corresponds to the contents of the binary counter being zero. As long as Z is not zero, a pair of AND gates (A1 and A3, or A2 and A4) is enabled, permitting phase A and phase B signals to be sent to the stepper motor. The pair of gates enabled is determined by the sign bit. When the sign bit is high, A1 and A3 are enabled and the stepper motor advances the throttle as long as Z is not zero. Similarly, when the sign bit is low, A2 and A4 are enabled and the stepper motor retards the throttle.

To control the number of steps, the controller loads a binary value into the binary counter. With the contents not zero the appropriate pair of AND gates is enabled. When loaded with data, the binary counter counts down at the frequency of a clock (C_K in Figure 8.9). When the countdown reaches zero, the gates are disabled and the stepper motor stops moving.

The time required to count down to zero is determined by the numerical value loaded into the binary counter. By loading signed binary numbers into the binary counter, the cruise controller regulates the amount and direction of movement of the stepper motor and thereby the corresponding movement of the throttle.

Vacuum-Operated Actuator

The driver electronics for a cruise control based on a vacuum-operated system generates a variable-duty-cycle signal as described in Chapter 6. In this type of system, the duty cycle at any time is proportional to the control signal. For example, if at any given instant a large positive error exists between the command and actual signal then a relatively large control signal will be generated. This control signal will cause the driver electronics to produce a large duty cycle signal to operate the solenoid so that most of the time the actuator

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

cylinder chamber is nearly at manifold vacuum level. Consequently, the piston will move against the restoring spring and cause the throttle opening to increase. As a result the engine will produce more power and will accelerate the vehicle until its speed matches the command speed.

It should be emphasized that, regardless of the actuator type used, a microprocessor-based cruise control system will:

1. Read the command speed.
2. Measure actual vehicle speed.
3. Compute an error (error = command – actual).
4. Compute a control signal using P, PI, or PID control law.
5. Send the control signal to the driver electronics.
6. Cause driver electronics to send a signal to the throttle actuator such that the error will be reduced.

An example of electronics for a cruise control system that is basically analog is shown in Figure 8.10. Notice that the system uses four operational amplifiers (op amps) as described in Chapter 3 and that each op amp is used for

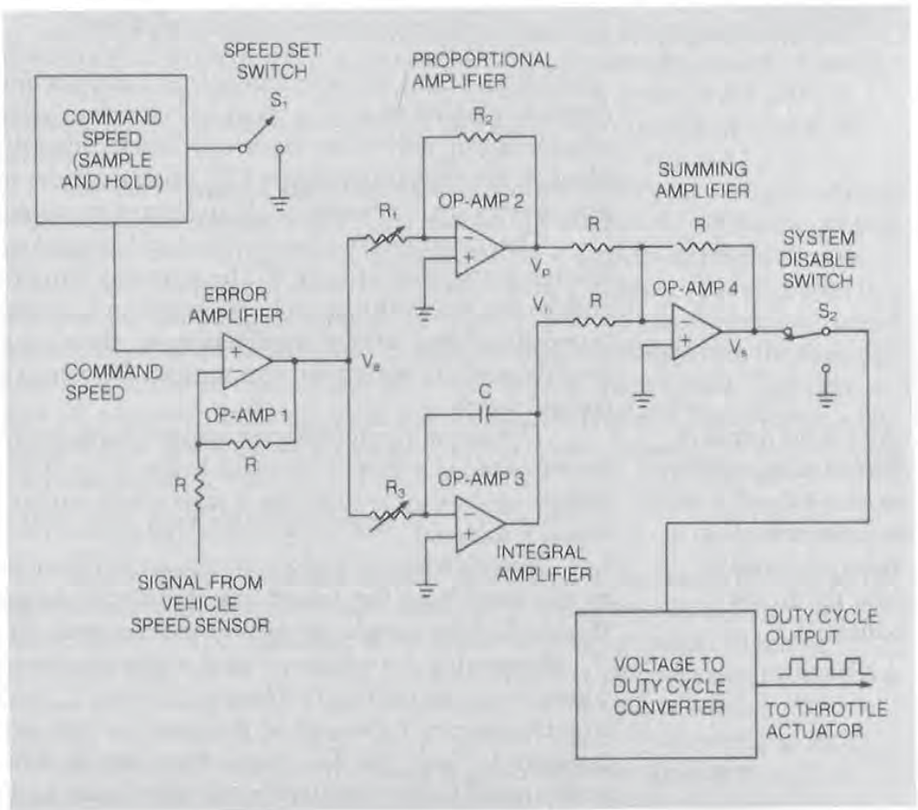


Figure 8.10 Cruise Control Electronics (Analog)

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

a specific purpose. Op amp 1 is used as an error amplifier. The output of op amp 1 is proportional to the difference between the command speed and the actual speed. The error signal is then used as an input to op amps 2 and 3. Op amp 2 is a proportional amplifier with a gain of $K_P = -R_2/R_1$. Notice that R_1 is variable so that the proportional amplifier gain can be adjusted. Op amp 3 is an integrator with a gain of $K_I = -1/R_3C$. Resistor R_3 is variable to permit adjustment of the gain. The op amp causes a current to flow into capacitor C that is equal to the current flowing into R_3. The voltage across R_3 is the error amplifier output voltage, V_e. The current in R_3 is found from Ohm's law to be

$$I = \frac{V_e}{R_3}$$

which is identical to the current flowing into the capacitor. If the error signal V_e is constant, the current I will be constant and the voltage across the capacitor will steadily change at a rate proportional to the current flow. That is, the capacitor voltage is proportional to the integral of the error signal:

$$V_I = -\frac{1}{R_3C}\int V_e\,dt$$

The output of the integral amplifier, V_I, increases or decreases with time depending on whether V_e is above or below zero volts. The voltage V_I is steady or unchanging only when the error is exactly zero; this is why the integral gain block in the diagram in Figure 8.10 can reduce the system steady-state error to zero. Even a small error causes V_I to change to correct for the error.

The outputs of the proportional and integral amplifiers are added using a summing amplifier, op amp 4. The summing amplifier adds voltages V_P and V_I and inverts the resulting sum. The inversion is necessary because both the proportional and integral amplifiers invert their input signals while providing amplification. Inverting the sum restores the correct sense, or polarity, to the control signal.

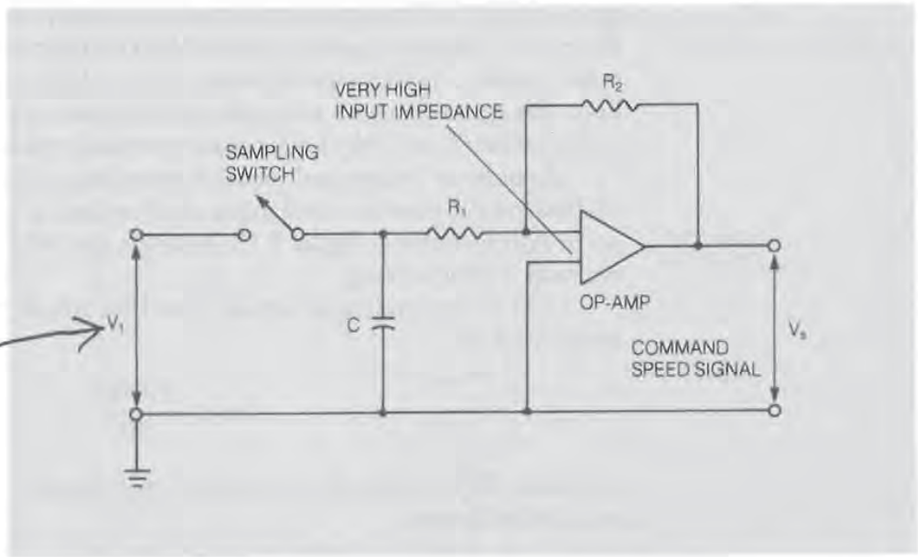
Because the output of the summing amplifier is an analog signal, it must be converted into a duty-cycle signal to pulse the throttle actuator.

The summing amplifier op amp produces an analog voltage, V_s, that must be converted to a duty-cycle signal before it can drive the throttle actuator. A voltage-to-duty-cycle converter is used whose output directly drives the throttle actuator solenoid.

Two switches, S_1 and S_2, are shown in Figure 8.10. Switch S_1 is operated by the driver to set the desired speed. It signals the sample-and-hold electronics (Figure 8.11) to sample the present vehicle speed and hold that value. Voltage V_I, representing the vehicle speed at which the driver wishes to set the cruise controller, is sampled and it charges capacitor C. A very high input impedance amplifier detects the voltage on the capacitor without causing the charge on the capacitor to "leak" off. The output from this amplifier is a voltage, V_s, proportional to the command speed that is sent to the error amplifier.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Figure 8.11
Typical Sample-and-Hold Circuit



Sensor voltage (V_1) represents vehicle speed.

Switch S_2 is used to disable the speed controller by interrupting the control signal to the throttle actuator. Switch S_2 disables the system whenever the ignition is turned off, the controller is turned off, or the brake pedal is pressed. The controller is switched on when the driver presses the speed set switch S_1.

For safety reasons, the brake turnoff is often performed two ways. As just mentioned, pressing the brake pedal turns off or disables the electronic control. In certain cruise control configurations that use a vacuum-operated throttle actuator, the brake pedal also mechanically opens a separate valve that is located in a hose connected to the throttle actuator cylinder. When the valve is opened by depression of the brake pedal, it allows outside air to flow into the throttle actuator cylinder so that the throttle plate instantly snaps closed. The valve is shut off whenever the brake pedal is in its inactive position. This ensures a fast and complete shutdown of the speed control system whenever the driver presses the brake pedal.

ANTILOCK BRAKING SYSTEM

One of the most readily accepted applications of electronics in automobiles has been the antilock brake system (ABS). ABS is a safety-related feature that assists the driver in deceleration of the vehicle in poor or marginal braking conditions (e.g., wet or icy roads). In such conditions, panic braking by the driver (in non-ABS-equipped cars) results in reduced braking effectiveness and, typically, loss of directional control due to the tendency of the wheels to lock.

In ABS-equipped cars, the wheel is prevented from locking by a mechanism that automatically regulates braking force to an optimum for any

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

given low-friction condition. The physical configuration for an ABS is shown in Figure 8.12. In addition to the normal brake components, including brake pedal, master cylinder, vacuum boost, wheel cylinders, calipers/disks, and brake lines, this system has a set of angular speed sensors at each wheel, an electronic control module, and a hydraulic brake pressure modulator (regulator).

In order to understand the ABS operation, it is first necessary to understand the physical mechanism of wheel lock and vehicle skid that can occur during braking. Figure 8.13 illustrates the forces applied to the wheel by the road during braking.

The car is traveling at a speed U and the wheels are rotating at an angular speed w where

$$w = \frac{\pi \text{RPM}}{30}$$

and where RPM is the wheel revolutions per minute. When the wheel is rolling (no applied brakes),

$$U = Rw$$

where R is the tire radius. When the brake pedal is depressed, the calipers are forced by hydraulic pressure against the disk, as explained in Chapter 1. This force acts as a torque T_b in opposition to the wheel rotation. The actual force that decelerates the car is shown as F_b in Figure 8.13. The lateral force that maintains directional control of the car is shown as F_L in Figure 8.13.

The wheel angular speed begins to decrease, causing a difference between the vehicle speed U and the tire speed over the road (i.e., wR). In effect, the tire

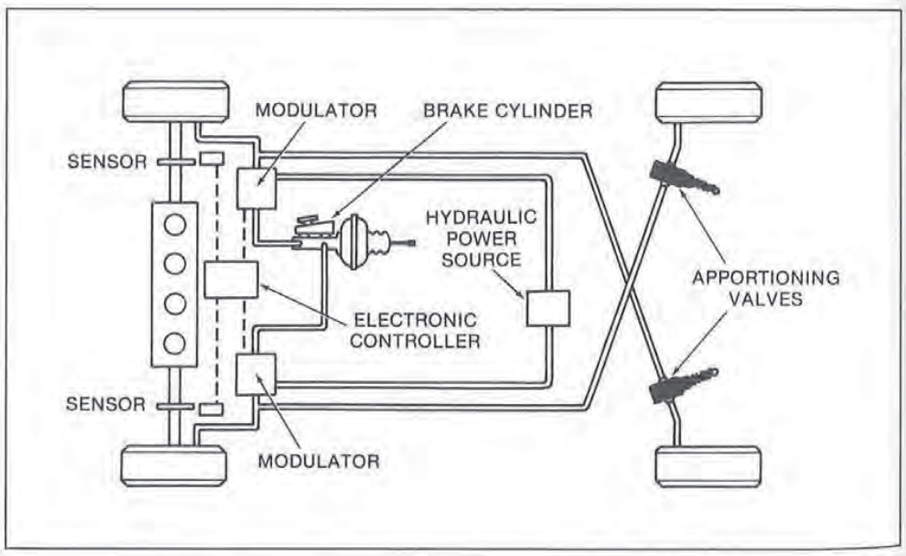


Figure 8.12 Antilock Braking System

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

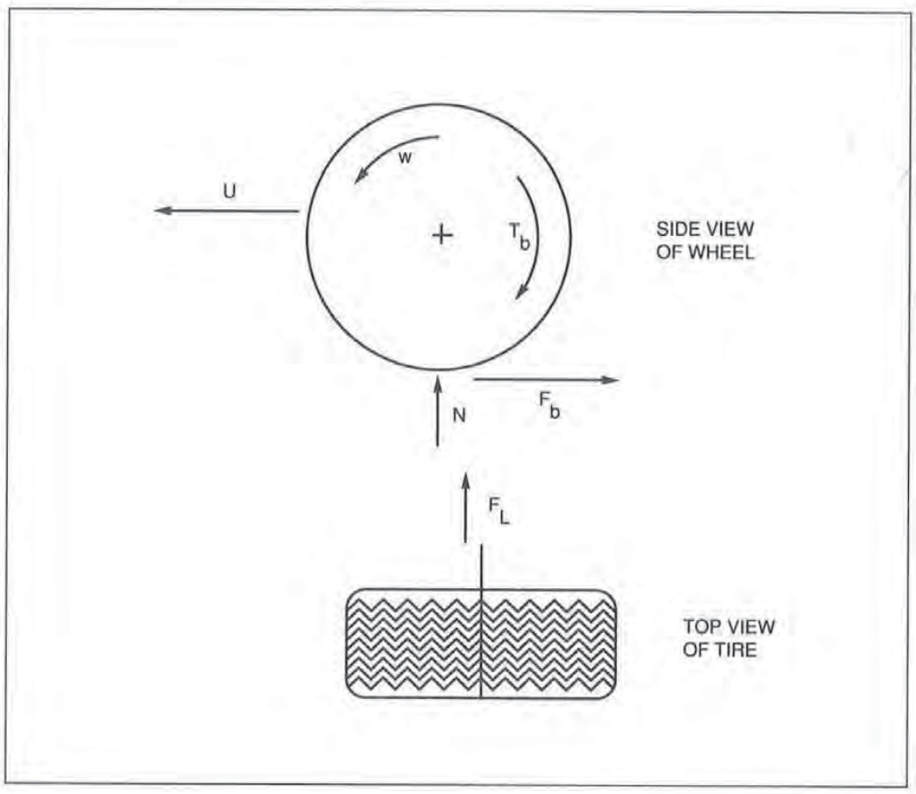


Figure 8.13
Forces During Braking

slips relative to the road surface. The amount of slip (S) determines the braking force and lateral force. The slip, as a percentage of car speed, is given by

$$S = \frac{U - wR}{U} \times 100\%$$

Note: A rolling tire has slip $S = 0$, and a fully locked tire has $S = 100\%$.

The braking and lateral forces are proportional to the normal force (from the weight of the car) acting on the tire/road interface (N in Figure 8.13) and the friction coefficients for braking force (F_b) and lateral force (F_L):

$$F_b = N\mu_b$$
$$F_L = N\mu_L$$

where

μ_b is the braking friction coefficient
μ_L is the lateral friction coefficient

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

These coefficients depend markedly on slip, as shown in Figure 8.14. The solid curves are for a dry road and the dashed curves for a wet or icy road. As brake pedal force is increased from zero, slip increases from zero. For increasing slip, μ_b increases to $S = S_o$. Further increase in slip actually decreases μ_b, thereby reducing braking effectiveness.

On the other hand, μ_L decreases steadily with increasing S such that for fully locked wheels the lateral force has its lowest value. For wet or icy roads, μ_L at $S = 100\%$ is so low that the lateral force is insufficient to maintain directional control of the vehicle. However, directional control can often be maintained even in poor braking conditions if slip is optimally controlled. This is essentially the function of the ABS, which performs an operation equivalent to pumping the brakes as done by experienced drivers before the development of ABS. In ABS-equipped cars under marginal or poor braking conditions, the driver simply applies a steady brake force and the system adjusts tire slip to optimum value automatically.

In a typical ABS configuration, control over slip is effected by controlling the brake line pressure under electronic control. The configuration for ABS is shown in Figure 8.12. This ABS regulates or modulates brake pressure to maintain slip as near to optimum as possible (e.g., at S_o in Figure 8.14). The

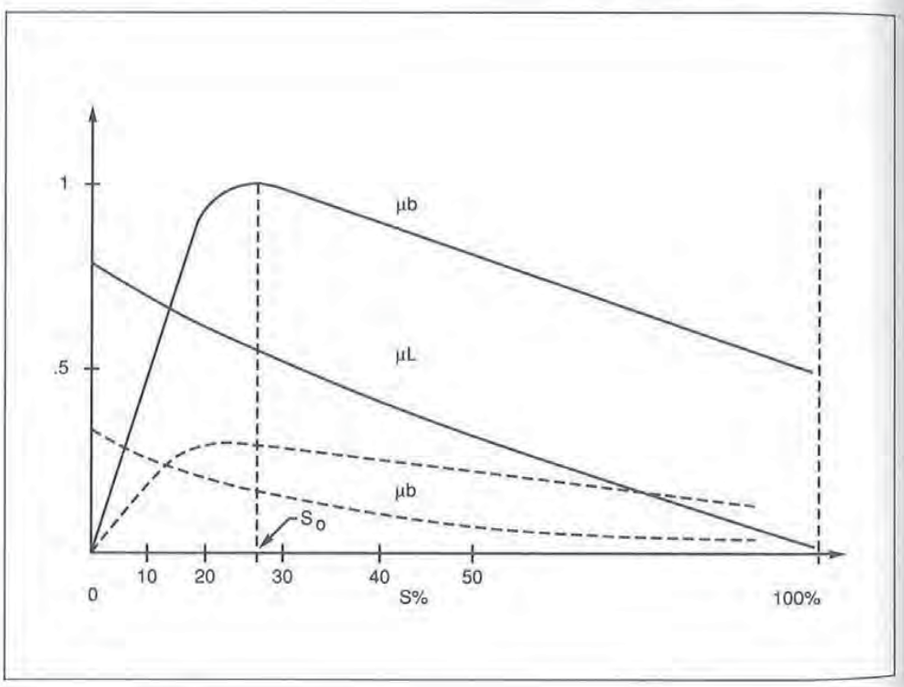


Figure 8.14 Braking Coefficients versus Tire Slip (Solid curves for dry road, dashed curves for wet or icy road):

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

operation of this ABS is based on estimating the torque T_w applied to the wheel at the road surface by the braking force F_b:

$$T_w = RF_b$$

In opposition to this torque is the braking torque T_b applied to the disk by the calipers in response to brake pressure P:

$$T_b = k_b P$$

where k_b is a constant for the given brakes.

The difference between these two torques acts to decelerate the wheel. In accordance with basic Newtonian mechanics, the wheel torque T_w is related to braking torque and wheel deceleration by the following equation:

$$T_w = T_b + I_w \dot{W}$$

where

I_w is the wheel moment of inertia

$\dot{W}$ is the wheel deceleration (dw/dt, that is, the rate of change of wheel speed)

During heavy braking under marginal conditions, sufficient braking force is applied to cause wheel lock-up (in the absence of ABS control). We assume such heavy braking for the following discussion of the ABS. As brake pressure is applied, T_b increases and w decreases, causing slip to increase. The wheel torque is proportional to μ_b, which reaches a peak at slip S_o. Consequently, the wheel torque reaches a maximum value (assuming sufficient brake force is applied) at this level of slip.

Figure 8.15 is a sketch of wheel torque versus slip illustrating the peak T_w. After the peak wheel torque is sensed electronically, the electronic control system commands that brake pressure be reduced (via the brake pressure modulator). This point is indicated in Figure 8.15 as the limit point of slip for the ABS. As the brake pressure is reduced, slip is reduced and the wheel torque again passes through a maximum.

The wheel torque reaches a value below the peak on the low slip side and at this point brake pressure is again increased. The system will continue to cycle, maintaining slip near the optimal value as long as the brakes are applied and the braking conditions are poor.

The mechanism for modulating brake pressure is illustrated in Figure 8.16. The numbers in Figure 8.16a refer to the following:

1. Applied master cylinder pressure
2. Bypass brake fluid
3. Normally open solenoid valve
4. EMB braking action
5. DC motor pack

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

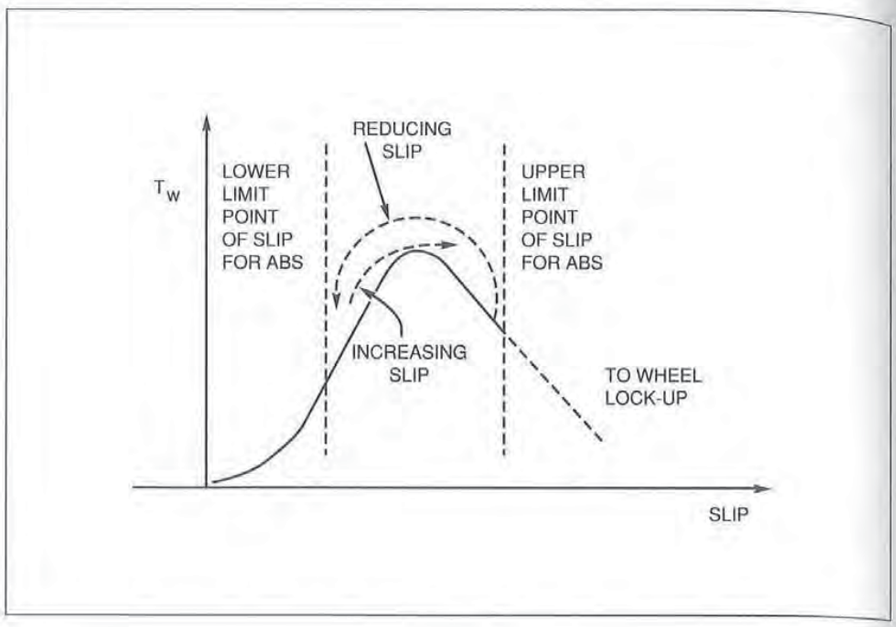


Figure 8.15
Wheel Torque versus Slip

6. ESB braking
7. Gear assembly
8. Ball screw
9. Check valve unseated
10. Outlet to brake cylinders
11. Piston

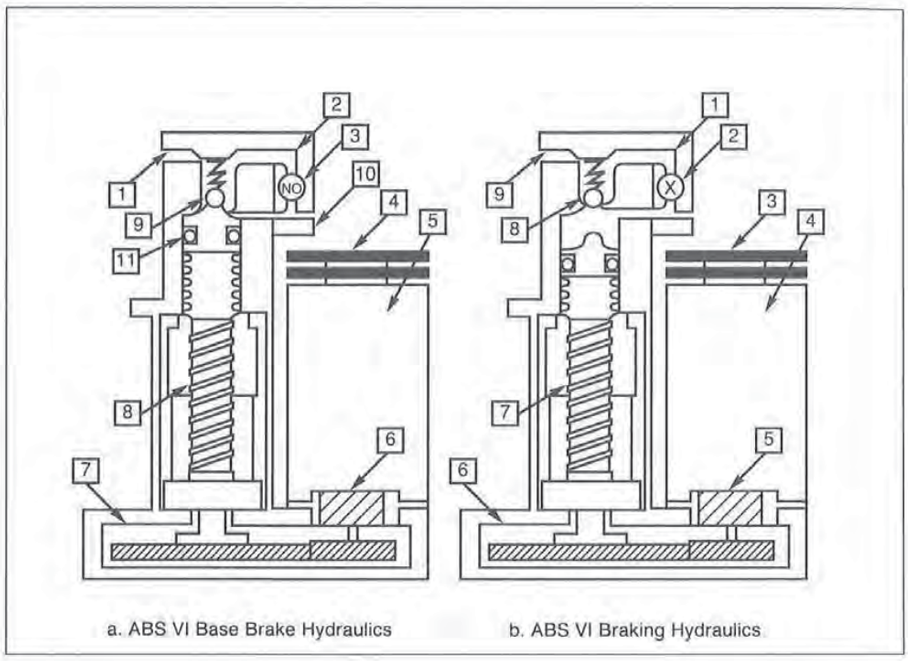
The numbers in Figure 8.16b refer to the following:

1. Trapped bypass brake fluid
2. Solenoid valve activated
3. EMB action released
4. DC motor pack
5. ESB braking action released
6. Gear assembly
7. Ball screw
8. Check valve seated
9. Applied master cylinder pressure

Under normal braking, brake pressure from the master cylinder passes without reduction through the passageways associated with check valve 9 and solenoid valve 3 in Figure 8.16a.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Figure 8.16
Brake Pressure Modulating Mechanism



Whenever the wheel slip limit is reached, the solenoid valve is closed and the piston (11) retracts, closing the check valve. This action effectively isolates the brake cylinders from the master cylinder, and brake line pressure is controlled by the position of piston 11. This piston retracts, lowering the brake pressure sufficiently so that slip falls below S_o. At this point, the control system detects low T_w and the piston moves up, thereby increasing brake line pressure. The ABS system will continue to cycle until the vehicle has stopped, the braking conditions are normal, or the driver removes the brake pressure from the master cylinder.

In the latter case, the operation of the brake pressure modulator restores normal braking function. For example, should the driver release the brake pedal, then the pressure at the inlet (1) is reduced. At this point, the check valve (9) opens and brake line pressure is also removed. The solenoid valve opens and the piston returns to its normal position (fully up) such that the check valve is held open.

Figure 8.17 illustrates the braking during an ABS action. In this illustration, the vehicle is initially traveling at 55 mph and the brakes are applied as indicated by the rising brake pressure. The wheel speed begins to drop until the slip limit is reached. At this point, the ABS reduces brake pressure and the wheel speed increases. With the high applied brake pressure,

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

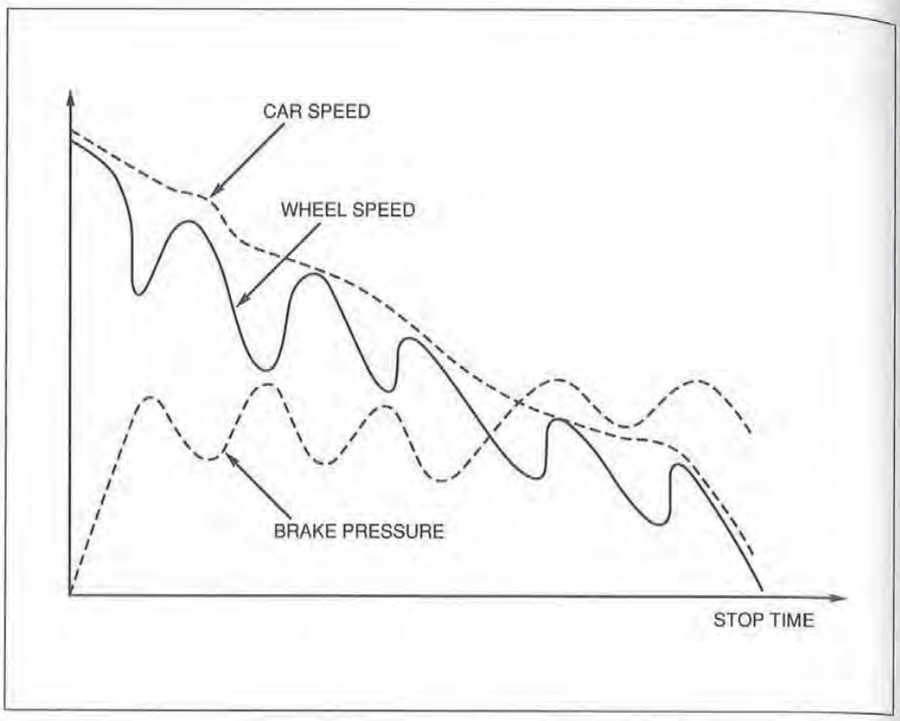


Figure 8.17
ABS Braking Action

the wheels again tend toward lock-up and ABS reduces brake pressure. The cycle continues until the vehicle is stopped.

It should be noted that by maintaining slip near S_o, the maximum deceleration is achieved for a given set of conditions. Some reduction in lateral force occurs from its maximum value by maintaining slip near S_o. However, in most cases the lateral force is large enough to maintain directional control.

In some antilock brake systems, the slip oscillations are shifted below S_o, sacrificing some braking effectiveness to enhance directional control. This can be accomplished by adjusting the upper and lower slip limits.

Tire-Slip Controller

Another benefit of the ABS is that the brake pressure modulator can be used for tire-slip control. Tire slip is effective in moving the car forward just as it is in braking. Under normal driving circumstances, the slip that was defined previously for braking is negative. That is, the tire is actually moving at a speed that is greater than for a purely rolling tire. In fact, the traction force is proportional to slip.

For wet or icy roads, the friction coefficient can become very low and excessive slip can develop. In extreme cases, one of the driving wheels may be

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

on ice or in snow while the other is on a dry (or drier) surface. Because of the action of the differential (see Chapter 1), the low-friction tire will spin and relatively little torque will be applied to the dry-wheel side. In such circumstances, it may be difficult for the driver to move the car even though one wheel is on a relatively good friction surface.

The difficulty can be overcome by applying a braking force to the free spinning wheel. In this case, the differential action is such that torque is applied to the relatively dry wheel surface and the car can be moved. In the example ABS, such braking force can be applied to the free spinning wheel by the hydraulic brake pressure modulator (assuming a separate modulator for each drive wheel). Control of this modulator is based on measurements of the speed of the two drive wheels. Of course, the ABS already incorporates wheel speed measurements, as discussed previously.

The ABS electronics have the capability to perform comparisons of these two wheel speeds and to determine that braking is required of one drive wheel to prevent wheel spin.

ELECTRONIC SUSPENSION SYSTEM

In Chapter 1, we described automotive suspension systems as consisting of springs, shock absorbers, and various linkages to connect the wheel assembly to the car frame. The purpose of the suspension system is to isolate the car body motion as much as possible from wheel motion due to rough road input. In Chapters 1 and 2, it was shown that the performance of the suspension system is strongly influenced by the damping parameter of the shock absorber.

The two primary subjective performance measures are ride and handling. *Ride* refers to the motion of the car body in response to road bumps or irregularities. *Handling* refers to how well the car body responds to dynamic vehicle motion such as cornering or hard braking.

Generally speaking, ride is improved by lowering the shock absorber damping, whereas handling is improved by increasing this damping. In traditional suspension design, the damping parameter is fixed and is chosen to achieve a compromise between ride and handling (i.e., an intermediate value for shock absorber damping is chosen).

In electronically controlled suspension systems, this damping can be varied depending on driving conditions and road roughness characteristics. That is, the suspension system adapts to inputs to maintain the best possible ride subject to handling constraints that are associated with safety.

There are two major classes of electronic suspension control system: active and semiactive. The semiactive suspension system is purely dissipative (i.e., power is absorbed by the shock absorber under control of a microcontroller). In this system, the shock absorber damping is regulated to absorb the power of the wheel motion in accordance with the driving conditions.

In an active suspension system, power is added to the suspension system via a hydraulic or pneumatic power source. At the time of the writing of this

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

book, commercial suspension systems are primarily semiactive. The active suspension system has potential to be in production in the future and is explained in Chapter 11. In this chapter, we explain only the semiactive system.

The primary purpose of the semiactive suspension system is to provide a good ride for as much of the time as possible without sacrificing handling. Good ride is achieved if the car's body is isolated as much as possible from the road. A semiactive suspension controls the shock absorber damping to achieve the best possible ride.

In addition to providing isolation of the sprung mass (i.e., car body and contents), the suspension system has another major function. It must also dynamically maintain the tire normal force as the unsprung mass (wheel assembly) travels up and down due to road roughness. Recall from the discussion of antilock braking that cornering forces depend on normal tire force. Of course in the long-term time average, the normal forces will total the vehicle weight plus any inertial forces due to acceleration, deceleration, or cornering.

However, as the car travels over the road, the unsprung mass moves up and down in response to road input. This motion causes a variation in normal force, with a corresponding variation in potential cornering or braking forces. For example, while driving on a rough curved road, there is a potential loss of steering or braking effectiveness if the suspension system doesn't have good damping characteristics.

Figure 8.18 illustrates typical tire normal force variation as a function of frequency of excitation for a fixed-amplitude, variable-frequency sinusoidal excitation (see Chapter 2 for a discussion of sinusoidal frequency response). The solid curve is the response for a relatively low-damping-coefficient shock absorber and the dashed curve is the response for a relatively high damping coefficient.

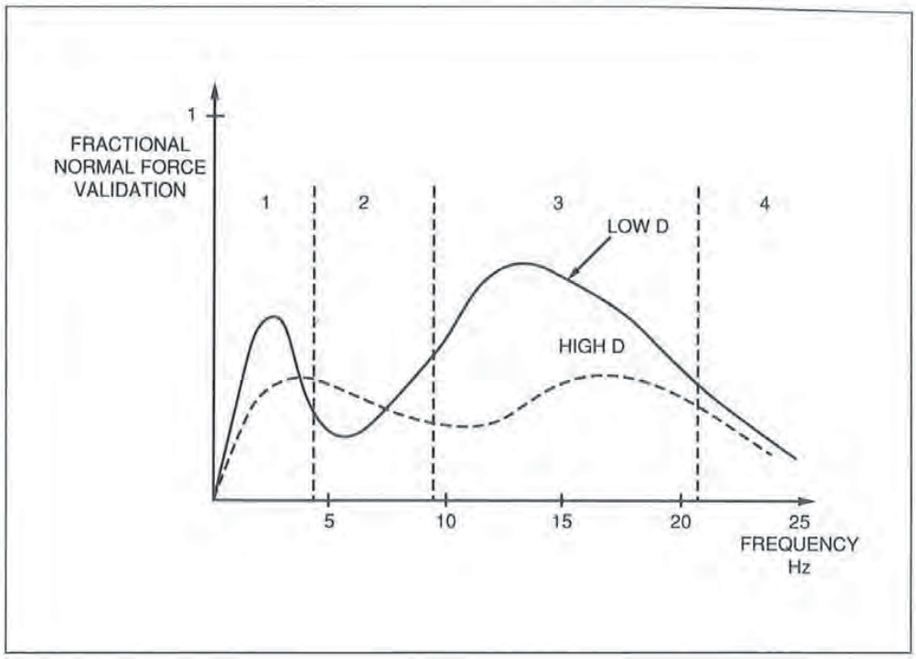
In Figure 8.18, the ordinate is the ratio of amplitude of force variation to the average normal load (i.e., due to weight). There are two relative peaks in this response. The lower peak is approximately 1 to 2 Hz and is generally associated with spring/sprung mass oscillation. The second peak, which is in the general region of 12 to 15 Hz, is resonance of the spring/unsprung mass combination.

Generally speaking, for any given fixed suspension system ride and handling cannot both be optimized simultaneously, as explained in Chapter 1. A car with a good ride is one in which the sprung mass motion/acceleration due to rough road input is minimized. In particular, the sprung mass motion in the frequency region from about 2 to 8 Hz is most important for good subjective ride. Good ride is achieved for relatively low damping (low D in Figure 8.18).

For low damping, the unsprung mass moves relatively freely due to road input while the sprung mass motion remains relatively low. Note from Figure 8.18 that this low damping results in relatively high variation in normal force, particularly near the two peak frequencies. That is, low damping results in relatively poor handling characteristics.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Figure 8.18
Tire Force Variation



With respect to the four frequency regions of Figure 8.18, the following generally desired suspension damping characteristics can be identified.

Region	Frequency (Hz)	Damping
1: Sprung mass mode	1–2	High
2: Intermediate ride	2–8	Low
3: Unsprung mass resonance	8–20	High
4: Harshness	> 20	Low

Another major input to the vehicle that affects handling is steering input that causes maneuvers parallel to the road surface (e.g., cornering). Whenever the car is executing such maneuvers, there is a lateral acceleration. This acceleration acting through the center of gravity causes the vehicle to roll in a direction opposite to the maneuver.

Car handling generally improves if the amount of roll for any given maneuver is reduced. The rolling rate for a given car and maneuver is improved if spring rate and shock absorber damping are increased. Although the semiactive control system regulates only the damping, handling is improved by increasing this damping as lateral acceleration increases.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Lateral acceleration A_L is proportional to vehicle speed and input steering angle:

$$A_L = kVq_s$$

where

V is the speed of the car

q_s is the steering angle

Although there are many potential control strategies for regulating shock absorber damping, we consider here only switched damping as in our example. In such a system, the shock absorber damping is switched to the higher value whenever lateral acceleration exceeds a predetermined threshold. Figure 8.19 illustrates such a system in which the threshold for switching to firm damping (i.e., higher damping) is 0.35 g.

In Chapter 2, we discussed the dynamics of a spring/mass/damping system, identifying resonant frequency and critical damping D_c:

$$D_c = 2\sqrt{KM}$$

For good ride, the damping should be as low as possible. However, from practical design considerations, the minimum damping is generally in the region of $0.1 < D/D_c < 0.2$. For optimum handling, the damping is in the region of $0.6 < D/D_c < 0.8$.

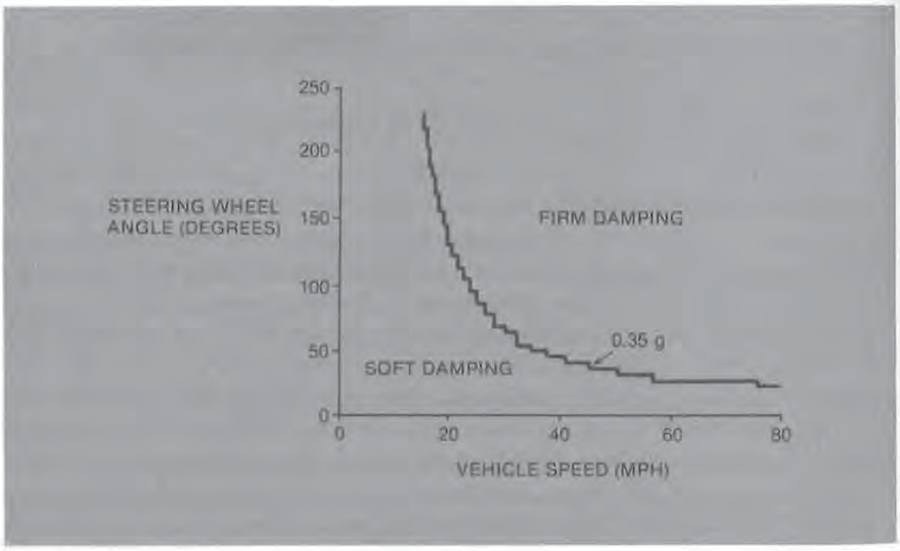


Figure 8.19 Switching Threshold versus Speed and Steering Inputs

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

The variation in shock absorber damping is achieved by varying the aperture in the oil passage through the piston (see Chapter 1 for discussion of shock absorber configuration). In practical semiactive suspension systems, there are two means used to vary this aperture size—a solenoid-operated bypass valve and a motor-driven variable-orifice valve (Figure 8.20).

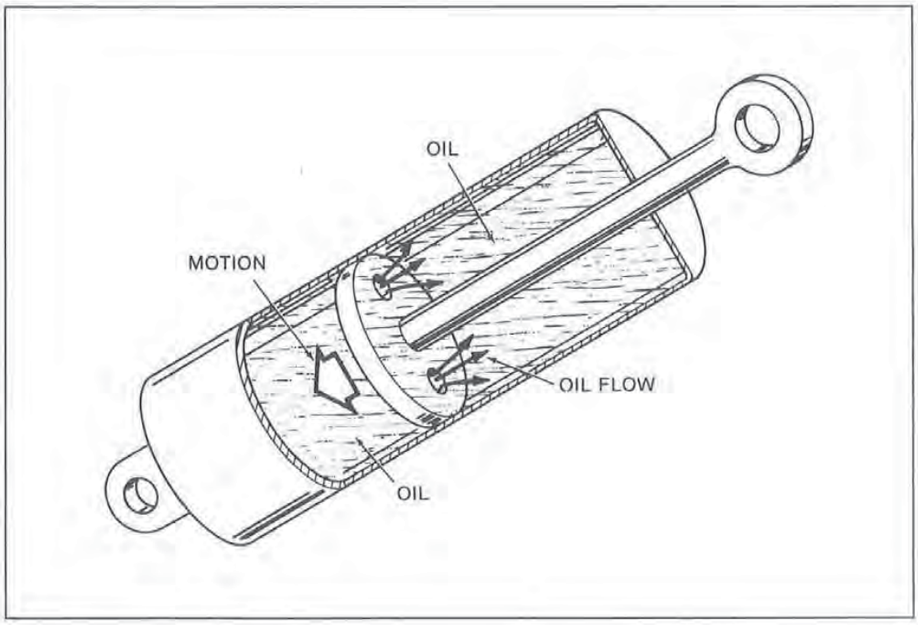
Figure 8.21 is an illustration of the force/relative velocity characteristics of a shock absorber having a solenoid-switched aperture.

The control system for a typical semiactive electronic suspension system has a similar configuration to any electronic control system, as depicted in the block diagram of Figure 8.22.

The control system typically is in the form of a microcontroller or microprocessor-based digital controller. The inputs from each sensor are sampled, converted to digital format, and stored in memory. The sampling is typically at about 500 Hz. In this control configuration, sensors are provided to measure body (sprung mass) acceleration, the relative position and motion of the wheel/body (unsprung/sprung mass), the steering wheel input, and vehicle speed. The body acceleration measurement can be used to evaluate ride quality. The controller does this by computing a weighted average of the spectrum of the acceleration. The relative body/wheel motion can be used to estimate tire normal force.

Under program control in accordance with the control strategy, the electronic control system generates output electrical signals to the actuators in

Figure 8.20 Adjustable Shock Absorber



PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

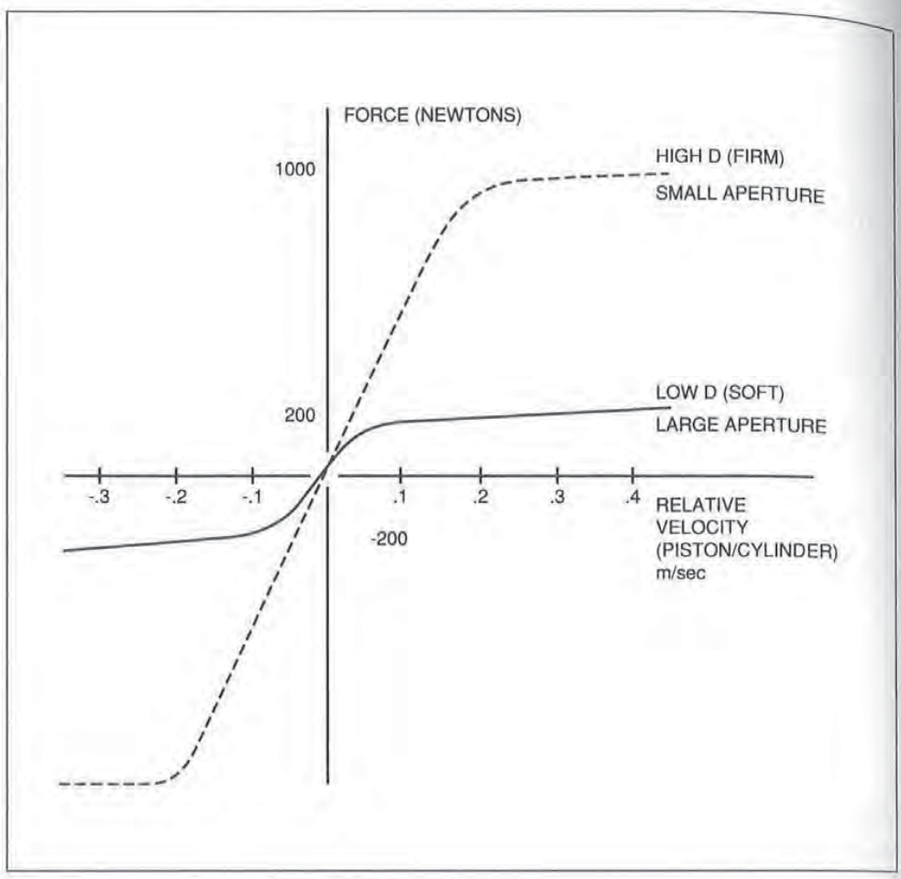


Figure 8.21 Force versus Relative Velocity of a Solenoid-Switched Aperture Shock Absorber

each shock absorber. These actuators vary the oil passage orifice independently at each wheel to obtain the desired damping for that wheel.

There are many possible control strategies and many of these are actually used in production vehicles. For the purposes of this book, it is perhaps most beneficial to present a representative control strategy that typifies features of a number of actual production systems. We assume a solenoid-switched shock absorber.

The important inputs to the vehicle suspension system come from road roughness induced forces and inertial forces (due, for example, to cornering or maneuvering), steering inputs, and vehicle speed. In our hypothetical simplified control strategy these inputs are considered separately. When driving along a nominally straight road with small steering inputs, the road input is dominant. In this case, the control is based on the spectral content (frequency region) of the relative motion. The controller (under program control) calculates the spectrum of the relative velocity of the sprung and unsprung mass at each wheel

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

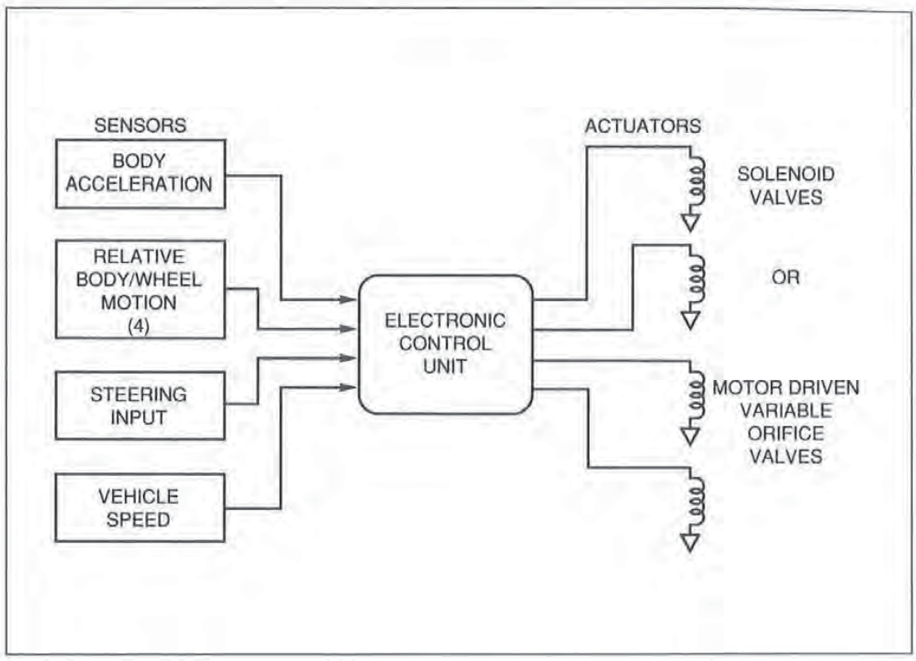


Figure 8.22 Semiactive Electronic Suspension System

(from the corresponding sensor's data). Whenever the weighted amplitude of the spectrum near the peak frequencies exceeds a threshold, the oil passage aperture is switched smaller, causing relatively high damping (firm ride). Otherwise, the aperture is switched to the larger opening, resulting in relatively low damping (soft suspension).

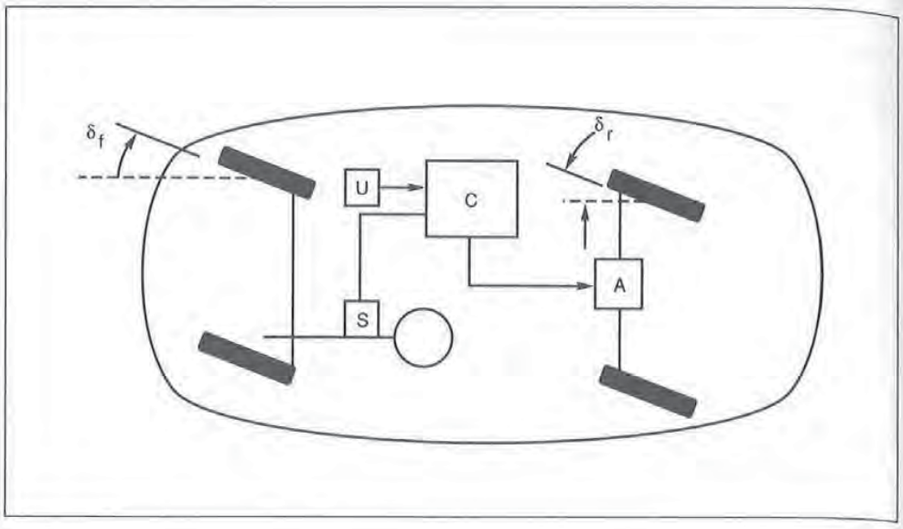
If in addition the vehicle is equipped with an accelerometer (usually located in the car body near the center of gravity) and with motor-driven variable-aperture shock absorbers, then an additional control strategy is possible. In this latter control strategy, the shock absorber apertures are adjusted to minimize sprung mass acceleration in the 2 to 8 Hz frequency region, thereby providing optimum ride control. However, at all times, the damping is adjusted to control unsprung mass motion to maintain wheel normal force variation at acceptably low levels for safety reasons. Whenever a relatively large steering input is sensed, such as during a cornering maneuver, then the control strategy switches to the smaller aperture, yielding a "stiffer" suspension and improved handling.

ELECTRONIC STEERING CONTROL

In Chapter 1, the steering system was explained. There it was shown that the steering effort required of the driver to overcome restoring torque generally decreases with vehicle speed and increases with steering angle. Traditionally, the steering effort required by the driver has been reduced by incorporating a hydraulic power steering system in the vehicle. Whenever there is a steering

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Figure 8.23
4WS Configuration



input from the driver, hydraulic pressure from an engine-driven pump is applied to a hydraulic cylinder that boosts the steering effort of the driver.

Typically, the effort available from the pump increases with engine speed (i.e., with vehicle speed), whereas the required effort decreases. It would be desirable to reduce steering boost as vehicle speed increases. Such a feature can potentially be incorporated into a power steering system featuring electronic controls. An electronically controlled power steering system adjusts steering boost adaptively to driving conditions. Using electronic control of power steering, the available boost is reduced by controlling a pressure relief valve on the power steering pump.

An alternative power steering scheme utilizes a special electric motor to provide the boost required instead of the hydraulic boost. Electric boost power steering has several advantages over traditional hydraulic power steering. Electronic control of electric boost systems is straightforward and can be accomplished without any energy conversion from electrical power to mechanical actuation. Moreover, electronic control offers very sophisticated adaptive control in which the system can adapt to the driving environment.

An example of an electronically controlled steering system that has had commercial production is for four-wheel steering systems (4WS). In the 4WS-equipped vehicles, the front wheels are directly linked mechanically to the steering wheel, as in traditional vehicles. There is a power steering boost for the front wheels as in a standard two-wheel steering system. The rear wheels are steered under the control of a microcontroller via an actuator. Figure 8.23 is an illustration of the 4WS configuration.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

In this illustration, the front wheels are steered to a steering angle δ_f by the driver's steering wheel input. A sensor (S) measures the steering angle and another sensor (U) gives the vehicle speed. The microcontroller (C) determines the desired rear steering angle δ_r under program control as a function of speed and front steering angle.

The details of the control strategy are proprietary and not available for this book. However, it is within the scope of this book to describe a representative example control strategy as follows.

For speeds below 10 mph, the rear steering angle is in the opposite direction to the front steering angle. This control strategy has the effect of decreasing the car's turning radius from the value it has for front wheel steering only. Consequently, the maneuvering ability of the car at low speeds is enhanced (e.g., for parking).

At intermediate speeds (e.g., 11 mph < U < 30 mph), the steering might be front wheel only. At higher speeds (including highway cruise), the front and rear wheels are steered in the same direction. At least one automaker has an interesting strategy for higher speeds (e.g., at highway cruise speed). In this strategy, the rear wheels turn in the opposite direction to the front wheels for a very short period (on the order of one second) and then turn in the same direction as the front wheels. This strategy has a beneficial effect on maneuvers such as lane changes on the highway. Figure 8.24 illustrates the lane change for front wheel steering and for this latter 4WS strategy, in which the same front steering angle was used. Notice that the 4WS strategy yields a lane change in a shorter distance and avoids the overshoot common in a standard-steering vehicle.

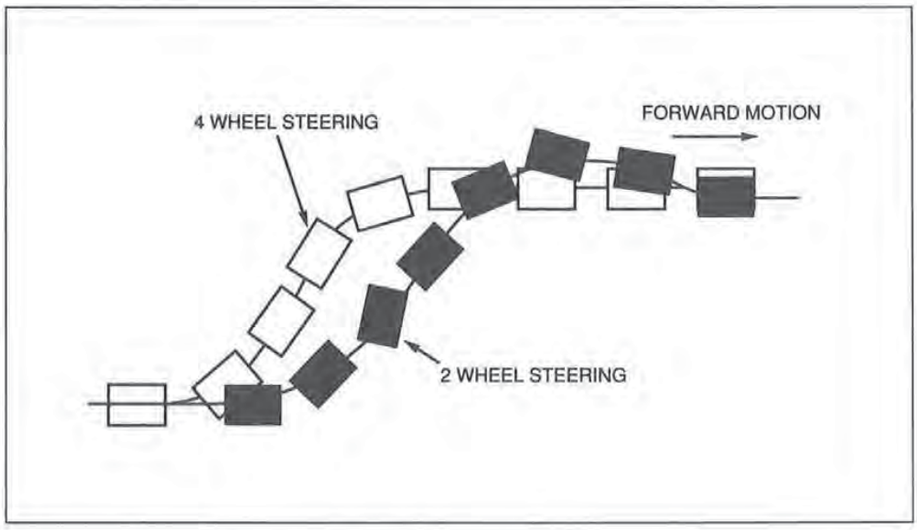


Figure 8.24
Lane Change Maneuver

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

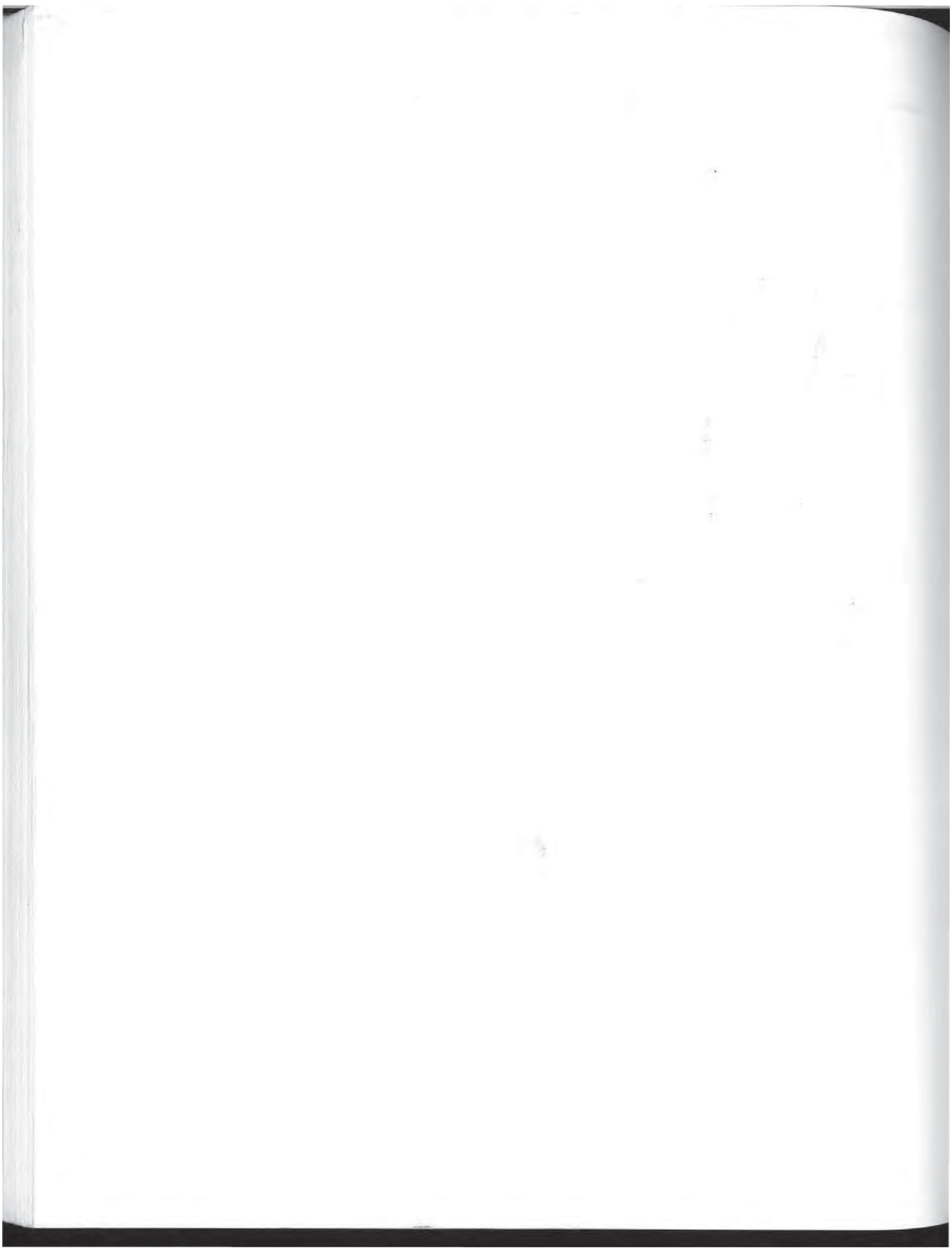
Quiz for Chapter 8

1. A typical cruise control system senses the difference between
   - **a.** vehicle speed and tire speed
   - **b.** set speed and actual vehicle speed
   - **c.** engine angular speed and wheel speed
   - **d.** none of the above
2. A cruise control system controls vehicle speed using
   - **a.** a feedback carburetor
   - **b.** a distributorless ignition system
   - **c.** a throttle actuator
   - **d.** an MAF sensor
3. One of the major drawbacks to a proportional controller is
   - **a.** steady-state error
   - **b.** integral of the error
   - **c.** gain error
   - **d.** all of the above
4. A critically damped system has a response to a step input that
   - **a.** has overshoot
   - **b.** rises smoothly to the final value with no overshoot
   - **c.** can only be achieved with a proportional control system
   - **d.** is the slowest of all possible responses
5. A digital cruise control system
   - **a.** operates on samples of the error signal
   - **b.** computes a control signal numerically
   - **c.** obtains a digital measurement of vehicle speed
   - **d.** all of the above
6. In the example digital cruise control system of this chapter, the vehicle speed sensor
   - **a.** counts pulses of light at a frequency that is proportional to vehicle speed
   - **b.** generates an analog signal
   - **c.** measures crankshaft rotation speed directly
   - **d.** none of the above
7. One advantage of a digital motion control system is
   - **a.** the ability to work with analog signals
   - **b.** the stability of operation with respect to environmental extremes
   - **c.** the exclusive ability to generate integrals of the error signal
   - **d.** all of the above
8. A practical tire-slip controller is based on measurement of
   - **a.** wheel speed
   - **b.** vehicle speed
   - **c.** both of the above
   - **d.** neither of the above
9. An ideal antilock braking system measures skid by
   - **a.** measuring the difference between wheel speed and vehicle speed
   - **b.** differentiating vehicle speed with respect to time
   - **c.** measuring crankshaft angular speed
   - **d.** none of the above

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

10. The example digital ride control system of this chapter incorporates
- **a.** a special electrically adjustable shock absorber
- **b.** a measurement of steering angle
- **c.** a measurement of vehicle speed and brake line pressure
- **d.** all of the above

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565



Automotive Instrumentation

Automotive instrumentation includes the equipment and devices that measure engine and other vehicle variables and display their status to the driver. From about the late 1920s until the late 1950s, the standard automotive instrumentation included the speedometer, oil pressure gauge, coolant temperature gauge, battery charging rate gauge, and fuel quantity gauge. Strictly speaking, only the latter two are electrical instruments. In fact, this electrical instrumentation was generally regarded as a minor part of the automotive electrical system. By the late 1950s, however, the gauges for oil pressure, coolant temperature, and battery charging rate were replaced by warning lights that were turned on only if specified limits were exceeded. This was done primarily to reduce vehicle cost and because of the presumption that many people did not necessarily regularly monitor these instruments.

Low-cost solid-state electronics, including microprocessors, display devices, and some sensors, have brought about major changes in automotive instrumentation.

Automotive instrumentation was not really electronic until the 1970s. At that time, the availability of relatively low-cost solid-state electronics brought about a major change in automotive instrumentation; the use of low-cost electronics has increased with each new model year. Some of the electronic instrumentation presently available is described in this chapter.

In addition to providing measurements for display, modern automotive instrumentation performs limited diagnosis of problems with various subsystems. Whenever a problem is detected, a warning indicator alerts the driver of a problem and indicates the appropriate subsystem. For example, whenever self-diagnosis of the engine control system detects a problem, such as a loss of signal from a sensor, a lamp illuminates the "Check Engine" message on the instrument panel.

MODERN AUTOMOTIVE INSTRUMENTATION

The evolution of instrumentation in automobiles has been influenced by electronic technological advances in much the same way as the engine control system, which has already been discussed. Of particular importance has been the advent of the microprocessor, solid-state display devices, and solid-state sensors. In order to put these developments into perspective, recall the general block diagram for instrumentation (first given in Chapter 2), which is repeated here as Figure 9.1.

In electronic instrumentation, a sensor is required to convert any nonelectrical signal to an equivalent voltage or current. Electronic signal processing is then performed on the sensor output to produce an electrical signal that is capable of driving the display device. The display device is read by

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

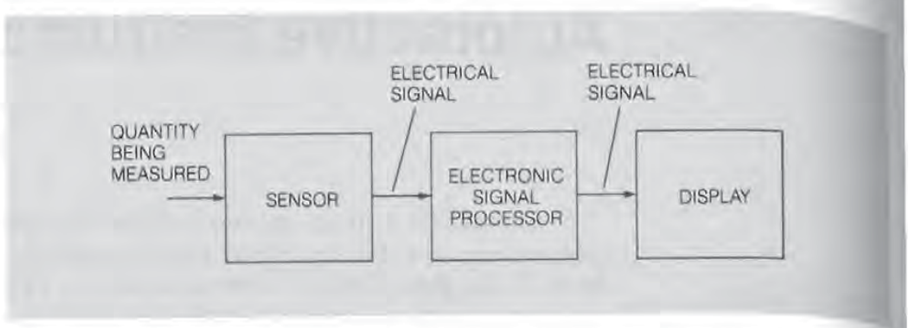


Figure 9.1 General Instrumentation Block Diagram

the vehicle driver. If a quantity to be measured is already in electrical form (e.g., the battery charging current) this signal can be used directly and no sensor is required.

In some modern automotive instrumentation, a microcomputer performs all of the signal processing operations for several measurements. The primary motivation for computer-based instrumentation is the great flexibility offered in the design of the instrument panel. A block diagram for such an instrumentation system is shown in Figure 9.2.

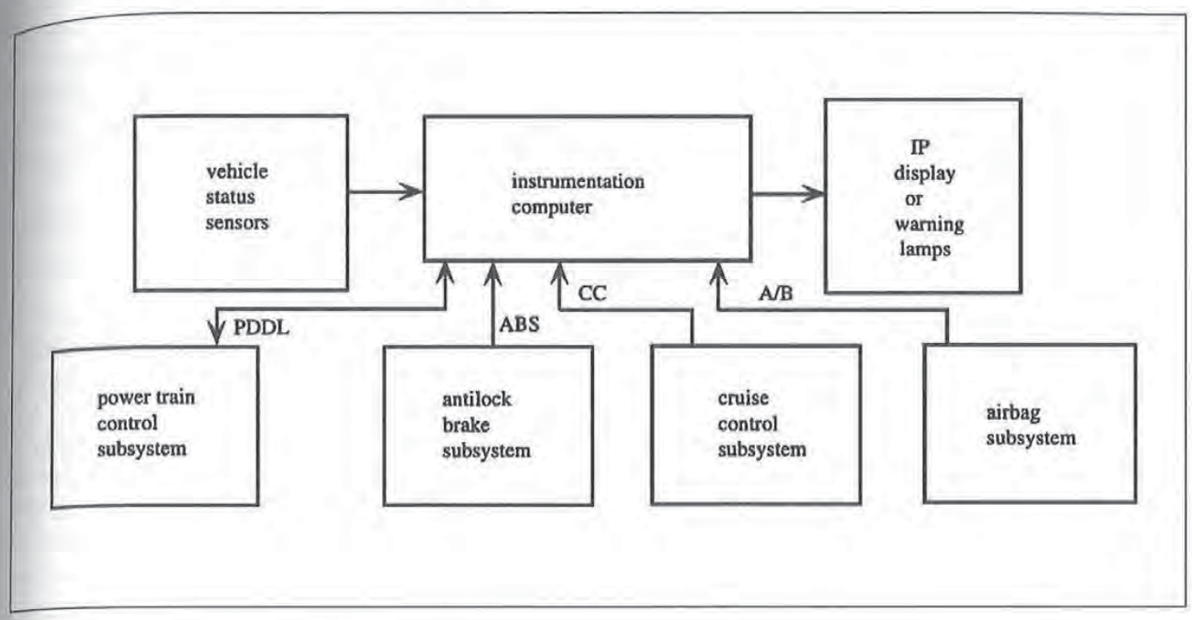
All measurements from the various sensors and switches are processed in a special-purpose digital computer. The processed signals are routed to the appropriate display or warning message. It is common practice in modern automotive instrumentation to integrate the display or warning in a single module that may include both solid-state alphanumeric display, lamps for illuminating specific messages, and traditional electromechanical indicators. For convenience, this display will be termed the instrument panel (IP).

The inputs to the instrumentation computer include sensors (or switches) for measuring (or sensing) various vehicle variables as well as diagnostic inputs from the other critical electronic subsystems. The vehicle status sensors may include any of the following:

1. Fuel quantity
2. Fuel pump pressure
3. Fuel flow rate
4. Vehicle speed
5. Oil pressure
6. Oil quantity
7. Coolant temperature
8. Outside ambient temperature
9. Windshield washer fluid quantity
10. Brake fluid quantity

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Figure 9.2
Computer-Based Instrumentation System



In addition to these variables, the input may include switches for detecting open doors and trunk, as well as IP selection switches for multifunction displays that permit the driver to select from various display modes or measurement units. For example, the driver may be able to select vehicle speed in miles per hour (mph) or kilometers per hour (kph).

An important function of modern instrumentation systems is to receive diagnostic information from certain subsystems and to display appropriate warning messages to the driver. The power train control system, for example, continuously performs self-diagnosis operations (see Chapter 10). If a problem has been detected, a fault code is set indicating the nature and location of the fault. This code is transmitted to the instrumentation system via a power train digital data line (PDDL in Figure 9.2). This code is interpreted in the instrumentation computer and a "Check Engine" warning message is displayed. Similar diagnostic data is sent to the instrumentation system from each of the subsystems for which driver warning messages are deemed necessary (e.g., ABS, airbag, cruise control). The way in which a fault is detected is explained in greater detail in Chapter 10.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

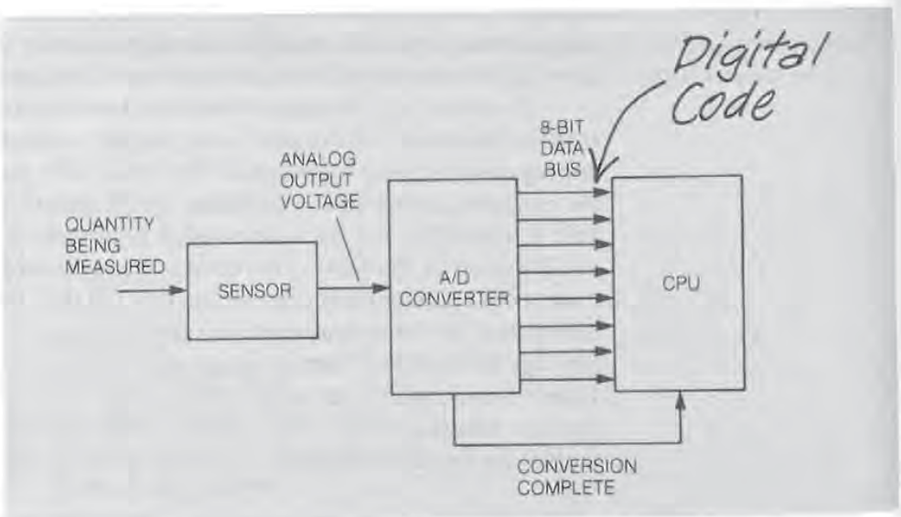
INPUT AND OUTPUT SIGNAL CONVERSION

Most sensors provide an analog output, whereas computers require digital inputs. A/D converters convert analog signals to digital codes appropriate for signal processing by the computer.

It should be emphasized that any single input can be either digital switched or analog, depending on the technology used for the sensor. A typical instrumentation computer is an integrated subsystem that is designed to accept all of these input formats. A typical system is designed with a separate input from each sensor or switch. An example of an analog input is the fuel quantity sensor, which is normally a potentiometer attached to a float, as described in detail later in this chapter. The measurement of vehicle speed given in Chapter 8 is an example of a measurement that is already in digital format.

The analog inputs must all be converted to digital format using an analog to digital (A/D) converter as explained in Chapter 4 and illustrated in Figure 9.3. The digital inputs are, of course, already in the desired format. The conversion process requires an amount of time that depends primarily on the A/D converter. After the conversion is complete, the digital output generated by the A/D converter is the closest possible approximation to the equivalent analog voltage, using an M-bit binary number (where M is chosen by the designer and is normally between 8 and 32). The A/D converter then signals the computer by changing the logic state on a separate lead (labeled "conversion complete" in Figure 9.3) that is connected to the computer. (Recall the use of interrupts for this purpose, as discussed in Chapter 4.) The output voltage of each analog sensor for which the computer performs signal processing must be converted in this way. Once the conversion is complete, the digital output is transferred into a register in the computer. If the output is to drive a digital display, this output can be used directly. However, if an analog display is used, the binary number must be converted to the appropriate analog signal by using a digital-to-analog (D/A) converter (see Chapter 4).

Figure 9.3 Analog-to-Digital Conversion



PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

When an analog output signal is required to drive an analog display, a D/A converter is used. The D/A converter generates a voltage that is proportional to the binary number that the computer sends to the converter.

Figure 9.4 illustrates a typical D/A converter used to transform digital computer output to an analog signal. The eight digital output leads ($M = 8$ in this example) transfer the results of the signal processing to a D/A converter. When the transfer is complete, the computer signals the D/A converter to start converting. The D/A output generates a voltage that is proportional to the binary number in the computer output. A low, pass filter (which could be as simple as a capacitor) is often connected across the D/A output to smooth the analog output between samples. The sampling of the sensor output, A/D conversion, digital signal processing, and D/A conversion all take place during the time slot allotted for the measurement of the variable in a sampling time sequence, to be discussed shortly.

Multiplexing

The computer monitors each sensor individually and provides output signals to its display component before going on to another sensor.

Of course, the computer can only deal with the measurement of a single quantity at any one time. Therefore, the computer input must be connected to only one sensor at a time, and the computer output must be connected only to the corresponding display. The computer performs any necessary signal processing on a particular sensor signal and then generates an output signal to the appropriate display device.

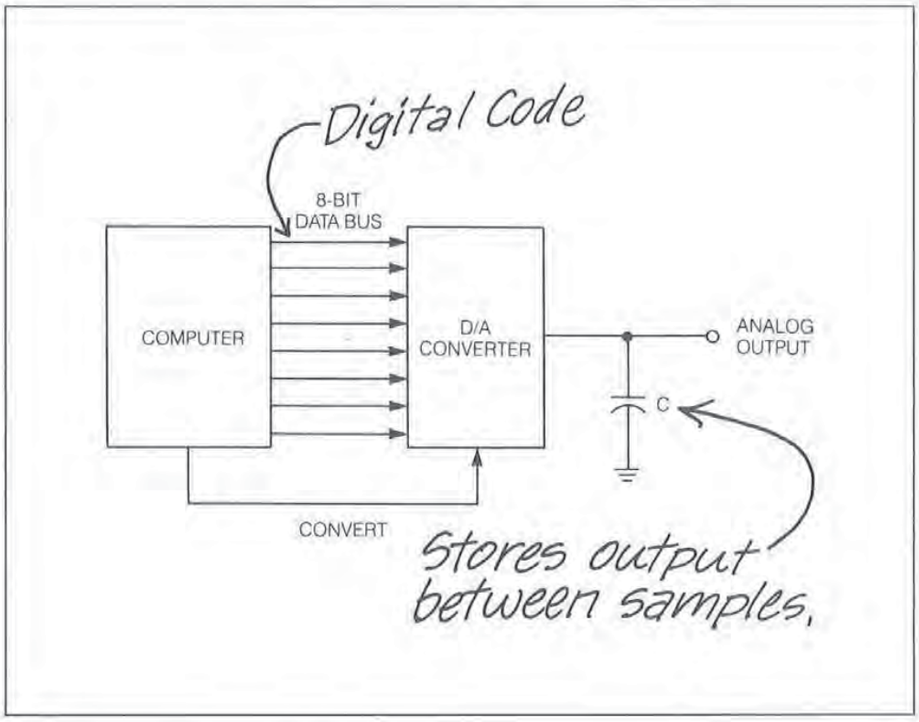


Figure 9.4 Digital-to-Analog Conversion

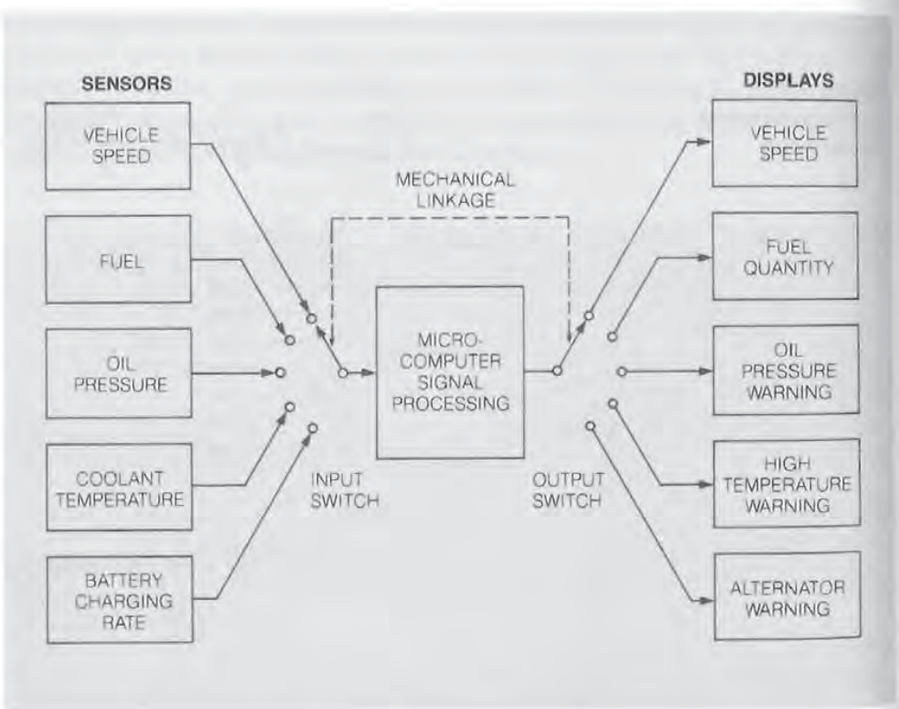
PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

In Figure 9.5 the various sensor outputs and display inputs are connected to a pair of multiposition rotary switches—one for the input and one for the output of the computer. The switches are functionally connected such that they rotate together. Whenever the input switch connects the computer input to the appropriate sensor for measuring some quantity, the output switch connects the computer output to the corresponding display or warning device. Thus, with the switches in a specific position, the automotive instrumentation system corresponds to the block diagram shown in Figure 9.1. At that instant of time, the entire system is devoted to measurement of the quantity corresponding to the given switch position.

The switching of sensor and display inputs is performed with solid-state switches known as multiplexers; output switching is performed by demultiplexers.

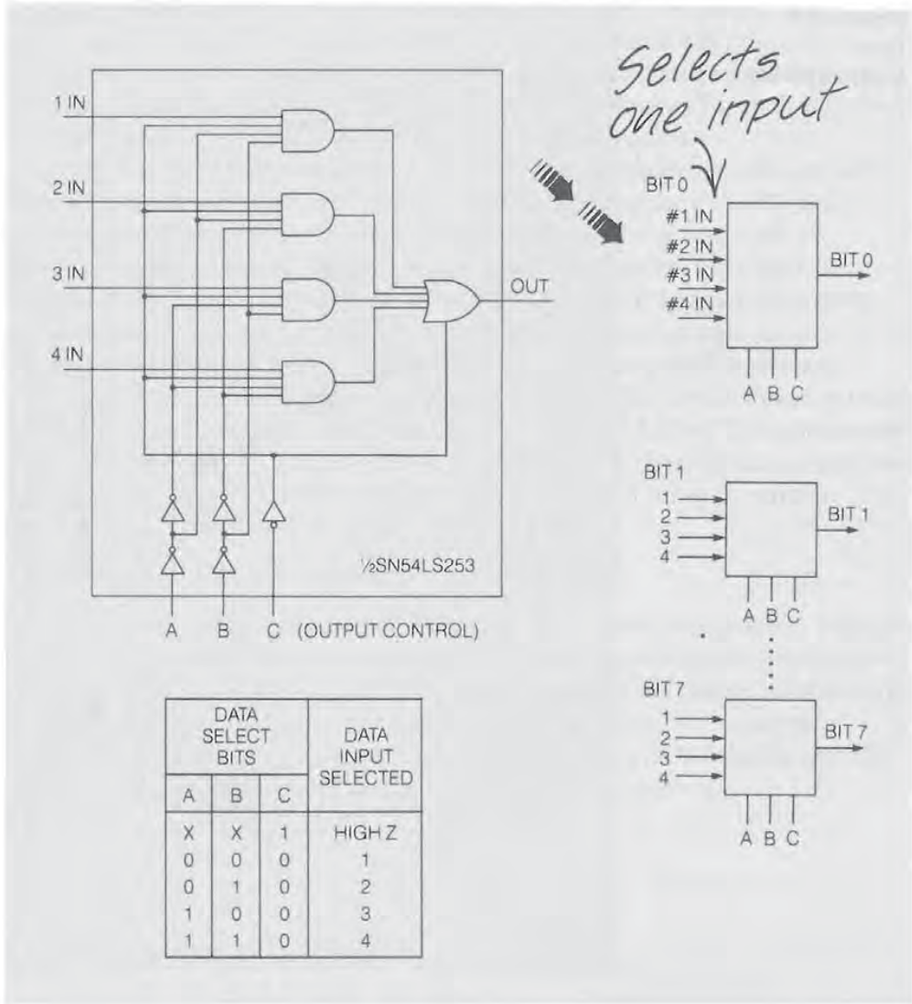
Typically, the computer controls the input and output switching operation. However, instead of a mechanical switch as shown in Figure 9.5, the actual switching is done by means of a solid-state electronic switching device called a *multiplexer* (MUX) that selects one of several inputs for each output. Multiplexing can be done either with analog or digital signals. Figure 9.6 illustrates a digital MUX configuration. Here it is assumed that there are four inputs to the MUX (corresponding to data from four sensors). It is further presumed that the data is available in 8-bit digital format. Each of the

Figure 9.5 Input/Output Switching Scheme for Sampling



PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Figure 9.6
Data Multiplexer



DATA SELECT BITS			DATA INPUT SELECTED
A	B	C	
X	X	1	HIGH Z
0	0	0	1
0	1	0	2
1	0	0	3
1	1	0	4

multiplexers selects a single bit from each of the four inputs. There must be eight such MUX circuits, each supplying one data bit. The output lines from each MUX are connected to a corresponding data bus line in the digital computer (see Chapter 4). Similarly, the output switching (which is often called demultiplexing, or DEMUX) is performed with a MUX connected in reverse, as shown in Figure 9.7. The MUX and DEMUX selection is controlled by the computer. Note that in Figures 9.6 and 9.7, each bit of the digital code is multiplexed and demultiplexed.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

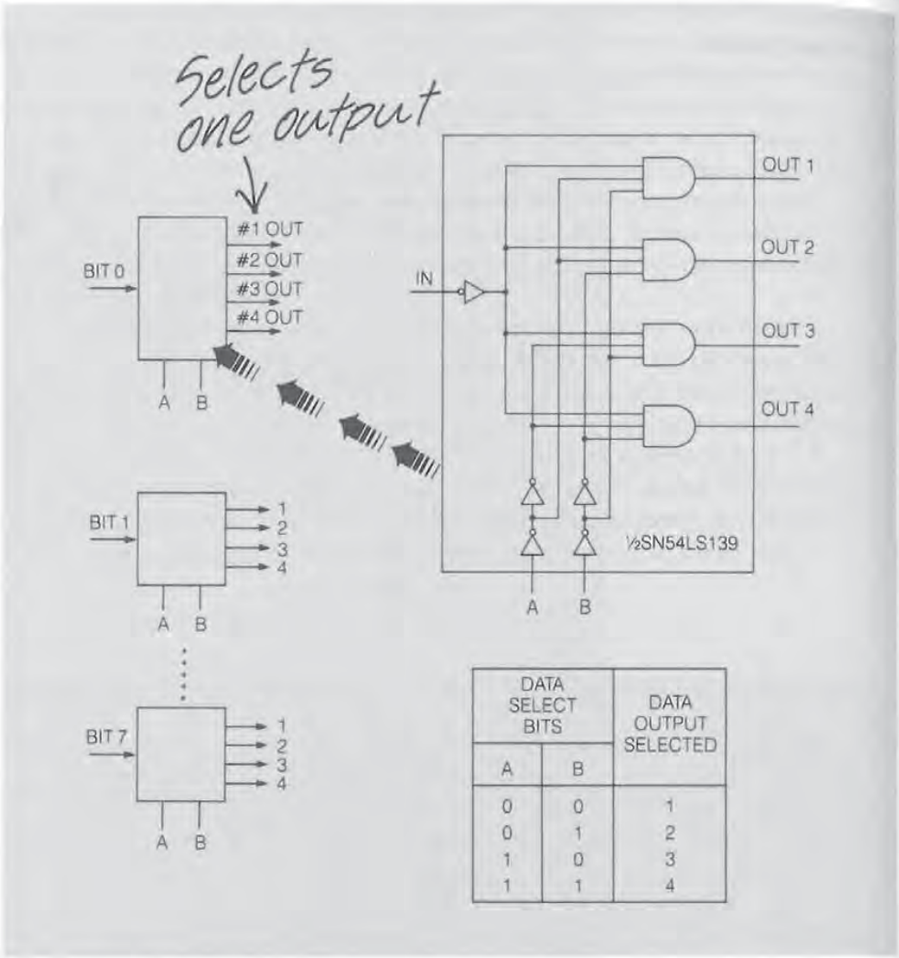


Figure 9.7
Data Demultiplexer

SAMPLING

Only one variable can be sampled by the computer at a time. The other variables must wait a set period of time before being sampled again by the computer.

The measurement of any quantity takes place only when the input and output switches (MUX and DEMUX) functionally connect the corresponding sensor and display to the computer, respectively. There are several variables to be measured and displayed, but only one variable can be accommodated at any given instant. Once a quantity has been measured, the system must wait until the other variables have been measured before that particular variable is measured again. This process of measuring a quantity intermittently is called *sampling*, and the time between successive samples of the same quantity is called the *sample period*, as explained in Chapter 2.

One possible scheme for measuring several variables by this process is to sample each quantity sequentially, giving each measurement a fixed time slot, t,

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

out of the total sample period, *T*, as illustrated in Figure 9.8. This method is satisfactory as long as the sample period is small compared with the time in which any quantity changes appreciably. Certain quantities, such as coolant temperature and fuel quantity, change very slowly with time. For such variables, a sample period of a few seconds or longer is often adequate.

Some variables, such as speed and battery charge, change much faster than others. To effectively monitor these differences the computer uses different sampling times.

On the other hand, variables such as vehicle speed, battery charge, and fuel consumption rate change relatively quickly and require a much shorter sample period, perhaps every second or every few tenths of a second. To accommodate the various rates of change of the automotive variables being measured, the sample period varies from one quantity to another. The most rapidly changing quantities are sampled with a very short sample period, whereas those that change slowly are sampled with a long sample period.

In addition to sample period, the time slot allotted for each quantity must be long enough to complete the measurement and any A/D or D/A conversion required. The computer program is designed with all of these factors in mind so that adequate time slots and sample periods are allowed for each variable. The computer then simply follows the program schedule.

Advantages of Computer-Based Instrumentation

One of the big advantages of computer-based instrumentation is its great flexibility. To change from the instrumentation for one vehicle or one model to another requires only a change of computer program. This change can often be implemented by replacing one ROM (read-only memory) with another. Remember that the program is permanently stored in a ROM that is typically packaged in a single integrated circuit package (see Chapter 4).

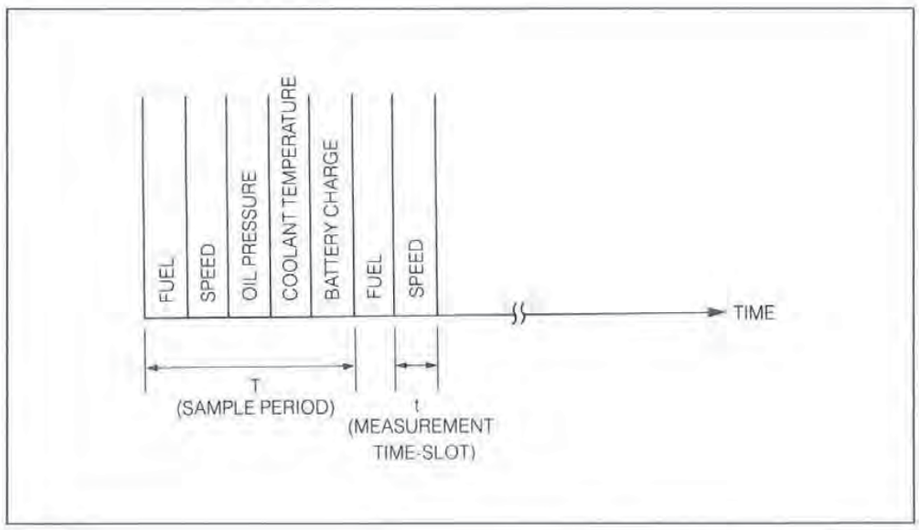


Figure 9.8 Sequential Sampling

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Computer-based instrumentation is more accurate and, due to the computer's program, more easily changed than conventional instrumentation.

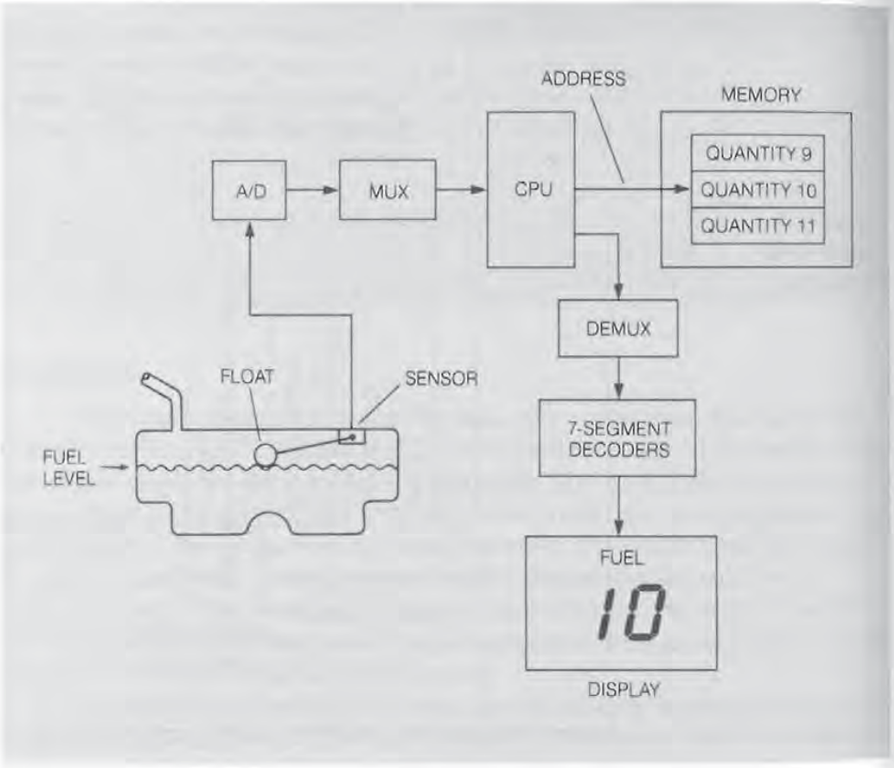
Another benefit of microcomputer-based electronic automotive instrumentation is its improved performance compared with conventional instrumentation. For example, the conventional fuel gauge system has errors that are associated with variations in the mechanical and geometrical characteristics of the tank, the sender unit, the instrument voltage regulator, and the indicator (galvanometer). The electronic instrumentation system eliminates the error that results from imperfect voltage regulation. Generally speaking, the electronic fuel quantity measurement maintains calibration over essentially the entire range of automotive electrical system conditions. Moreover, it significantly improves the display accuracy by replacing the electromechanical galvanometer display with an all-electronic digital display.

FUEL QUANTITY MEASUREMENT

Some fuel quantity sensors use a float within the fuel tank; the float is mechanically linked to a potentiometer that operates as a voltage divider.

During a measurement of fuel quantity, the MUX switch functionally connects the computer input to the fuel quantity sensor, as shown in Figure 9.9. This sensor output is converted to digital format and then sent to the computer for signal processing. (Note: In some automotive systems the analog sensor output is sent to the instrumentation subsystem, where the A/D conversion takes place.)

Figure 9.9 Fuel Quantity Measurement



PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Several fuel quantity sensor configurations are available. Figure 9.10 illustrates the type of sensor to be described, which is a potentiometer connected via mechanical linkage to a float. Normally, the sensor is mounted so that the float remains laterally near the center of the tank for all fuel levels. A constant current passes through the sensor potentiometer, since it is connected directly across the regulated voltage source. The potentiometer is used as a voltage divider so that the voltage at the wiper arm is related to the float position, which is determined by fuel level.

The sensor output voltage is not directly proportional to fuel quantity in gallons because of the complex shape of the fuel tank. The computer memory contains the functional relationship between sensor voltage (in binary number equivalent) and fuel quantity for the particular fuel tank used on the vehicle.

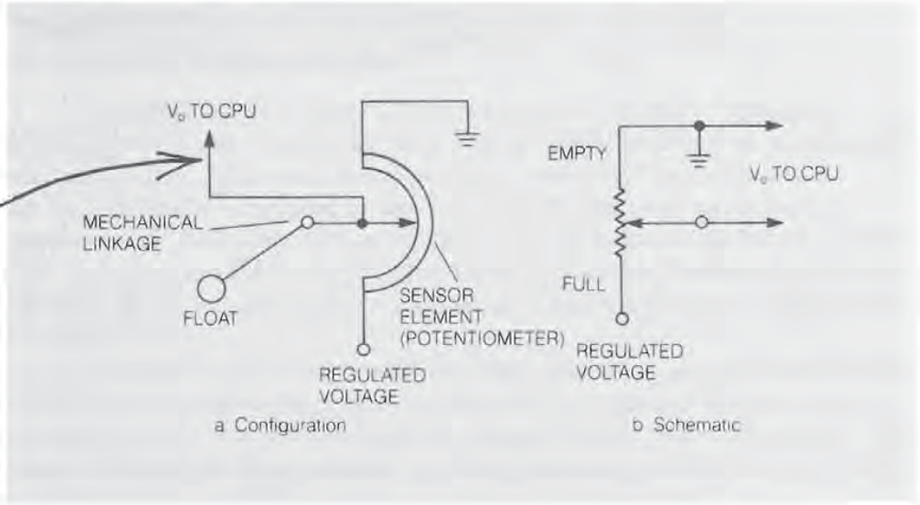
The computer reads the binary number from the A/D converter that corresponds to sensor voltage and uses it to address a particular memory location. Another binary number corresponding to the actual fuel quantity in gallons for that sensor voltage is stored in that memory location. The computer then uses the number from memory to generate the appropriate display signal—either analog or digital, depending on display type—and sends that signal via DEMUX to the display.

The computer compensates for fuel slosh by averaging float sensor readings over a period of time.

Computer-based signal processing can also compensate for fuel slosh. As the car moves over the road, the fuel sloshes about and the float moves up and down around the average position that corresponds to the correct level for a stationary vehicle. The computer compensates for slosh by computing a running average. It does this by storing several samples over a few seconds and computing the arithmetic average of the sensor output. The oldest samples are continually discarded as new samples are obtained. The averaged output

Figure 9.10
Fuel Quantity Sensor

Voltage level represents fuel level.



PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

becomes the signal that drives the display. It should be noted that this is actually a form of digital filtering.

COOLANT TEMPERATURE MEASUREMENT

Another important automotive parameter that is measured by the instrumentation is the coolant temperature. The measurement of this quantity is different from that of fuel quantity because usually it is not important for the driver to know the actual temperature at all times. For safe operation of the engine, the driver only needs to know that the coolant temperature is less than a critical value. A block diagram of the measuring system is shown in Figure 9.11.

The coolant temperature sensor used in most cars is a solid-state sensor called a *thermistor.* Recall that this type of sensor was discussed in Chapter 6, where it was shown that the resistance of this sensor decreases with increasing temperature. Figure 9.12 shows the circuit connection and a sketch of a typical sensor output voltage versus temperature curve.

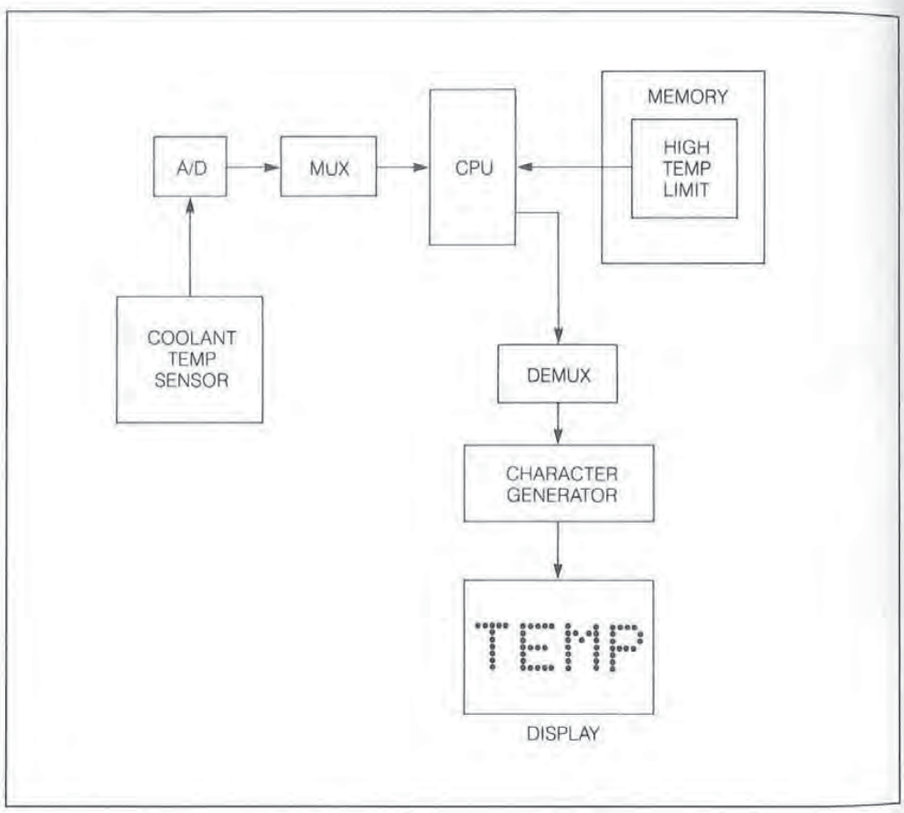


Figure 9.11 Coolant Temperature Measurement

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

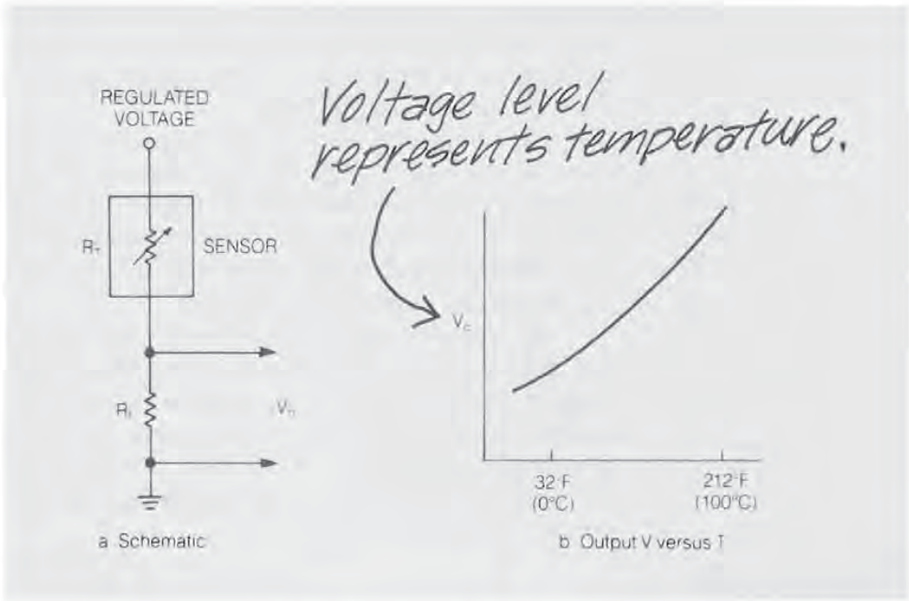


Figure 9.12 Coolant Temperature Sensor

To measure coolant temperature, the sensor output from a thermistor is converted into a digital signal and compared to a maximum safe value stored in memory.

The sensor output voltage is sampled during the appropriate time slot and is converted to a binary number equivalent by the A/D converter. The computer compares this binary number to the one stored in memory that corresponds to the high temperature limit. If the coolant temperature exceeds the limit, an output signal is generated that activates the warning indicator. If the limit is not exceeded, the output signal is not generated and the warning message is not activated. A proportional display of actual temperature can be used if the memory contains a cross-reference table between sensor output voltage and the corresponding temperature, similar to that described for the fuel quantity table.

OIL PRESSURE MEASUREMENT

Oil pressure warning systems use a variable-resistance sensor as part of a voltage divider. This arrangement provides a varying voltage that corresponds to changes in oil pressure.

Engine oil pressure measurement is similar to coolant temperature measurement in that it uses a warning message display rather than an indicated numerical value. Whenever the oil pressure is outside allowable limits, a warning message is displayed to the driver. In the case of oil pressure, it is important for the driver to know whenever the oil pressure falls below a lower limit. It is also possible for the oil pressure to go above an allowable upper limit; however, many manufacturers do not include a high oil pressure warning in the instrumentation.

The simplest oil pressure warning system involves a spring-loaded switch connected to a diaphragm. The switch assembly is mounted in one of the oil passageways such that the diaphragm is exposed directly to the oil pressure. The force developed on the diaphragm by the oil pressure is sufficient to overcome

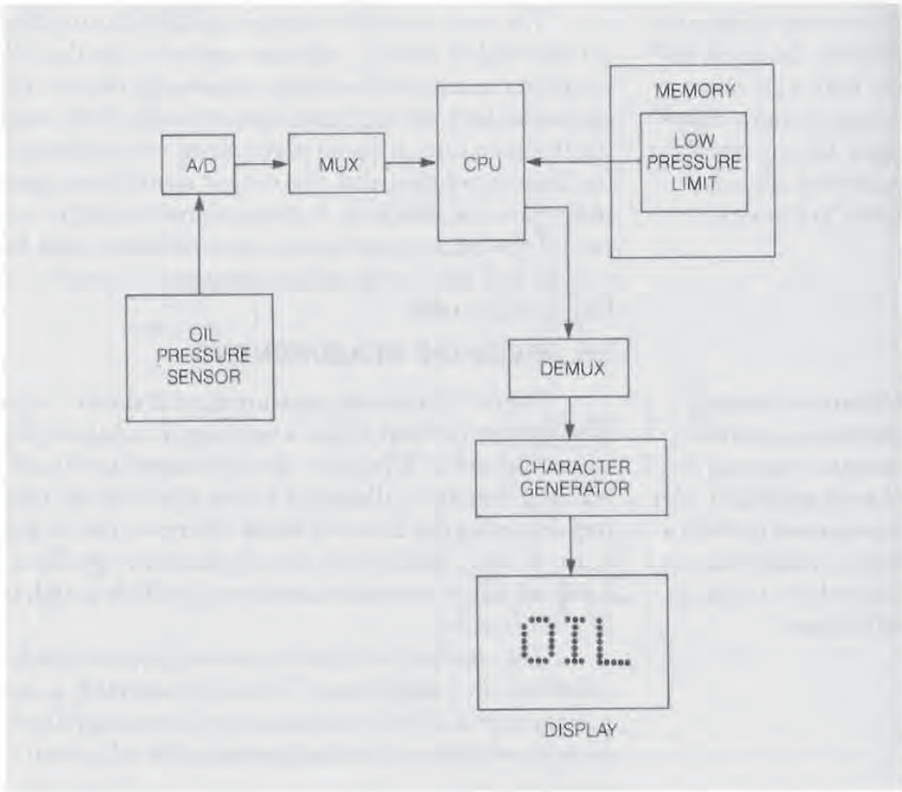
PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

the spring and to hold the switch open as long as the oil pressure exceeds the lower limit. Whenever the oil pressure falls below this limit the spring force is sufficient to close the switch. Switch closure is used to switch on the low oil pressure warning message lamp.

One of the deficiences of this simple switch-based oil pressure warning system is that it has a single fixed low oil pressure limit. In fact, the threshold oil pressure for safe operation varies with engine load. Whereas a relatively low oil pressure can protect bearing surfaces at low loads (e.g., at idle), a proportionately higher oil pressure threshold is required with increasing load (i.e., increasing horsepower and RPM).

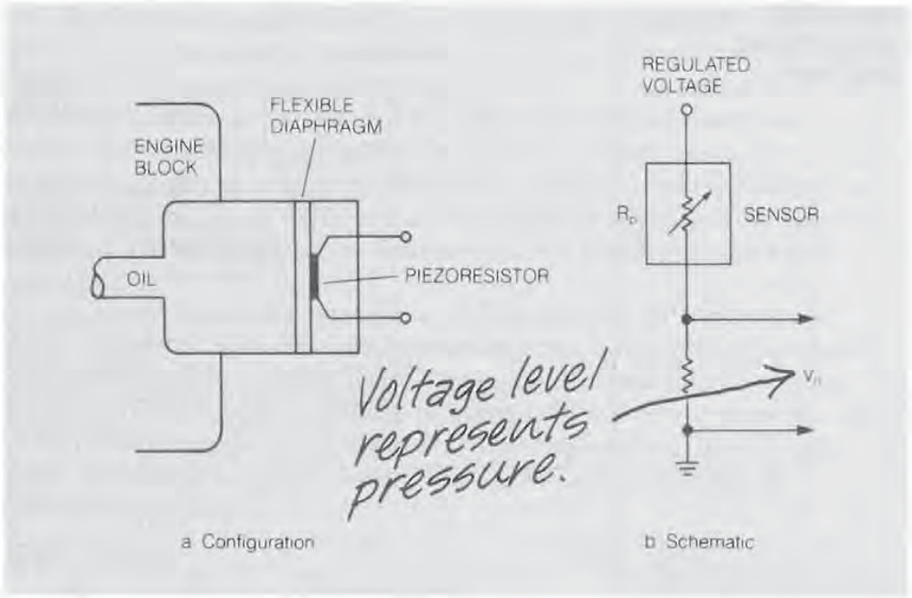
An oil pressure instrument that operates with a load- or speed-dependent threshold requires an oil pressure sensor rather than a switch. Such an oil pressure warning system is illustrated in Figure 9.13. This system uses a variable-resistance oil pressure sensor such as seen in Figure 9.14. A voltage is developed across a series of fixed resistance that is proportional to oil pressure. It should be noted that this assumed pressure sensor is hypothetical and used only for illustrative purposes.

Figure 9.13 Oil Pressure Measurement



PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Figure 9.14
Oil Pressure Sensor



During the measurement time slot, the oil pressure sensor voltage is sampled through the MUX switch and converted to a binary number in the A/D converter. The computer reads this binary number and compares it with the binary number in memory for the allowed oil pressure limits. The oil pressure limit is determined from load or crankshaft speed measurements that are already available in the engine control system. These measurement data can be sent to the instrument subsystem via the PDDL (see Figure 9.1). These measurements serve as the address for a ROM lookup table to find the oil pressure limit. If the oil pressure is below the allowed lower limit or above the allowed upper limit, an output signal is generated that activates the oil pressure warning light through the DEMUX.

It is also possible to use a proportional display of actual oil pressure if a cross-reference table, similar to the fuel quantity table, is used. A digital display can be driven directly from the computer. An analog display, such as the electric gauge, requires a D/A converter.

VEHICLE SPEED MEASUREMENT

Digital measurement of vehicle speed is possible using a binary counter and a sensor having an output signal frequency that is proportional to speed.

An example of a digital speed sensor has already been described in Chapter 8 for a cruise control system. A sensor of this type is assumed to be used for car speed measurements. The output of this sensor is a binary number, P, that is proportional to car speed S. This binary number is contained in the output of a binary counter (see Chapter 8). A block diagram of the instrumentation for vehicle speed measurement that uses this digital speed sensor is shown in Figure 9.15.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

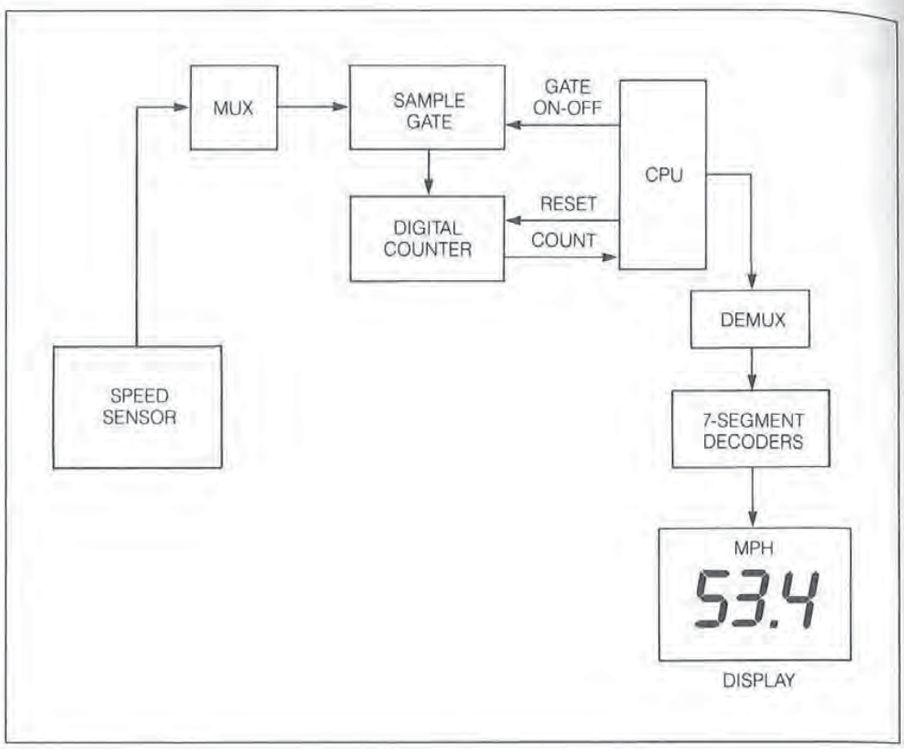


Figure 9.15 Vehicle Speed Measurement

The computer reads the number P in the binary counter, then resets the counter to zero to prepare it for the next count. After performing computations and filtering, the computer generates a signal for the display to indicate the vehicle speed. A digital display can be directly driven by the computer. Either mph or kph may be selected. If an analog display is used, a D/A converter must drive the display. Both mph and kph usually are calibrated on an analog scale.

DISPLAY DEVICES

One of the most important components of any measuring instrument is the display device. In automotive instrumentation, the display device must present the results of the measurement to the driver in a form that is easy to read and understand. The speedometer, ammeter, and fuel quantity gauge were originally electromechanical devices. Then automotive manufacturers began using warning lamps instead of gauges to cut cost. A warning lamp can be considered as a type of electro-optical display.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Electromechanical and simple electro-optical displays are being replaced by sophisticated electronic displays that provide the driver with numeric or alphabetic information.

Recent developments in solid-state technology in the field called optoelectronics have led to sophisticated electro-optical display devices that are capable of indicating alphanumeric data. This means that both numeric and alphabetic information can be used to display the results of measurements of automotive variables or parameters. This capability allows messages in English or other languages to be given to the driver. The input for these devices is an electronic digital signal, which makes these devices compatible with computer-based instrumentation, whereas electromechanical displays require a D/A converter.

Automobile manufacturers have considered many different types of electronic displays for automotive instrumentation, but only four have been really practical: light-emitting diode (LED), liquid crystal (LCD), vacuum-fluorescent (VFD), and the cathode ray tube (CRT). It now appears that the VFD will be the predominant type of instrumentation for at least the near future. Each of these types is discussed briefly to explain their uses in automotive applications.

LED

LEDs are solid-state devices that emit light when current is passed through the diode. LEDs are difficult to view in bright sunlight.

The light-emitting diode is a semiconductor diode that is constructed in a manner and of a material so that light is emitted when an electrical current is passed through it. The semiconductor material most often used for an LED that emits red light is gallium arsenide phosphide. Light is emitted at the diode's PN junction when the positive carriers combine with the negative carriers at the junction (see Chapter 3 for a discussion of PN junctions). The diode is constructed so that the light generated at the junction can escape from the diode and be seen.

An LED display is normally made of small dots or rectangular segments arranged so that numbers and letters can be formed when selected dots or segments are turned on. The configuration for these segments is described in greater detail later in this chapter in the section on VFD. A single LED is not well suited for automotive display use because of its low brightness. Although it can be seen easily in darkness, it is difficult to impossible to see in bright sunlight. It also requires more electrical power than an LCD display; however, its power requirements are not great enough to be a problem for automotive use.

LCD

LCDs use a liquid that possesses the ability to rotate the polarization of polarized light. LCD displays have low power requirements.

The LCD display is commonly used in electronic digital watch displays because of its extremely low electrical power and relatively low voltage requirements. The heart of an LCD is a special liquid that is called a *twisted nematic liquid crystal.* This liquid has the capability of rotating the polarization of linearly polarized light. Linearly polarized light has all of the vibrations of the optical waves in the same direction. Light from the sun and from most artificial light sources is not polarized, and the waves vibrate randomly in many directions.

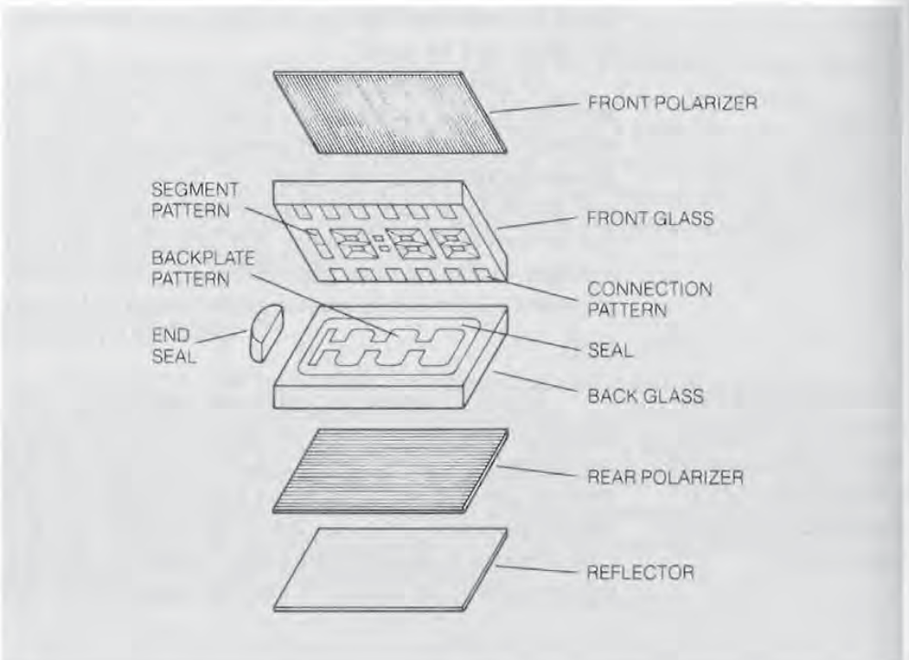
PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Nonpolarized light can be polarized by passing the light through a polarizing material. To illustrate, think of a picket fence with narrow gaps between the pickets. If a rope is passed between two of the pickets and its end is whipped up and down, the ripples in the rope will pass through the fence. The ripples represent light waves and the picket fence represents a polarizing material. If you whip the rope in any direction other than vertically, the ripples will not pass through.

Now visualize another picket fenced turned 90° so that the pickets are horizontal. Place this fence behind the vertical picket fence. This arrangement is called a cross-polarizer. If the rope is now whipped in any direction, no ripples will pass through both fences. Similarly, if a cross-polarizer is used for light, no light will pass through this structure.

The configuration of an LCD can be understood from the schematic drawings of Figure 9.16. The liquid crystal is sandwiched between a pair of glass plates that have transparent, electrically conductive coatings. The transparent conductor is deposited on the front glass plate in the form of the character, or segment of a character, that is to be displayed. Next, a layer of dielectric (insulating) material is coated on the glass plate to produce the desired alignment of the liquid crystal molecules. The polarization of the molecules is vertical at the front, and they gradually rotate through the liquid crystal structure until the molecules at the back are horizontally polarized. Thus, the molecules of the liquid crystal rotate 90° from the front plate to the back plate so that their polarization matches that of the front and back polarizers with no voltage applied.

Figure 9.16 Typical LCD Construction



PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

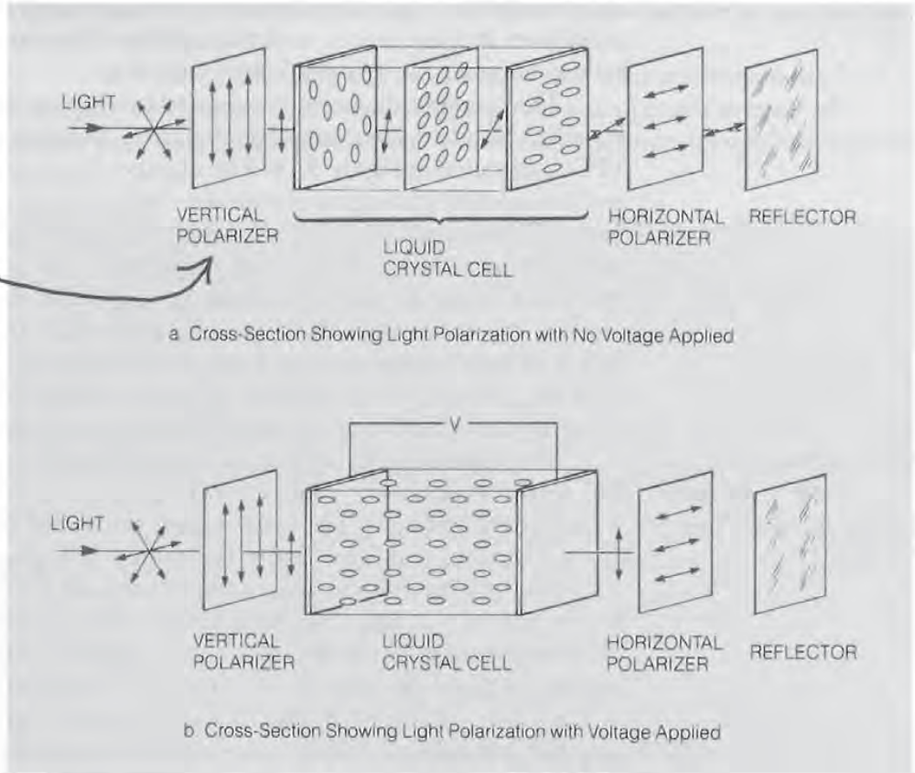
When current is not being applied to an LCD display, light entering the crystal is polarized by the front polarizer, rotated, passed through the rear polarizer, and then reflected off the reflector.
When a voltage is applied to a display segment, the crystal's molecules change and do not rotate the polarized light. Since the light cannot align with the rear polarizer, it is not reflected and the segment appears dark.

The operation of the LCD in the absence of applied voltage can be understood with reference to Figure 9.17a. Ambient light enters through the front polarizer so that the light entering the front plate is vertically polarized. As it passes through the liquid crystal, the light polarization is changed by the orientation of the molecules. When the light reaches the back of the crystal, its polarization has been rotated 90° so that it is horizontally polarized. The light is reflected from the reflector at the rear. It passes back through the liquid crystal structure, the polarization again being rotated, and passes out of the front polarizer. Thus, a viewer sees reflected ambient light.

The effect of an applied voltage to the transmission of light through this device can be understood from Figure 9.17b. A voltage applied to any of the segments of the display causes the liquid crystal molecules under those segments only to be aligned in a straight line rather than twisted. In this case, the light that enters the liquid crystal in the vicinity of the segments passes through the crystal structure without the polarization being rotated. Since the light has been vertically polarized by the front vertical polarizing plate, the light is blocked by the horizontal polarizer so it cannot reach the reflector. Thus, light that enters the cell in the vicinity of energized segments is not returned to the front face. These segments will appear dark to the viewer, the

Figure 9.17 Liquid Crystal Polarization

Only pass light in a specific direction.



PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

surrounding area will be light, and the segments will be visible in the presence of ambient light.

The LCD is an excellent display device because of its low power requirement and relatively low cost. However, a big disadvantage of the LCD for automotive application is the need for an external light source for viewing in the dark. Its characteristic is just the opposite of the LED; that is, the LCD is readable in the daytime, but not at night. For night driving, the display must be illuminated by small lamps inside the display. Another disadvantage is that the display does not work well at the low temperatures that are encountered during winter driving in some areas. These characteristics of the LCD have limited its use in automotive instrumentation.

VFD

VFDs use a phosphor (a material that emits light when bombarded by electrons). VFDs provide readability over a wide range of conditions.

One of the most common automotive display devices in use today is the vacuum-fluorescent display (VFD). This device generates light in much the same way as a television picture tube does; that is, a material called phosphor emits light when it is bombarded by energetic electrons. The display uses a filament coated with material that generates free electrons when the filament is heated. The electrons are accelerated toward the anode by a relatively high voltage. When these high-speed electrons strike the phosphor on the anode, the phosphor emits light. A common VFD has a phosphor that emits a blue-green light that provides good readability in the wide range of ambient light conditions that are present in an automobile. However, other colors (e.g., red or yellow) are available by using other phosphors.

The numeric characters are formed by shaping the anode segments in the form of a standard seven-segment character. The basic structure of a typical VFD is depicted in Figure 9.18. The filament is a special type of resistance wire and is heated by passing an electrical current through it. The coating on the heated filament produces free electrons that are accelerated by the electric field produced by a voltage on the accelerating grid. This grid consists of a fine wire mesh that allows the electrons to pass through. The electrons pass through because they are attracted to the anode, which has a higher voltage than the grid. The high voltage is applied only to the anode of the segments needed to form the character to be displayed. The instrumentation computer selects the set of segments that are to emit light for any given message.

VFD brightness can be controlled by varying the voltage on the accelerator grid.

Since the ambient light in an automobile varies between sunlight and darkness, it is desirable to adjust the brightness of the display in accordance with the ambient light. The brightness is controlled by varying the voltage on the accelerating grid. The higher the voltage, the greater the energy of the electrons striking the phosphor and the brighter the light. Figure 9.19 shows the brightness characteristics for a typical VFD device. A brightness of 200 fL (foot-lamberts) might be selected on a bright sunny day, whereas the brightness might be only 20 fL at night. The brightness can be set manually by the driver, or automatically. In the latter case, a photoresistor is used to vary the grid voltage in accordance with the amount of ambient light. A

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

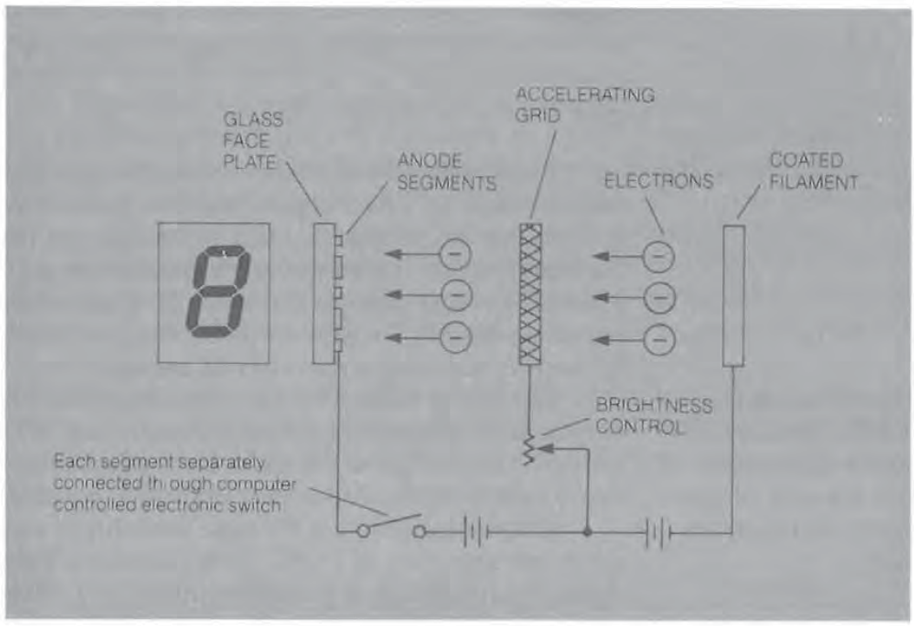


Figure 9.18 Simplified Vacuum-Fluorescent Display Configuration

photoresistor is a device whose resistance varies in proportion to the amount of light striking it.

The VFD is likely to be the most widely used instrumentation display for some time. It operates with relatively low power and operates over a wide temperature range. The most serious drawback for automotive application is its

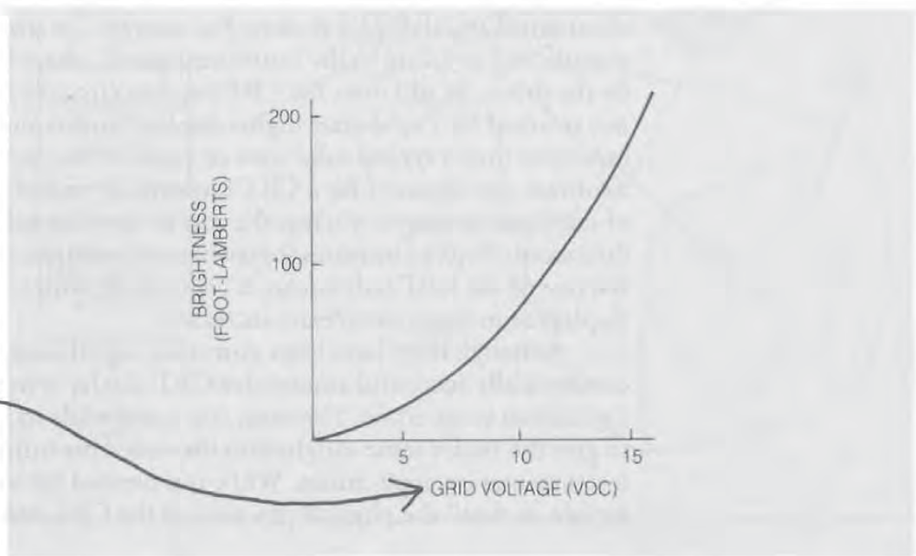


Figure 9.19 Brightness Control Range for Vacuum-Fluorescent Display

Increasing grid voltage increases brightness.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

susceptibility to failure due to vibration and mechanical shock. However, this problem can be reduced by mounting the display on a shock-absorbing isolation mount.

CRT

The display devices that have been discussed to this point have one rather serious limitation. The characters that can be displayed are limited to those symbols that can be approximated by the segments that can be illuminated. Furthermore, illuminated warning messages such as "Check Engine" or "Oil Pressure" are *fixed* messages that are either displayed or not, depending on the engine conditions. The primary disadvantage of such ad hoc display devices is the limited flexibility of the displayed messages.

The cathode ray tube (CRT) is similar to a TV picture tube and has great potential for automotive display applications.

The display device that has the greatest flexibility for displaying messages or pictorial information is the cathode ray tube (CRT). The CRT that is perhaps most familiar to the reader is the television picture tube. The CRT is also the display device most commonly used in personal computers.

A technology that has the same flexibility of display as the CRT is the solid-state equivalent of a CRT. Such a display is commonly called a *flat-panel display.* Such a display, if it can be produced at sufficiently low cost, has enormous potential in future automotive IP displays. However, as it is functionally equivalent to the CRT and as the CRT is an existing, very mature technology, we will describe such displays using the CRT example.

The CRT is being used increasingly for display purposes in the aerospace industry, where it is used to display aircraft attitude information (sometimes pictorially), aircraft engine or airframe parameters, navigational data, and warning messages. Clearly, the CRT has great potential for automotive instrumentation display.

It has, however, certain disadvantages compared to solid-state or electromechanical display devices. For example, its size and shape make it complicated to locate in the instrument panel, where it can most easily be read by the driver. In addition, the CRT requires circuitry for its operation that is not required by a solid-state digital display. Furthermore, the CRT is more expensive than a typical solid-state or vacuum-fluorescent display. The hardware cost incurred for a CRT is essentially independent of the complexity of displayed messages, whereas the cost of alternate solid-state or vacuum-fluorescent displays increases somewhat with complexity of the messages. Thus, the cost of the CRT only becomes comparable with vacuum-fluorescent displays as message complexity increases.

Although there have been numerous experimental and a few commercially successful automotive CRT display systems, the future of this application is uncertain. However, it is worthwhile to describe the technology to give the reader some insight into the varied potential automotive instrumentation applications. While it is beyond the scope of this book to explain in detail the physical processes of the CRT and its associated electronic

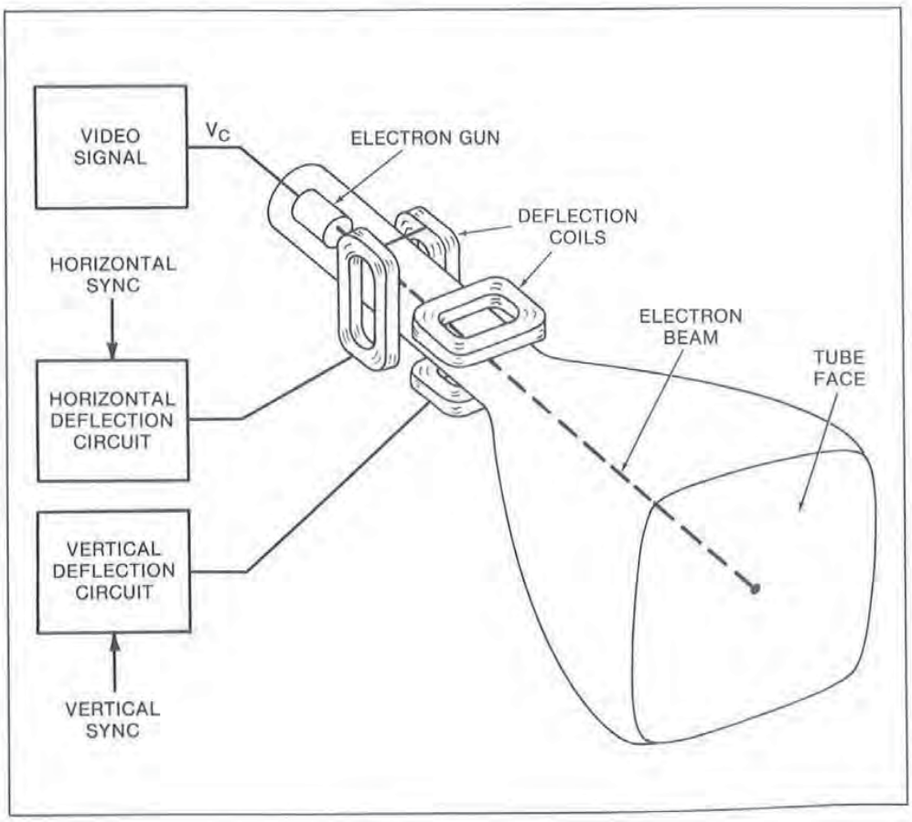
PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

circuits, a relatively simple overview of the functional operation of the CRT as a display device is straightforward and should serve to illustrate some potential automotive applications.

Figure 9.20 is a sketch of a typical CRT. It is an evacuated glass tube that has a nominally flat surface that is coated with a phosphorescent material. This surface is the surface or face on which the displayed messages appear. At the rear is a somewhat complex structure called an *electron gun.* This device generates a stream of electrons that is accelerated toward the screen and brought to convergence at a spot on the screen. A system of coils in the form of electromagnets causes this convergence of electrons (or beam) and is referred to as the *magnetic focusing system.* The focused stream of electrons is called the *beam.*

The electron beam generates a spot of light at the point on the screen. The intensity of the light is proportional to the electron beam current. This current is controlled by the voltage (V_c), which is called the *video signal,* on an electrode that is located near the electron gun.

Figure 9.20 CRT and Associated Circuitry



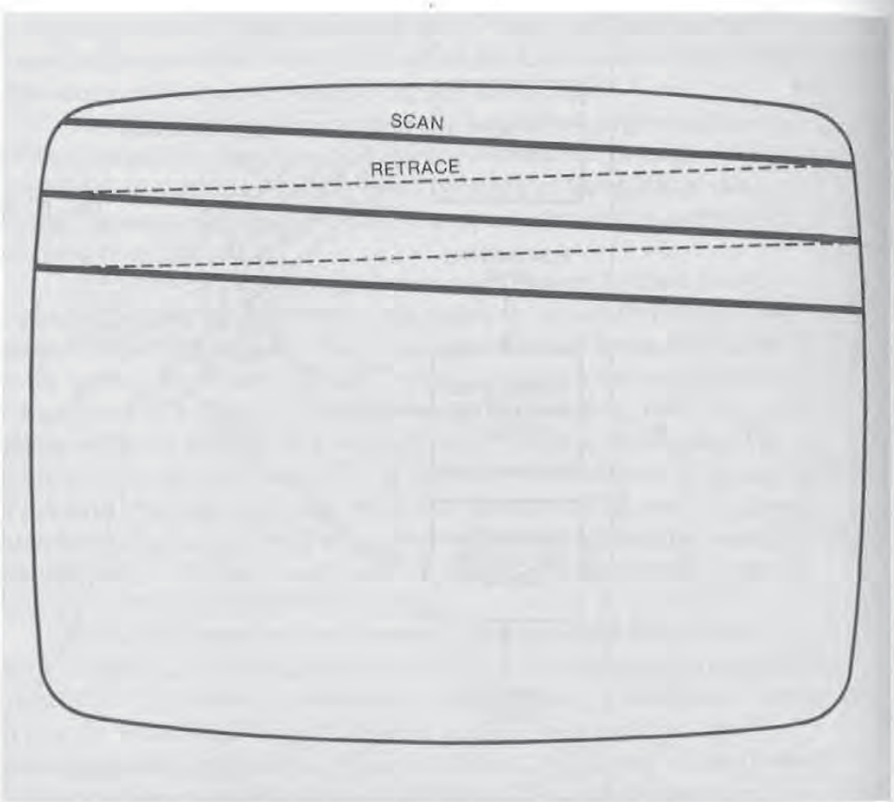
PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

In the majority of applications (including TV), the electron beam is scanned in a pattern known as a *raster* by means of specially located electromagnets (see Figure 9.20). The magnetic fields created by the scanning coils deflect the beam horizontally and vertically. The amount of deflection is proportional to the current flowing through the respective coils. The raster pattern traced by the beam is illustrated on the face of the CRT in Figure 9.21.

The scanning motion is done in synchronism with the source of information being displayed. At the end of each horizontal scan line, a synchronizing pulse (called *horizontal sync*) causes the beam to deflect rapidly to the left and then to begin scanning at a constant rate to the right. A similar synchronizing pulse is generated at a time when the beam is at the bottom of the CRT. This pulse (called *vertical sync*) causes the beam to deflect rapidly to the top of the CRT face and then to begin scanning downward at a uniform speed.

The information (or picture) displayed on the face of the CRT is controlled by the voltage V_c as a function of time relative to the horizontal and vertical sync pulses. Thus, to generate a message on an automotive CRT

Figure 9.21
Raster Pattern



PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

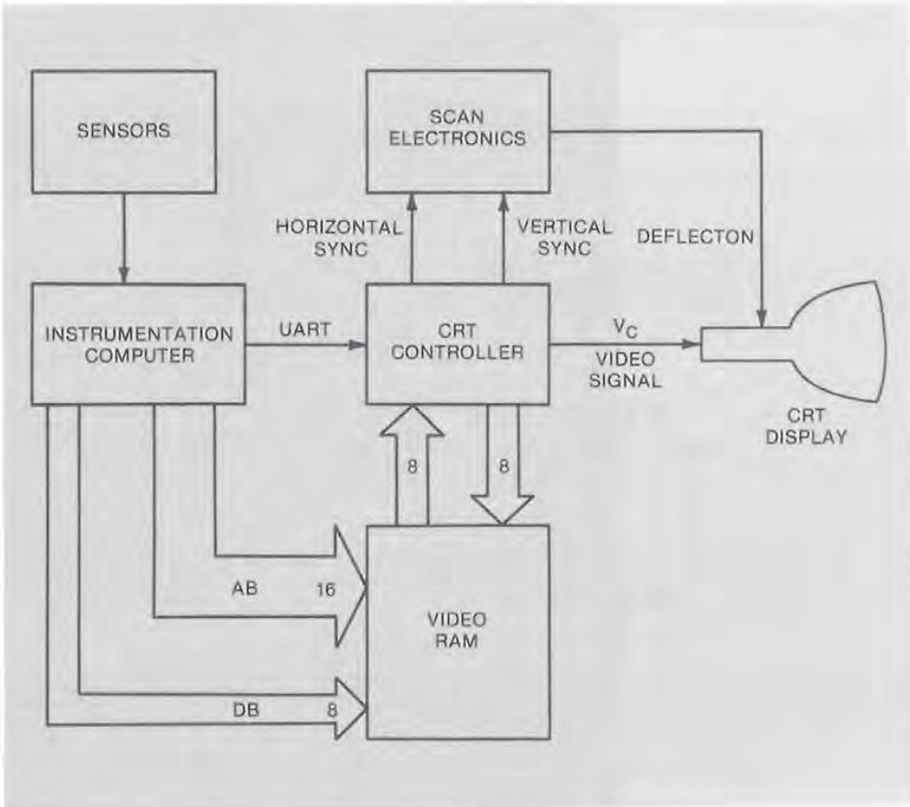
In automotive instrumentation applications, a CRT display is driven by a special electronics system called the CRT controller.

display, a specific voltage pattern for V_c must be generated in timed relationship to the sync pulses. This voltage is typically referred to as the *video voltage.*

In a typical CRT display device, the video voltage and sync pulses are generated in a special circuit called the *CRT controller.* A simplified block diagram for a system incorporating a CRT display with the associated CRT controller is depicted in Figure 9.22. The sensors and instrumentation computer, which are microprocessor (MPU) based, shown at the left of this illustration have the same function as the corresponding components of the system in Figure 9.2. The output of the instrumentation computer controls the CRT display, working through the CRT controller.

The instrumentation computer communicates with the CRT controller via data and address buses (DB and AB), and via a serial link along a line labeled UART (universal asynchronous receiver/transmitter). The data that is sent over the DB is stored in a special memory called video RAM. This memory stores digital data that is to be displayed in alphanumeric or pictorial patterns on the CRT screen. The CRT controller obtains data from the video RAM and

Figure 9.22 Automotive CRT Instrumentation System



PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

converts it to the relevant video signal (V_c). At the same time, the CRT controller generates the horizontal and vertical sync necessary to operate the raster scan in synchronism with the video signal.

The video controller in the example system (Figure 9.23) itself incorporates an MPU for controlling the CRT display. The video signals that are required to operate the CRT—V_c (video), H_s (horizontal sync), and V_s (vertical sync)—are typically generated in a special-purpose integrated circuit, which in Figure 9.23 is labeled the video generator.

The data to be displayed is stored in the video RAM via the system buses under control of the instrumentation computer. The operation of the MPU is controlled by programs stored in a display ROM (DROM). This ROM might also store data that is required to generate particular characters. The various components of the CRT controller are internally connected by means of data and address buses similar to those used in the instrumentation computer.

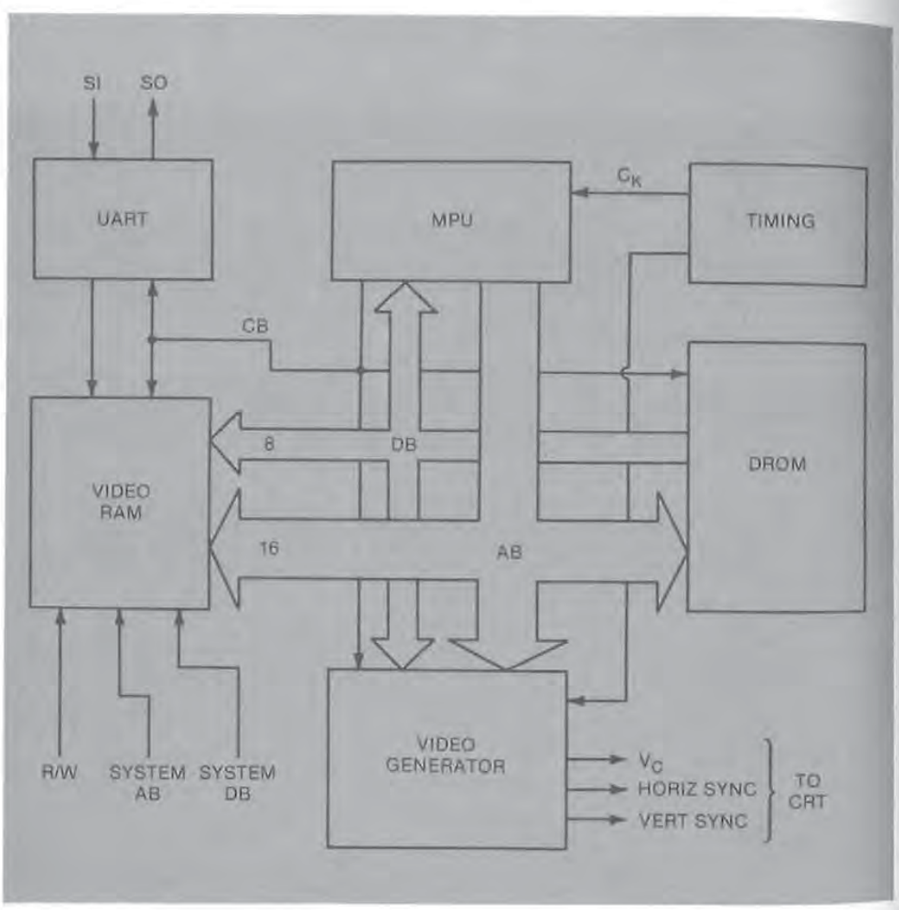


Figure 9.23 CRT Controller Configuration

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

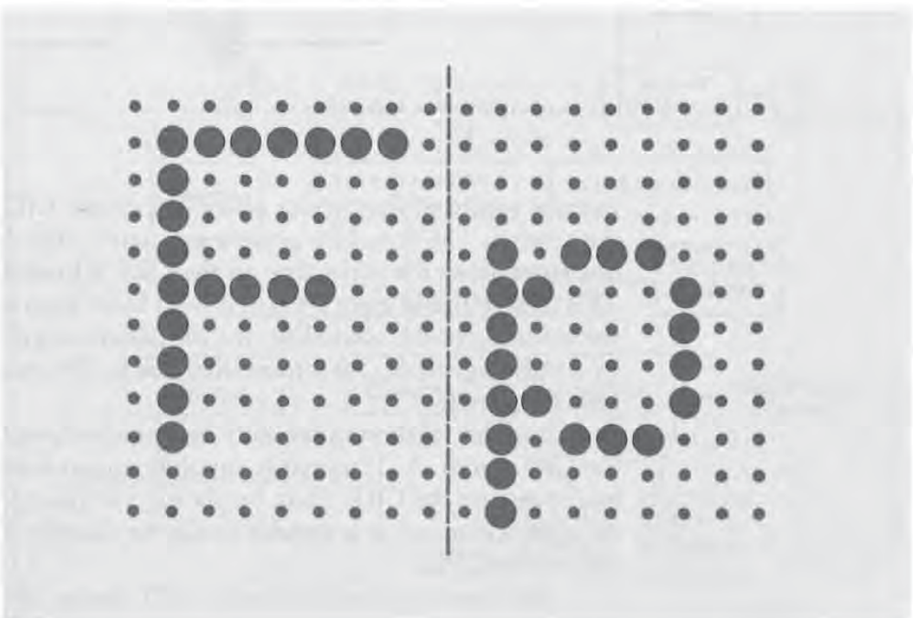
The operation of the CRT controller is under control of the instrumentation computer. This computer transfers data that is to be displayed to the video RAM, and signals the CRT controller via the UART link. During the display time, the MPU operates under control of programs stored in the DROM. These programs cause the MPU to transfer data from the video RAM to the video IC (chip) in the correct sequence for display.

The details of the transfer of data to the video IC and the corresponding generation of video signals vary from system to system. In the hypothetical system seen in Figure 9.22, the display on the CRT screen consists of a sequence of data arranged in 256 rows vertically by 256 horizontally. Here the display generates the characters F and P (see Figure 9.24). The dots are generated by switching on the electron beam at the desired location. The beam is switched by pulsing the video voltage at the time relative to H_s and V_s at which a dot is to appear. The resolution of the display is one dot, which is often termed a *pixel* (picture element).

A typical CRT uses a raster scan method and generates dots on the screen by means of suitably timed video signals.

A scheme for generating the suitable video signals for such a display is shown (greatly simplified) in the block diagram of Figure 9.25. During the horizontal retrace time when the electron beam is moving rapidly from right to left, the MPU (under program control) determines which data pattern is to be displayed during the next scanning line. The MPU maintains an

Figure 9.24 Display of Characters F and P



PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

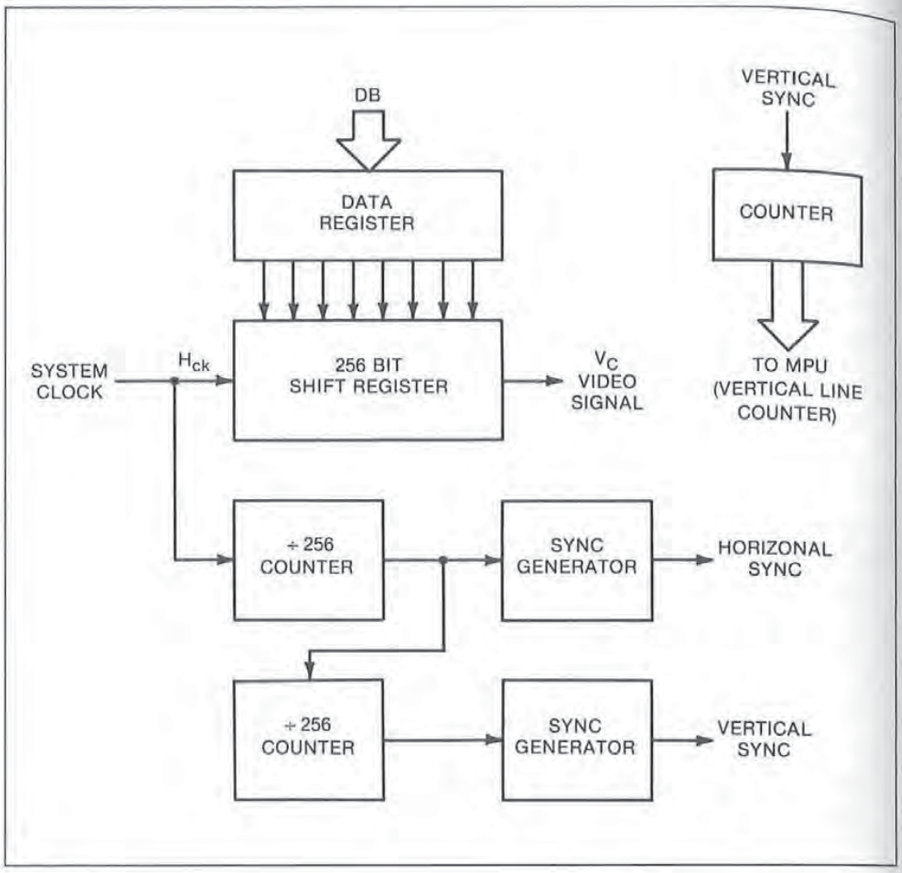


Figure 9.25 Video Signal Generation

internal record of the current active line on the CRT by counting vertical sync pulses. The actual bit pattern associated with the character being displayed along the active line on the CRT is loaded into the shift register. This data comes in eight separated 8-bit bytes from video RAM. Then during the scanning of the active line, the bit pattern is shifted out one bit at a time by a pulse signal, H_{ck}, at a frequency that is 256 times that of the horizontal sync frequency.

Each bit location in the shift register corresponds to a pixel location on the CRT screen. A "1" stored at any shift register location corresponds to a bright spot on the CRT. Thus, by placing a suitable pattern in the shift register for a particular line, it is possible to display complex alphanumeric or pictorial data on the CRT.

The enormous flexibility of the CRT display offers the potential for a very sophisticated automotive instrumentation system. In addition to displaying the

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

variables and parameters that have traditionally been available to the driver, the CRT can display engine data for diagnostic purposes (see Chapter 10), vehicle comfort control system parameters, and entertainment system variables. The data required for such displays can, for example, be transmitted via a high-speed digital data (HSDD) link between the various on-board electronics systems.

There are several reasons for using the serial HSDD link for transmitting data between the various systems rather than tying the internal data buses together. For example, it is desirable to protect any given system from a failure in another. A defect affecting the data bus of the comfort system could adversely affect the engine control system. In addition, each internal data bus tends to be busy handling internal traffic. Moreover, the transfer of data to the instrumentation computer can take place at relatively low data rates (for the diagnostic application outlined here).

Figure 9.26 is a block diagram of an integrated vehicle instrumentation system in which all on-board electronic systems are coupled by an HSDD link. This system requires a keyboard (KB) or similar input device for operator

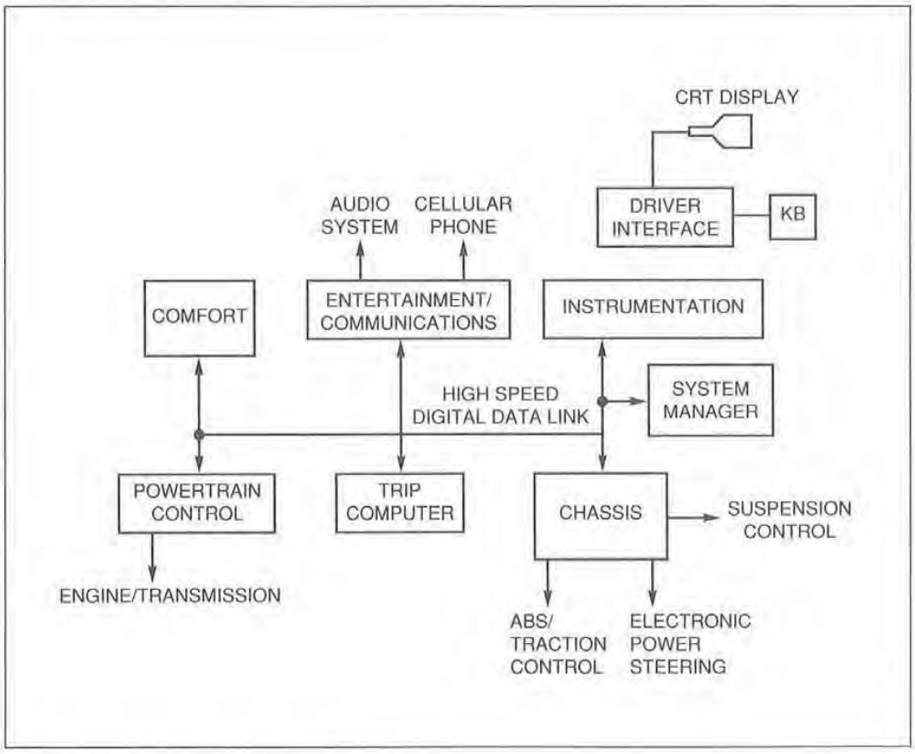


Figure 9.26 Integrated Vehicle Electronic Systems

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

control. The driver can, for example, select to display the entertainment system operation. This display mode permits the driver to select radio, tape, or CD, and to tune the radio to the desired station and set the volume. In vehicle diagnostic mode, the CRT can be configured to display the parameters required by the mechanic for performing a diagnosis of any on-board electronic system.

In Figure 9.26, several electronic systems are connected by the digital data link. Tying systems together this way has great potential performance benefits for the vehicle. Each automotive subsystem has its own primary variables, which are obtained through measurements via sensors. A primary variable in one subsystem might be a secondary variable in another system. It might not be cost-effective to provide a sensor for a secondary variable to achieve the best possible performance in a stand-alone subsystem. However, if measurement data can be shared via the digital data link, then the secondary measurement is potentially available for use in optimizing performance. Furthermore, redundant sensors for measuring primary variables can be eliminated by an integrated electronics system for the vehicle. For example, wheel speed measurements are primary variables for ABS systems and are also useful in electronic transmission control.

The various subsystems in Figure 9.26 have all been identified in other sections of this book and will not be discussed further here, except for the system manager. This subsystem is responsible for coordinating data transfer and regulating the use of the data bus so that no two systems are transmitting simultaneously.

Essentially, the digital data link provides a sophisticated communication system between various subsystems. Among the issues of importance for such a communication system are the physical protocol and message format. It is highly advantageous to have a standard protocol for all automobiles. The Society of Automotive Engineers (SAE) is working to develop a standard protocol for the high-speed digital data link. This link operates at a data rate of 1 megabit/sec and can be implemented with wire or optical fiber. Any of a number of bit-encoding schemes are useful for message formats, the details of which are unimportant for the present discussion.

Some form of network arbitration is required for determining priority of the use of the link whenever there is conflict between subsystems for its use. This feature is typically handled by the system manager.

The basic message structure is derived assuming that the majority of data on the link is regularly sent. This means that the content of each message is known (only the actual data varies).

The potential for incorporating the CRT as an automotive display will be greatly enhanced if the solid-state CRT becomes available at sufficiently low cost. It can, potentially, lead to the so-called glass cockpit described next. Such a

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

display device could use a raster-type display strategy similar to that explained above for a vacuum-tube CRT.

THE GLASS COCKPIT

The development of a cost-effective solid-state equivalent of the CRT can have enormous application in automotive instrumentation. It can yield a completely reconfigurable display system similar to the multifunction display used in some modern transport aircraft. Such displays are termed a *glass cockpit* in aircraft parlance. It is also known as an electronic flight information system (EFIS).

A single CRT acting as a display for a digital instrumentation system has the capability of displaying any of several choices of data readout, including

1. Navigation data
2. Subsystem status parameters
3. Attitude (artificial horizon)
4. Air data (airspeed, altitude, etc.)

It can also be used for diagnosis of problems with various aircraft subsystems. In this case it can present a pictorial diagram of any aircraft subsystem (hydraulic system or electrical system) so that the flight crew doesn't have to resort to hunting through a manual for the aircraft to diagnose a problem with a subsystem.

One of the benefits of an automotive glass cockpit is its great flexibility. Any message in any format can be displayed. In fact, the format can be chosen by the driver via a set of switches or by a keypad arrangement. The driver selects a particular display format from a number of choices and the display will be reconfigured to his choice by software, that is, by the program stored in the instrumentation computer. A likely default choice would include a standard display having speed and fuel quantity and the capability of displaying warning messages to the driver.

Another benefit of the EFIS-type display is the capability of displaying diagnostic information to a service technician. The service tech can select a display mode that presents fault codes from any vehicle subsystem whenever the car is taken for repairs or during routine maintenance operations.

Of particular importance is the capability of digital instrumentation to identify intermittent faults. The instrumentation computer can store fault codes with a time stamp that gives the time of occurrence to indicate to a service technician that a particular component or subsystem is experiencing intermittent failures. Such failures are extremely difficult to diagnose because they are often not present when the car is brought in for service. In this mode of operation the instrumentation computer along with its software-reconfigurable display is serving a role somewhat analogous to a flight data recorder on an aircraft.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

TRIP INFORMATION COMPUTER

The trip information computer analyzes fuel flow, vehicle speed, and fuel tank quantities, and then calculates information such as miles to empty, average fuel economy, and estimated arrival time.

One of the most popular electronic instruments for automobiles is the trip information system. This system has a number of interesting functions and can display many useful pieces of information, including the following:

1. Present fuel economy
2. Average fuel economy
3. Average speed
4. Present vehicle location (relative to total trip distance)
5. Total elapsed trip time
6. Fuel remaining
7. Miles to empty fuel tank
8. Estimated time of arrival
9. Time of day
10. Engine RPM
11. Engine temperature
12. Average fuel cost per mile

Additional functions can be performed, which no doubt will be part of future developments. However, we will discuss a representative system having features that are common to most available systems.

A block diagram of this system is shown in Figure 9.27. Not shown in the block diagram are MUX, DEMUX, and A/D converter components, which are normally part of a computer-based instrument. This system can be implemented as a set of special functions of the main automotive instrumentation system, or it can be a stand-alone system employing its own computer.

The vehicle inputs to this system come from the three sensors that measure the following variables:

1. Quantity of fuel remaining in the tank
2. Instantaneous fuel flow rate
3. Vehicle speed

Other inputs that are obtained by the computer from other parts of the control system are

1. Odometer mileage
2. Time (from clock in the computer)

The driver enters inputs to the system through the keyboard. At the beginning of a trip, the driver initializes the system and enters the total trip distance and fuel cost. At any time during the trip, the driver can use the keyboard to ask for information to be displayed.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

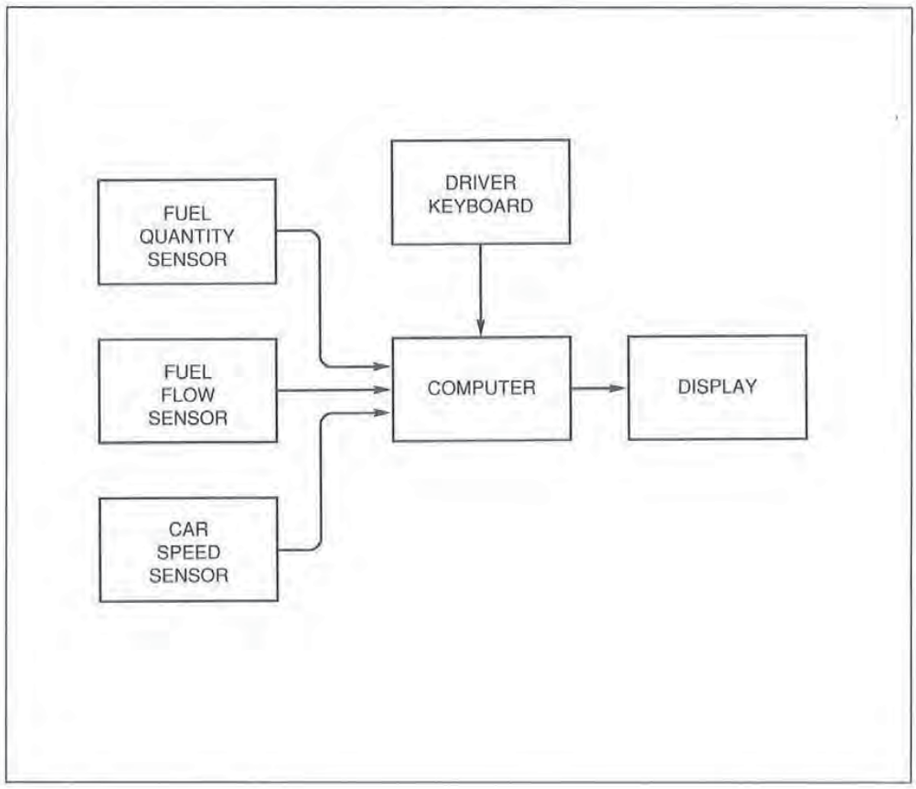


Figure 9.27
Trip Information System

The system computes a particular trip parameter from the input data. For example, fuel economy in miles per gallon (MPG) can be found by computing

$$MPG = S/F$$

where

S is the speed in miles per hour
F is the fuel consumption rate in gallons per hour

As operating conditions change, the values provided by a trip information computer may also change.

Of course, this computation varies markedly as operating conditions vary. At a steady cruising speed along a level highway with a constant wind, fuel economy is constant. If the driver then depresses the accelerator (e.g., to pass traffic), the fuel consumption rate temporarily increases faster than speed, and MPG is reduced for that time. Various averages can be computed such that instant fuel economy, short-term average fuel economy, or long-term average fuel economy can be displayed.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Another important trip parameter that this system can display is the miles to empty fuel tank, D. This can be found by calculating

$$D = \text{MPG} \times Q$$

where Q is the quantity of fuel remaining in gallons. Since D depends on MPG, it also changes as operating conditions change (e.g., during heavy acceleration). In such cases, the calculation of miles to empty based on the above simple equation is grossly incorrect. However, this calculation gives a correct estimate of the miles to empty for steady cruise along a highway in which operating conditions are constant.

Still another pair of parameters that can be calculated and displayed by this system are distance to destination, D_d, and estimated time of arrival, ETA. These can be found by computing

$$D_d = D_T - D_P$$

$$\text{ETA} = T_1 + (D_d/S)$$

where

D_T is the trip distance (entered by the driver)
D_P is the present position (in miles traveled since start)
S is the present vehicle speed
T_1 is the start time

The computer can calculate the present position D_P by subtracting the start mileage, D_1 (obtained from the odometer reading when the trip computer was initialized by the driver), from the present odometer mileage.

The average fuel cost per mile C can be found by calculating

$$C = (D_P/\text{MPG}) \times \text{fuel cost per gallon}$$

There are many other useful and interesting operations that can be performed by the variety of available systems. Actually, the number of such functions that can be performed is limited primarily by cost and by the availability of sensors to measure the required variables.

AUTOMOTIVE DIAGNOSTICS

The instrumentation computer can also be used as a diagnostic aid during vehicle manufacturing, operation, or repair.

In certain automobile models, the instrumentation computer can perform the important function of diagnosis of the electronic engine control system. This diagnosis takes place at several different levels. One level is used during manufacturing to test the system, and another level is used by mechanics or interested car owners to diagnose engine control system problems. Some levels operate continuously and others are available only on request from an external device that is connected to the car data link for diagnostic purposes by a technician. This application is explained in the next chapter.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

In the continuous monitor mode, the diagnosis takes place under computer control. The computer activates connections to the vehicle sensors and looks for an open- or short-circuited sensor. If such a condition is detected, a failure warning message is given to the driver on the alphanumeric display or by turning on a labeled warning light. A detailed discussion of automotive diagnosis appears in Chapter 10.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Quiz for Chapter 9

1. What is the primary purpose of automotive instrumentation?
   - **a.** to indicate to the driver the value of certain critical variables and parameters
   - **b.** to extend engine life
   - **c.** to control engine operation
   - **d.** entertainment of passengers
2. What are the three functional components of electronic instrumentation?
   - **a.** sensor, MAP, display
   - **b.** sensor, signal processing, error amplifier
   - **c.** display, sensor, signal processing
   - **d.** none of the above
3. What is the function of a multiplexer in computer-based instrumentation?
   - **a.** it measures several variables simultaneously
   - **b.** it converts sensor analog signals to digital format
   - **c.** it sequentially switches a set of sensor outputs to the instrumentation computer input
4. What is sampling?
   - **a.** a signal processing algorithm
   - **b.** a selective display method
   - **c.** a method of measuring a continuously varying quantity at discrete time instants
   - **d.** the rate of change of battery voltage
5. What is an A/D converter?
   - **a.** a device that changes a continuously varying quantity to a digital format
   - **b.** an 8-bit binary counter
   - **c.** an analog-to-decimal converter
   - **d.** a fluid coupling in the transmission
6. What type of sensor is commonly used for fuel quantity measurement?
   - **a.** a thermistor
   - **b.** a strain gauge
   - **c.** a potentiometer whose movable arm is connected to a float
   - **d.** a piezoelectric sensor
7. How is coolant temperature measured?
   - **a.** with a mercury bulb thermometer
   - **b.** with a strain gauge
   - **c.** with a thermistor as a sensor
   - **d.** none of the above
8. A digital vehicle speed sensor incorporates
   - **a.** a variable-frequency pulse generator and digital counter
   - **b.** a variable resistor
   - **c.** a variable capacitance
   - **d.** none of the above
9. What is the predominant type of automotive digital display?
   - **a.** light-emitting diode
   - **b.** galvanometer
   - **c.** vacuum-fluorescent
   - **d.** liquid crystal

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

10. What sensor input variables are used in a typical trip computer system?
- **a.** manifold pressure and engine speed
- **b.** RPM, barometric pressure, and fuel quantity remaining
- **c.** MPG and fuel consumption
- **d.** car speed, fuel flow rate, fuel quantity remaining in tank

11. A CRT display device uses
- **a.** a cathode ray tube scanned in a raster pattern
- **b.** a vacuum-fluorescent tube
- **c.** an incandescent light source
- **d.** none of the above

12. In the digital video signal generator used with a CRT display
- **a.** each bit in the shift register corresponds to a pixel location
- **b.** each pixel on the screen corresponds to a specific video voltage level
- **c.** scanning of the CRT by the electron beam is from right to left and from bottom to top
- **d.** all of the above are true

13. The term MUX refers to
- **a.** an electronic switch that selects one of a set of inputs per an input code
- **b.** a digital output device
- **c.** a time slot
- **d.** none of the above

14. A D/A converter
- **a.** is a disk access device
- **b.** converts the digital output of an instrumentation computer to analog form
- **c.** stores analog data
- **d.** enters digital data in a computer

15. In electronic instrumentation, fuel quantity is displayed by
- **a.** an ammeter
- **b.** a potentiometer
- **c.** a digital display
- **d.** none of the above

16. LED refers to
- **a.** level-equalizing detector
- **b.** light-emitting diode
- **c.** liquid crystal display
- **d.** none of the above

17. An LCD display uses
- **a.** a nematic liquid
- **b.** an incandescent lamp
- **c.** large electrical power
- **d.** a picket fence

18. Light is produced in a VFD by
- **a.** ionic bombardment of a filament
- **b.** ambient temperature
- **c.** bombardment of a phosphor by energetic electrons
- **d.** chemical action

19. Fuel economy is calculated in a trip computer by:
- **a.** $S \times F$
- **b.** F/S
- **c.** S/F
- **d.** none of the above

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565



Diagnostics

From the earliest days of the commercial sale of the automobile, it has been obvious that maintenance is required to keep automobiles operating properly. Of course, automobile dealerships have provided this service for years, as have independent repair shops and service stations. But until the early 1970s, a great deal of the routine maintenance and repair was done by car owners themselves, using inexpensive tools and equipment. However, the Clean Air Act affected not only the emissions produced by automobiles but also the complexity of the engine control systems and, as a result, the complexity of automobile maintenance and repair. Car owners can no longer, as a matter of course, do their own maintenance and repairs on certain automotive subsystems (particularly the engine).

The development of electronic engine control has increased the complexity of diagnosis and maintenance.

The change from traditional fluidic/pneumatic engine controls to microprocessor-based electronic engine controls was a direct result of the need to control automobile emissions, and has been chronicled throughout this book. However, little has been said thus far about the diagnostic problems involved in electronically controlled engines. This type of diagnostics requires a fundamentally different approach than that for traditionally controlled engines because it requires more sophisticated equipment than was required for diagnostics in pre-emission-control automobiles. In fact, the best diagnostic methods use special-purpose computers that are themselves microprocessor based. However, before launching into a discussion of electronic control system diagnostics, there are two nonmicroprocessor diagnostic instruments that are still used in garages and repair shops (particularly for older-model cars) that should be discussed: the timing light and the engine analyzer.

TIMING LIGHT

The timing light (Figure 10.1) is used to measure and set ignition timing. It is a special stroboscopic light source that generates very short duration light pulses, the timing of which coincides with ignition pulses. The timing of these pulses is obtained from a special probe connected to a spark-plug wire. Figure 10.2 is a block diagram of a typical timing light.

The probe generates a very short duration voltage pulse each time the spark plug fires. The pulse is amplified and then operates a trigger electrode on a flash lamp that is a gas discharge tube. When triggered, a current pulse flows through the flash lamp, generating a short burst of light.

In timing the ignition, the light from the flash lamp is directed at the pulley on the front end of the crankshaft. Adjacent to the pulley is a pointer, such as seen in Figure 10.3. On the pulley are several marks. The relationship

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Figure 10.1
Typical Engine
Timing Light

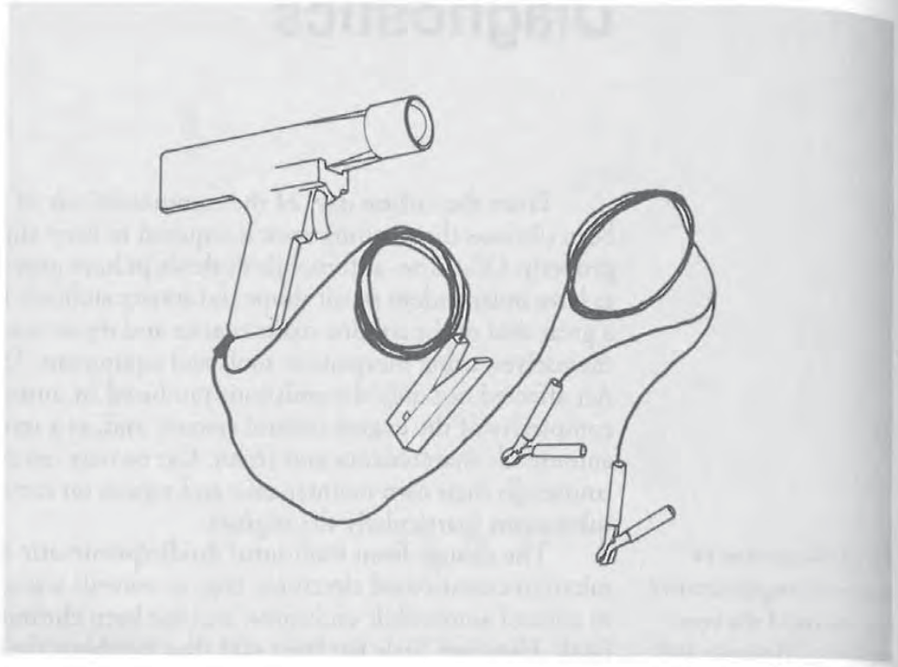
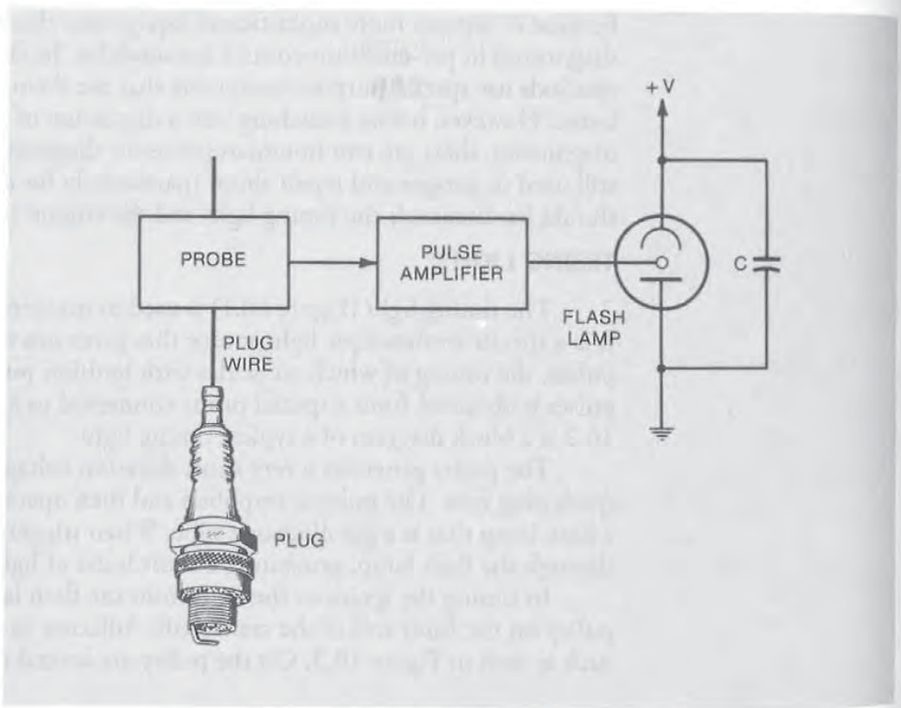
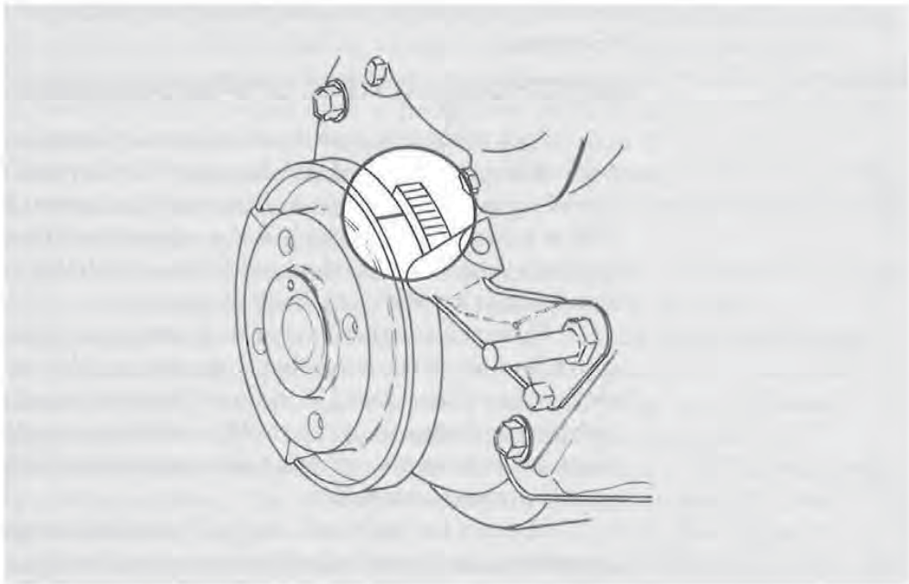


Figure 10.2
Timing Light Block
Diagram



PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Figure 10.3
Timing Marks



between the pointer and these marks corresponds to specific crankshaft angular positions relative to top dead center (TDC). The relationship of the pointer and crankshaft pulley marks at the time of ignition can be seen by viewing the pulley using the light from the flash lamp. When the ignition timing is correct, the pointer will align with the correct pulley mark.

ENGINE ANALYZER

The timing light and traditional engine analyzer are not enough for diagnosis of engine problems.

The engine analyzer is an instrument that has existed for many years and continues to be used in garages for several tuneup tasks. It provides, for example, a means for optimally setting the gap for ignition points (in cars that still have them, of course) by measuring the so-called dwell. *Dwell* is essentially the fractional duration that the ignition points are closed. However, an engine analyzer's role in diagnosing cars that have digital engine control systems is markedly different than its role in the diagnosis of cars that have analog or mechanical control systems. For example, ignition points have virtually been eliminated in digitally controlled cars. Nevertheless, the concept of dwell is still applicable, only today it represents the amount of time current flows through the coil primary circuit before this circuit is interrupted (see Chapter 7). In addition, in certain cases ignition timing can be measured by measuring the relative strength (peak voltage) of ignition pulses. Although the engine analyzer continues to be a useful instrument, it is not adequate for diagnosing problems in electronically controlled systems.

While it is true that both the timing light and the engine analyzer will continue to be used because there are many cars still on the roads whose engines are controlled either by analog or mechanical systems, it is probable

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

that the use of these two diagnostic instruments will be phased out within a few years.

ELECTRONIC CONTROL SYSTEM DIAGNOSTICS

Each microprocessor-based electronic subsystem has the capability of performing some limited self-diagnosis. A subsystem can, for example, detect a loss of signal from a sensor or detect an open circuit in an actuator circuit as well as other failures. As long as the subsystem computer is still functioning it can store fault codes for detected failures. Such diagnosis within a given subsystem is known as *on-board diagnosis.*

However, a higher level of diagnosis than the on-board diagnosis is typically done with an external computer-based system that is available in a service shop. Data stored in memory in an on-board subsystem is useful for completing diagnosis of any problem with the associated subsystem. Such diagnosis is known as *off-board diagnosis* and is usually conducted with a special-purpose computer.

In order for fault code data to be available to the off-board diagnosis computer, a communication link is required between the off-board equipment and the particular subsystem on board the vehicle. Such a communication system is typically in the form of a serial digital data link. A serial data link transmits digital data in a binary time sequence along a pair of wires (one of which is normally ground). Before discussing the details of on-board and off-board diagnosis, it is perhaps worthwhile to briefly discuss automotive digital communications.

Intermodule communications within an automobile itself and between each on-board subsystem and an off-board system are analogous to communications between computers. That is, they take the form of a local area network (LAN).

There are several important issues involved in any LAN, including the communication protocol, the bit rate, access to the network, and synchronization between the various subsystems. In a LAN, each subsystem connected to the serial data link is called a *node.* Normally one of the nodes serves as a *master* that has the capability of controlling access to the network. The other nodes are called *slaves* and respond to software-controlled commands issued by the master.

One of the possible problems that can occur in a LAN is the simultaneous transmission of messages by two separate nodes (called *collision*). Resolution of potential collisions is controlled by the master using a software capability known as *arbitration.*

An example of an automotive digital data system is the Controller Area Network (CAN) that was developed by the Robert Bosch Company in Germany. CAN is a serial asynchronous communication protocol that connects electronic control modules' sensors and actuators in automobiles. Among its many functions and services is a digital data link.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

CAN is an asynchronous system in that each node synchronizes to others' messages on the first bit leading edge of a message and on subsequent bit leading edges throughout the remainder of the message. The ability of any node to synchronize to another node is determined by the maximum differences in oscillator frequencies (see Chapter 4 for an explanation of microprocessor clocks). Other issues and critical periods include the duration of a bit, message duration and composition, and cooperative use of the network between master and slave, known as *handshaking*.

It is beyond the scope of this book to give a detailed account of CAN-type data communication. Rather, we wish to identify the use of data communication in automotive electronics and point out some critical issues.

One important application for digital communication in automobiles is the serial digital data link from the power train controller to an off-board diagnostic system. This data communications link has the capability of transmitting fault codes that have been stored in memory to the external device (among other uses). This off-board system can range in complexity from a computer-based diagnostic workstation (explained later in this chapter) to a simple portable scanner used to simply read and display fault codes in sequence as they are retrieved over the data link from the power train controller. Using these fault codes and following a fault tree diagnosis procedure, the service technician can normally diagnose power train control system problems. We consider next on-board and off-board diagnosis in detail, using specific examples.

On-board Diagnostics

Existing microprocessor-based engine control systems incorporate some self-diagnosis.

Limited diagnostic capability is provided in any modern microprocessor-based electronic control system. These diagnostic functions are performed by the microprocessor under the control of stored programs, and are performed only when the microprocessor is not fully committed to performing normal control calculations. While it is beyond the scope of this book to review the actual software involved in such diagnostic operations, the diagnostic procedures that are followed and explanations of on-board diagnostic functions can be reviewed.

During the normal operation of the car, there are intermittent periods during which various electrical and electronic components are tested. Whenever a fault is detected, the data is stored in memory using a specific fault code. At the same time, the controller generates or activates a warning lamp (or similar display) on the instrument panel, indicating that service is required.

The on-board diagnostic functions have one major limitation—they cannot detect intermittent failures reliably. For the system to detect and isolate a failure, the failure must be nonreversible. In most on-board diagnostics, the electronic control module stores trouble codes that are automatically cleared by the microprocessor after a set number of engine cycles have occurred without a fault reappearing.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

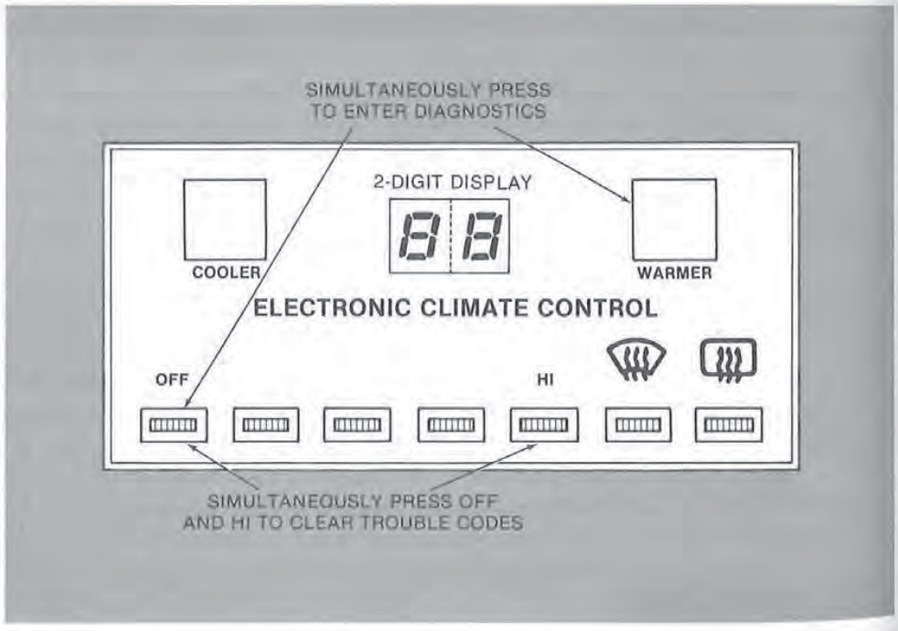
The on-board diagnostic capabilities can be manually activated by causing the engine controller to enter a diagnostic mode. The method for accomplishing this task varies from car to car. For example, in certain older-model fuel-injected Cadillac cars, the diagnostic mode is entered by first switching on the ignition, then simultaneously depressing the Off and Warmer buttons on the climate control system.

A two-digit fault code is assigned to each failure.

The use of on-board diagnostics can easily be illustrated by outlining typical procedures and using the Cadillac system as an example system. Although display of the fault codes varies from car to car, in each case the codes must be readable as a numeric code. A typical method involves flashing the "Check Engine" light. The mechanic enters the display mode and then counts the number of times that this light is flashed, in two-digit groups. For example, a fault code 24 would be given by 2 flashes then 4 flashes. After a short time interval the next code would similarly be flashed in two-digit sequence. At one time Cadillac used the environment controller to display a two-digit code. Figure 10.4 is a drawing of a Cadillac environmental system displaying code 88. This particular code is used to check that all display segments are working correctly and is the first display shown when the diagnostic mode is entered.

After verifying that all display segments are working, the fault codes for all component failures are displayed in sequence, beginning with the lowest and proceeding to the highest. The mechanic notes the fault codes that are displayed and, using a reference manual, identifies the failed components. Table 10.1 is a summary of the Cadillac fault codes, which we present here simply as

Figure 10.4
Fault Code Display



PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Table 10.1
Summary of Fault Codes

Circuit Affected	Two-Digit Fault Code
No distributor signal	12
EGO sensor not ready	13
Coolant sensor circuit (short)	14
Coolant sensor (open)	15
Generator voltage out of range	16
Crank signal (short)	17
Crank signal (open)	18
Fuel pump circuit (short)	19
Fuel pump circuit (open)	20
Throttle position sensor circuit (short)	21
Throttle position sensor (open)	22
Ignition/Bypass	23
Engine speed sensor	24
Throttle switch (short)	26
Throttle switch (open)	27
Idle speed control	30
MAP sensor circuit (short)	31
MAP sensor circuit (open)	32
MAP/Baro sensor correlation	33
MAP signal too high	34
Baro sensor circuit (short)	35
Baro sensor circuit (open)	36
Manifold air temp (short)	37
Manifold air temp (open)	38
Lean exhaust signal	44
Rich exhaust signal	45
PROM error indicator	51
Transmission not in drive	60
"Set" and "resume" circuits engaged simultaneously	61
Car speed exceeds maximum limit	62
Car and set speed tolerance exceeded	63
Car acceleration exceeds maximum limit	64
System ready for further tests	70
Cruise control brake circuit test	71

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Table 10.1 (cont.)

Circuit Affected	Two-Digit Fault Code
Throttle switch circuit test	72
Drive (ADL) circuit test	73
Reverse circuit test	74
Cruise on/off circuit test	75
"Set/Coast" circuit test	76
"Resume/Acceleration" circuit test	77
"Instant/Average" circuit test	78
"Reset" circuit test	79
Air conditioner clutch circuit test	80
Display check	88
System ready to display engine data	90
All diagnostics complete	00

an example of two-digit fault code assignment. After all fault codes have been displayed, the number 70 appears on the climate control head, and the engine control system awaits further action by the mechanic.

Typically, the "Check Engine" light on the instrument panel is illuminated whenever any fault occurs. For codes 12 through 38 and 51 in Table 10.1, this warning light goes out automatically if the malfunction clears. However, the control module stores the code associated with the detected failure until the diagnostic system is manually cleared, or until 20 engine cycles occur with no malfunction. For codes 44 and 45, the "Check Engine" light will not go out until cleared from memory by the mechanic. For codes 60 through 68, there is no activation of the "Check Engine" light.

Whenever a defect occurs (as indicated by a fault code), the mechanic must follow a specific procedure to isolate the particular problem. These procedures are outlined for the mechanic in charts in the shop manuals. An example procedure will be illustrated here by following the steps necessary to respond to the specific fault code 13, which indicates that the oxygen (O_2 or EGO) sensor is not ready. Recall from the discussion in Chapter 6 that the O_2 sensor switches between approximately 0 and 1 volt as the mixture switches between the extreme conditions of lean and rich. Recall also that this voltage swing requires that the O_2 sensor must be at a temperature above 200°C. Fault code 13 means that the O_2 sensor will not swing above or below its cold voltage of approximately 0.5 volt, and that the electronic control system will not go into closed-loop operation (see Chapters 5 and 7).

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Possible causes for fault code 13 include the following:

- O_2 sensor is not functioning correctly.
- Defective connections or leads.
- The control unit is not processing the O_2 sensor signal.

Further investigation is required to attempt to isolate the specific problem.

To check the operation of the O_2 sensor, the average value of its output voltage is measured using the electronic engine control system (the procedure for which is explained later in this chapter). The desired voltage is displayed on the climate control head in multiples of .01 volt. That is to say, "00" corresponds to 0 volts and "99" corresponds to 0.99 volts, and so forth.

Using this voltage, the mechanic follows a procedure outlined in Figures 10.5, 10.6, and 10.7. If the voltage is less than 0.37 volt or greater than 0.57 volt, the mechanic is asked to investigate the wiring harness for defects.

If the O_2 sensor voltage is between 0.37 volt and 0.57 volt, tests are performed to determine whether the O_2 sensor or the control unit is faulty. The mechanic must jumper the O_2 sensor leads together at the input to the control unit, simulating a sensor short circuit, and must read the sensor voltage value using the climate control display. If this voltage is less than 0.05 volt, the control unit is functioning correctly and the O_2 sensor must be investigated for defects. If the indicated sensor voltage is greater than 0.05 volt, the control unit is faulty and should be replaced.

When diagnosing a problem, the mechanic might wish to clear a fault code from the electronic control memory. A good reason to do this, for example, would be to test whether a failure is "hard" or intermittent. To clear trouble codes (with the system in diagnostic mode), the mechanic simultaneously pushes the Off and Hi buttons on the climate control head until "00" is displayed. After all fault codes are cleared, code 70 will appear.

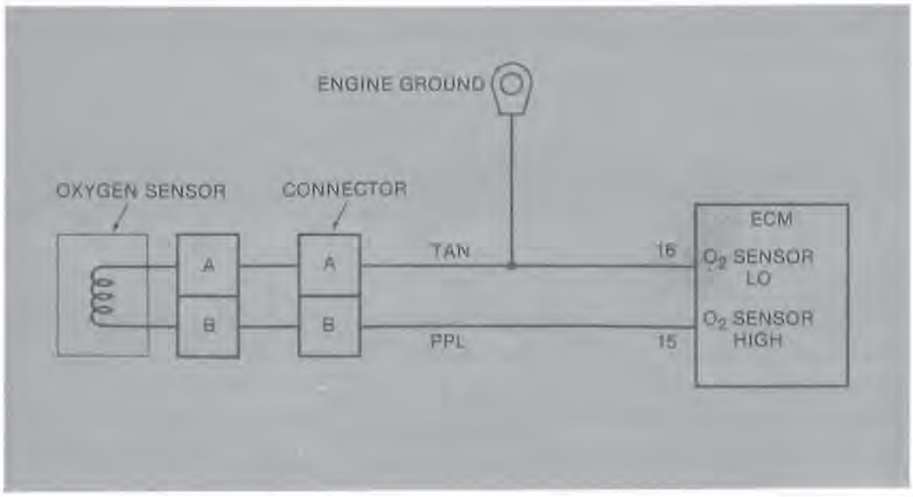


Figure 10.5
DFI Oxygen Sensor Circuit

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

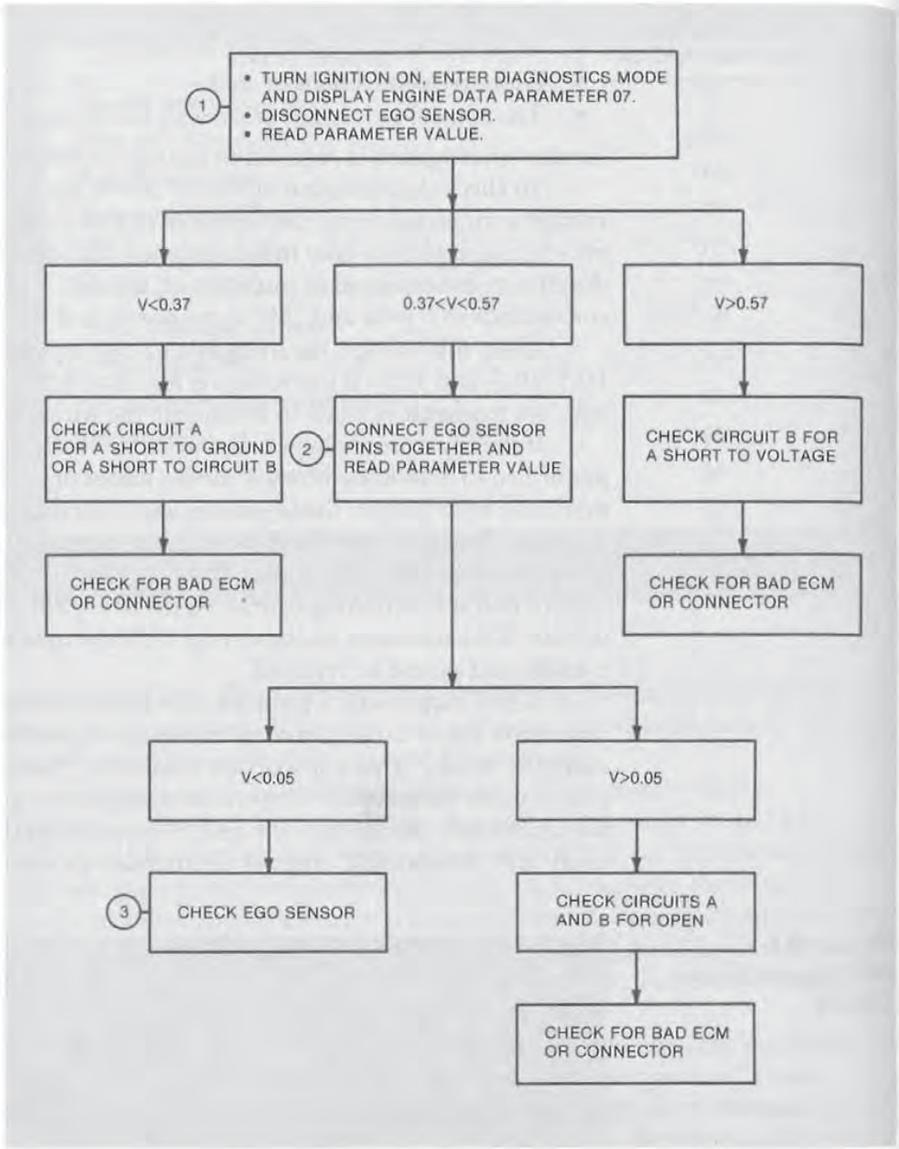


Figure 10.6
DFI Code 13: Oxygen Sensor Not Ready

On-board diagnosis also examines the status of several switches.

Code 70 represents a decision point in the diagnostic procedure. At this point, the mechanic has several choices, including:

Perform switch tests.
Display engine data.
Perform output cycling tests.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

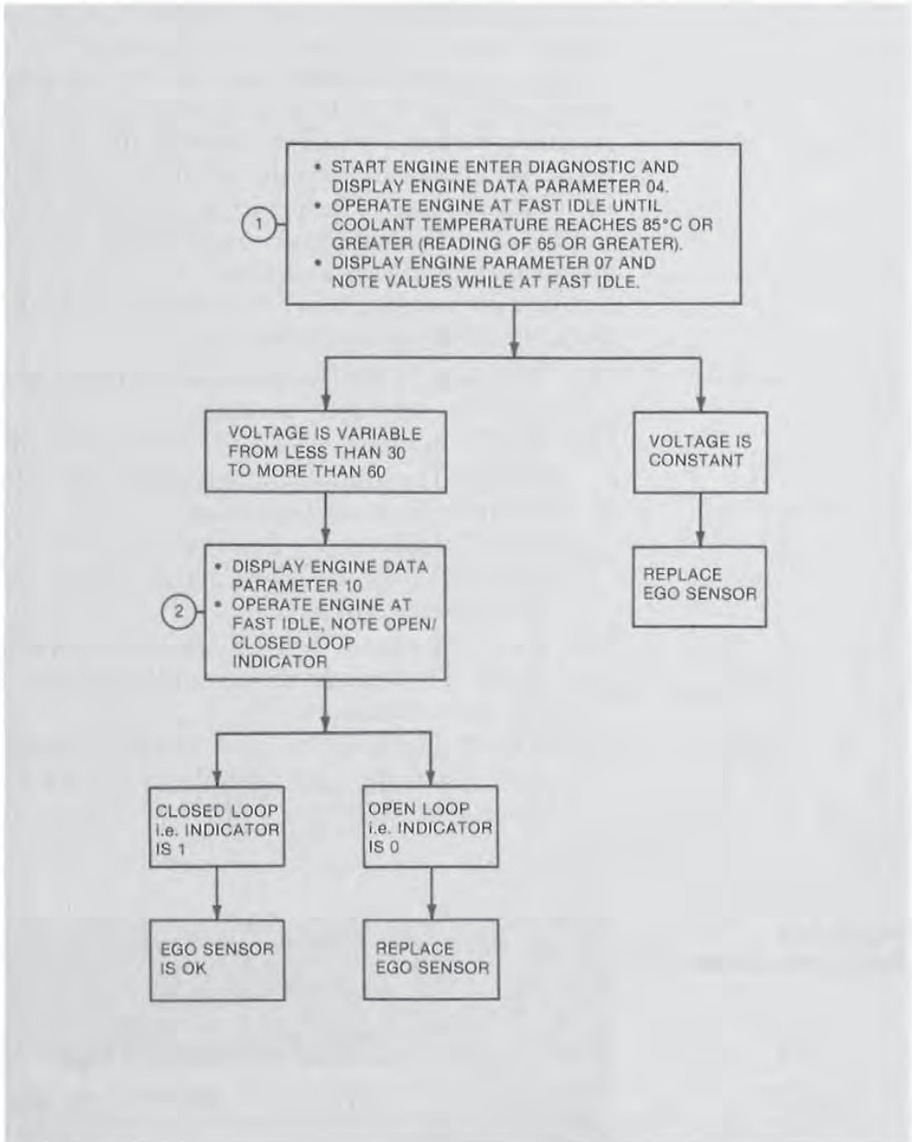


Figure 10.7
DFI Chart No. 14: Oxygen Sensor Test

Perform cylinder select tests.
Exit from diagnostic mode.

Each of the above procedures provides an important diagnostic capability to the mechanic.

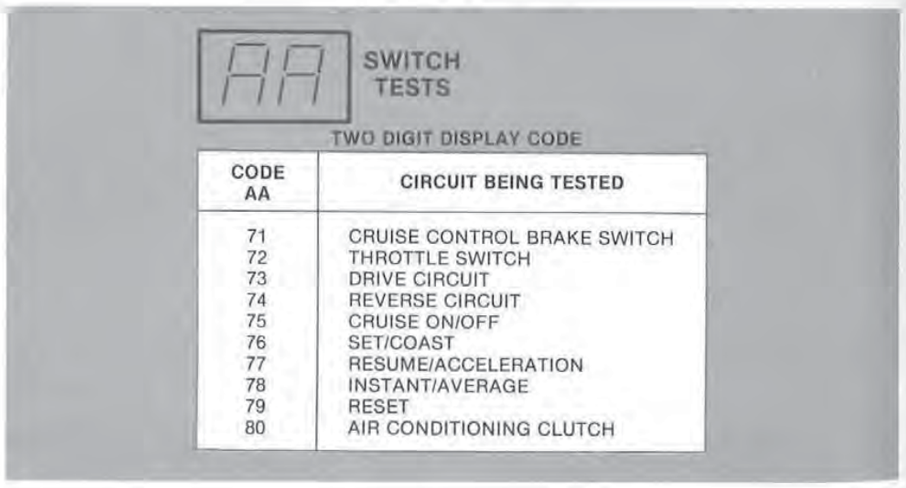
PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

The switch tests involve fault codes 71 to 80 and provide checks on the switches indicated in Figure 10.8. To begin the switch tests, the mechanic must depress and release the brake pedal. If there is no brake switch failure, then the code advances to 71. If the display doesn't advance, then the control unit is not processing the brake switch signal and further diagnosis is required. For such a failure, the mechanic locates the specific chart (such as seen in Figures 10.9 and 10.10) for diagnosis of the particular switch failure and follows the procedure outlined. The detailed tests performed by the mechanic are continuity checks that are performed with a test light.

Similar procedures are followed for each switch test in the sequence. This procedure sequence is as follows:

1. With code 71 displayed, depress and release brake pedal. For normal operation, the display advances.
2. With 72 displayed, depress the throttle from idle position to wide open position. The control unit tests the throttle switch, and advances the display to 73 for normal operation.
3. With 73 displayed, the transmission selector is moved to drive and then neutral. This operation tests the drive switch, and the display advances to 74 for normal operation.
4. With 74 displayed, the transmission selector is moved to reverse and then to park. This tests the reverse switch operation, and the display advances to 75 for normal operation.
5. With 75 displayed, the cruise control is switched from off to on and back to off, testing the cruise control switch. For normal operation, the display advances to 76.

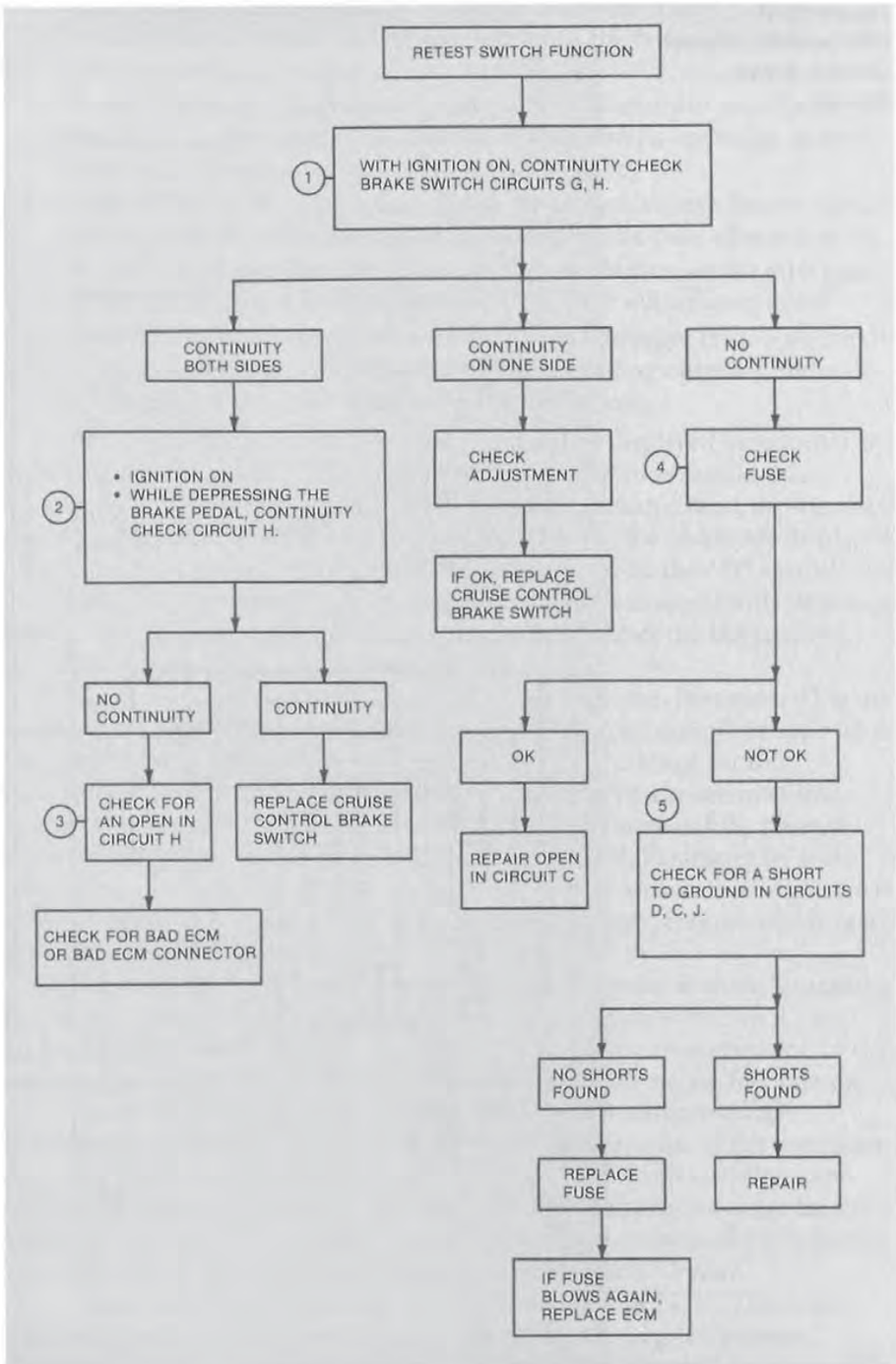
Figure 10.8
Switch Test Series



CODE AA	CIRCUIT BEING TESTED
71	CRUISE CONTROL BRAKE SWITCH
72	THROTTLE SWITCH
73	DRIVE CIRCUIT
74	REVERSE CIRCUIT
75	CRUISE ON/OFF
76	SET/COAST
77	RESUME/ACCELERATION
78	INSTANT/AVERAGE
79	RESET
80	AIR CONDITIONING CLUTCH

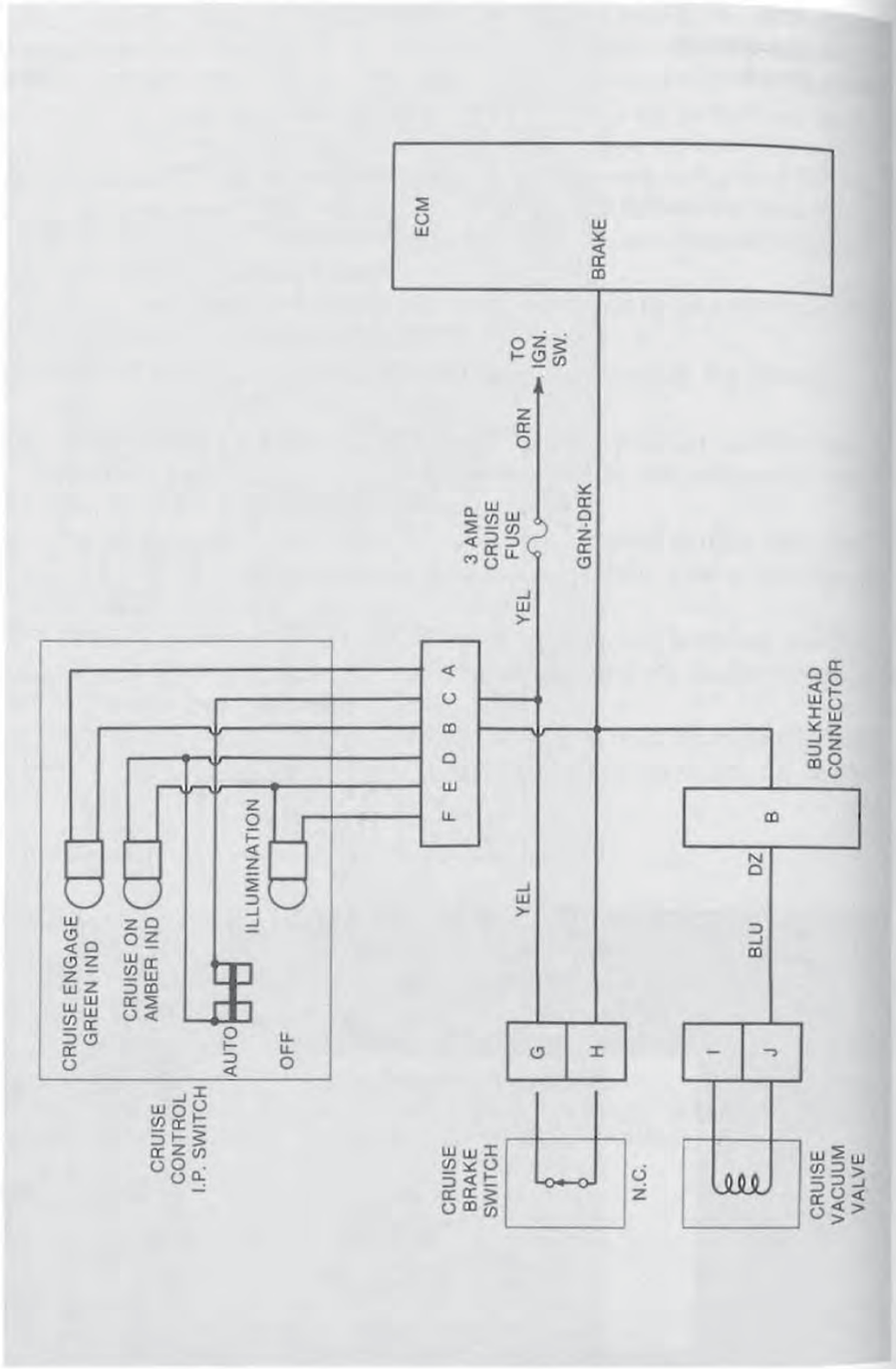
PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Figure 10.9
DFI Cruise Control Brake Circuit



PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Figure 10.10
DFI Code 71: Cruise Control Brake Circuit



PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

6. With code 76 displayed and the cruise control instrument panel switch on, depress and release the set/coast button. If the button (switch) is operating normally, the display advances to 77.
7. With 77 displayed and with the cruise control instrument on, depress and release the resume/acceleration switch. If the switch is operating normally, the display advances to 78.
8. With 78 displayed, depress and release the instant/average button on the MPG panel. If the button is working normally, the code advances to 79.
9. With 79 displayed, depress and release the reset button on the mph panel. If the reset button is working normally, the code will advance to 80.
10. With 80 displayed, depress and release the rear defogger button on the climate control head. If the defogger switch is working normally, the code advances to 70, thereby completing the switch tests.

With code 70 displayed, the engine data can be displayed in sequence by switching the cruise control instrument panel off. The code should then advance to 90. To further advance the display, the mechanic must depress the instant/average button on the MPG panel (to return to the previously displayed parameter, the mechanic must depress the reset button on the MPG panel). To exit the engine parameter display mode, the mechanic simultaneously depresses the Off and Hi buttons on the climate control head. After the last parameter has been displayed, the code advances to 95.

Figure 10.11 shows the parameter values in sequence. Parameter 01 is the angular deflection of the throttle in degrees from idle position. Parameter 02 is the manifold absolute pressure in kilopascals (kPa). The range for this parameter is 14 to 99, with 14 representing about the maximum manifold vacuum. Parameter 03 is the absolute atmospheric pressure in kPa. Normal atmospheric pressure is roughly 90–100 kPa at sea level. Parameter 04 is the coolant temperature. The conversion from this code to an actual temperature is given in Table 10.2. Parameter 05 is the manifold air temperature, which uses the same conversion as parameter 04.

Parameter 06 is the duration of the fuel injector pulse in msec. In reading this number, the mechanic assumes a decimal point between the two digits (i.e., 16 is read as 1.6 msec). Refer to Chapters 5, 6, and 7 for an explanation of the injector pulse widths and the influence of these pulse widths on fuel mixture.

Measurements of average O_2 sensor voltage are useful for diagnosis of this sensor.

Parameter 07 is the average value for the O_2 sensor output voltage. Reference was made earlier in this chapter to the diagnostic use of this parameter. Recall that the O_2 sensor switches between about 0 and 1 volt as the mixture oscillates between lean and rich. The displayed value is the time average for this voltage, which varies with the duty cycle of the mixture. A decimal point should be assumed at the left of the two digits (i.e., 52 is read as 0.52 volt).

Parameter 08 is the spark advance in degrees before TDC. This value should agree with that obtained using a timing light or engine analyzer. Parameter 09 is the number of ignition cycles that have occurred since a trouble

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

code was set in memory. If 20 such cycles have occurred without a fault, this counter is set to zero and all trouble codes are cleared.

Parameter 10 is a logical (binary) variable that indicates whether the engine control system is operating in open or closed loop. A value of 1 corresponds to closed loop, which means that data from the O_2 sensor is fed back to the controller to be used in setting injector pulse duration. Zero for this variable indicates open-loop operation, as explained in Chapters 6 and 7 Parameter 11 is the battery voltage minus 10. A decimal point is assumed between the digits. Thus, 2.3 is read as 12.3 volts.

After completion of parameter data values, the climate control display will advance to 95. The remaining codes are specific to certain Cadillac models and are not germane to the present discussion.

Once the mechanic has read all of the fault codes, he or she proceeds with the diagnosis using the shop manual in the same manner as explained for the Cadillac example. For each fault code there is a procedure to be followed that attempts to isolate the specific components that have failed. Obviously, the

Figure 10.11 Engine Data Display

ENGINE DATA

PARAMETER NUMBER	PARAMETER	NORMAL RANGE
01	THROTTLE POSITION	0-31
02	MANIFOLD PRESSURE	14-99
03	BAROMETRIC PRESSURE	14-99
04	COOLANT TEMPREATURE	0-99
05	MANIFOLD AIR TEMPERATURE	9-99
06	INJECTOR PULSE DURATION	0-9.9
07	EGO SENSOR VOLTAGE	0-0.99
08	SPARK ADVANCE (DEGREES)	0-52

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Table 10.2 Temperature Conversion Table

CODE	°F
0	–40
8	–12
12	1
16	15
21	32
25	46
30	64
35	81
40	98
45	115
50	133
52	140
54	147
56	153
58	160
60	167
62	174
64	181
66	188
68	195
70	202
72	209
73	212
75	219

process of diagnosing a problem can be lengthy and can involve many steps. However, without the aid of the on-board diagnostic capability of the electronic control system, such diagnosis would take much more time and might, in certain cases, be impossible.

On-board diagnosis has also been mandated by government regulation, particularly if a vehicle failure could damage emission control systems. The California Air Resources Board (CARB), which has been at the forefront of

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

automotive emission control regulations, has proposed a new, relatively severe requirement for on-board diagnosis that is known as OBDII (on-board diagnosis II). This requirement is intended to ensure that the emission control system is functioning as intended.

Automotive emission control systems, which have been discussed in Chapters 5 and 7, consist of fuel and ignition control, the three-way catalytic converter, EGR, secondary air injection, and evaporative emission. The OBDII regulations require real-time monitoring of the health of the emission control system components. For example, the performance of the catalytic converter must be monitored using a temperature sensor for measuring converter temperature and a pair of EGO sensors (one before and one after the converter).

Another requirement for OBDII is a misfire detection system. It is known that under misfiring conditions (failure of the mixture to ignite), exhaust emissions increase. In severe cases, the catalytic converter itself can be irreversibly damaged.

The only cost-effective means of meeting OBDII requirements involves electronic instrumentation. For example, one possible means of detecting misfire is based on measurements of the crankshaft instantaneous speed. That speed fluctuates about the average RPM in response to each cylinder firing event. Misfire can be detected in most cases by monitoring the crankshaft speed fluctuations using some relatively sophisticated electronic signal processing.

Off-board Diagnosis

An alternative to the on-board diagnostics is available in the form of a service bay diagnostic system. This system uses a computer that has a greater diagnostic capability than the vehicle-based system because its computer is typically much larger and has only a single task to perform—that of diagnosing problems in engine control systems.

Special-purpose digital computers are coming into use in service bay diagnosis systems.

An example of a service bay diagnostic system is General Motors' CAMS (Computerized Automotive Maintenance System). Although the system discussed here is essentially obsolete, it is at leats representative of this level of diagnosis. The GM-CAMS used an IBM PC/AT computer that had considerable computational capability for its time. Its memory included 640K of RAM, 1.2 million bytes on a 5.75 inch diskette drive and 20 million bytes on a fixed disk drive. This system was capable of detecting, analyzing, and isolating faults in late-model GM vehicles that are equipped with a digital engine control system. This system, commonly called the *technicians' terminal,* has a modem equivalent that operates in essentially the same way as the CAMS.

The technicians' terminal is mounted on a rugged portable cart (Figure 10.12) suitable for use in the garage. It connects to the vehicle through the assembly line data link (ALDL). The data required to perform diagnostics are obtained by the terminal through this link. The terminal has a color CRT monitor (similar to that of a typical home computer) that displays the data and procedures. It has a touch-sensitive screen for technician input to the system. The terminal features a keyboard for data entry, printer for hard copy output,

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

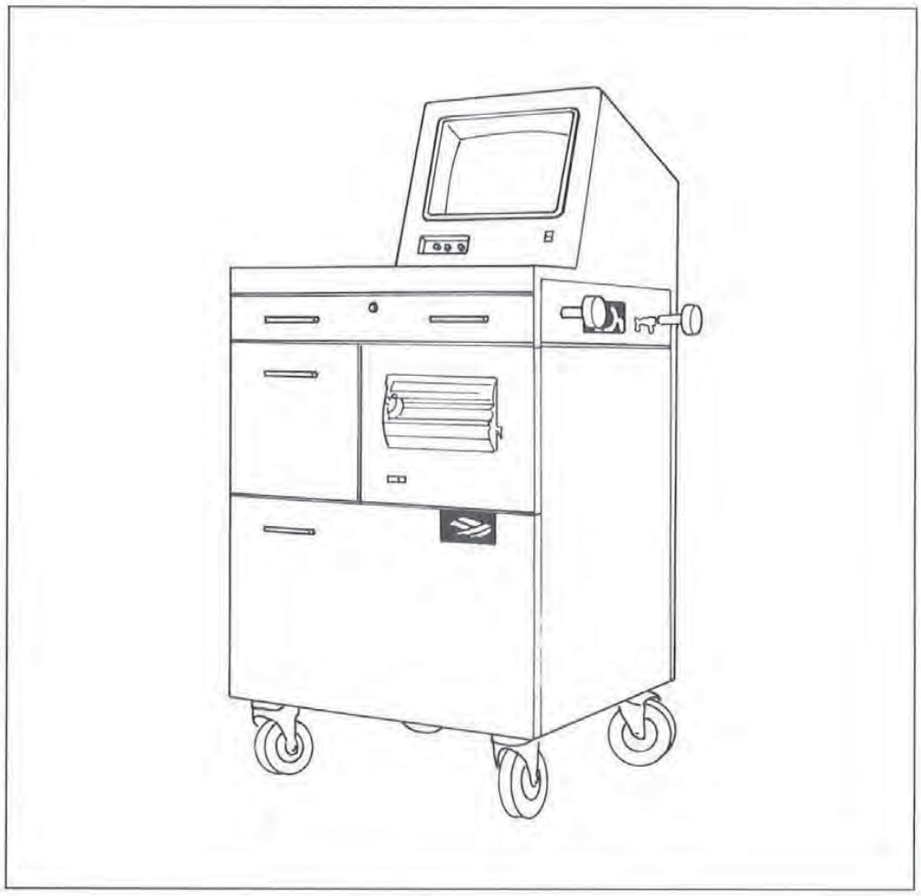


Figure 10.12
Engine Data
Display

and modem for a telephone link to a network that collects and routes GM-CAMS information.

The GM system also features a mainframe computer system at the General Motors Information Center (GMIC) that contains a master database that includes the most recent information relating to repair of applicable GM cars. This information, as well as computer software updates, is relayed throughout the network. Mechanics can also obtain diagnostic assistance by calling the GM-CAMS Customer Support Center.

When using the GM-CAMS, the mechanic enters the vehicle identification number (VIN) via the terminal. The computer responds by displaying a menu in which several choices are presented. To select a particular choice the technician touches the portion of the display associated with that choice. Next, the computer displays an additional menu of further choices; this continues until the mechanic has located the desired choice.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

The service bay diagnostic system can be readily updated with new service bulletins.

Among the many capabilities of the technicians' terminal is its ability to store and display the diagnostic charts that appear in the shop manual. Whenever a fault is located, the appropriate chart(s) are automatically displayed for the mechanic. This capability greatly increases the efficiency of the diagnostic process. In addition, the GM-CAMS computer can store all of the data that is associated with the diagnostic procedures for several vehicles and then locate and display, virtually instantaneously, each specific procedure as required. Furthermore, updates and the most recent service bulletins are brought into the mechanics' terminal over the phone network so that mechanics lose no time trying to find the most recent data and procedures for diagnosing vehicular electronic systems.

In addition to storing and displaying shop manual data and procedures, a computer-based garage diagnostic system can automate the diagnostic process itself. In achieving this objective, the technicians' terminal has the capability to incorporate what is commonly called an *expert system.*

EXPERT SYSTEMS

An *expert system* is a form of artificial intelligence that has great potential for automotive diagnosis.

Although it is beyond the scope of the present book to explain expert systems, it is perhaps worthwhile to introduce some of the major concepts involved in this rapidly developing technology. An expert system is a computer program that employs human knowledge to solve problems normally requiring human expertise. The theory of expert systems is part of the general area of computer science known as artificial intelligence (AI). The major benefit of expert system technology is the consistent, uniform, and efficient application of the decision criteria or problem-solving strategies.

The diagnosis of electronic engine control systems by an expert system proceeds by following a set of rules that embody steps similar to the diagnostic charts in the shop manual. The diagnostic system receives data from the electronic control system (e.g., via the ALDL connector in the GM-CAMS) or through keyboard entry by the mechanic. The system processes this data logically under program control in accordance with the set of internally stored rules. The end result of the computer-aided diagnosis is an assessment of the problem and recommended repair procedures. The use of an expert system for diagnosis can significantly improve the efficiency of the diagnostic process and can thereby reduce maintenance time and costs.

An expert system takes information from experts and converts this to a set of logical rules.

The development of an expert system requires a computer specialist who is known in AI parlance as a *knowledge engineer.* The knowledge engineer must acquire the requisite knowledge and expertise for the expert system by interviewing the recognized experts in the field. In the case of automotive electronic engine control systems the experts include the design engineers as well as the test engineers, mechanics, and technicians involved in the development of the control system. In addition, expertise is developed by the mechanics who routinely repair the system in the field. The expertise of this latter group can be incorporated as evolutionary improvements in the expert

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

system. The various stages of knowledge acquisition (obtained from the experts) are outlined in Figure 10.13. It can be seen from this illustration that several iterations are required to complete the knowledge acquisition. Thus, the process of interviewing experts is a continuing process.

Not to be overlooked in the development of an expert system is the personal relationship between the experts and the knowledge engineer. The experts must be fully willing to cooperate and to explain their expertise to the knowledge engineer if a successful expert system is to be developed. The personalities of the knowledge engineer and experts can become a factor in the development of an expert system.

Figure 10.14 represents the environment in which an expert system evolves. Of course, a digital computer of sufficient capacity is required for the

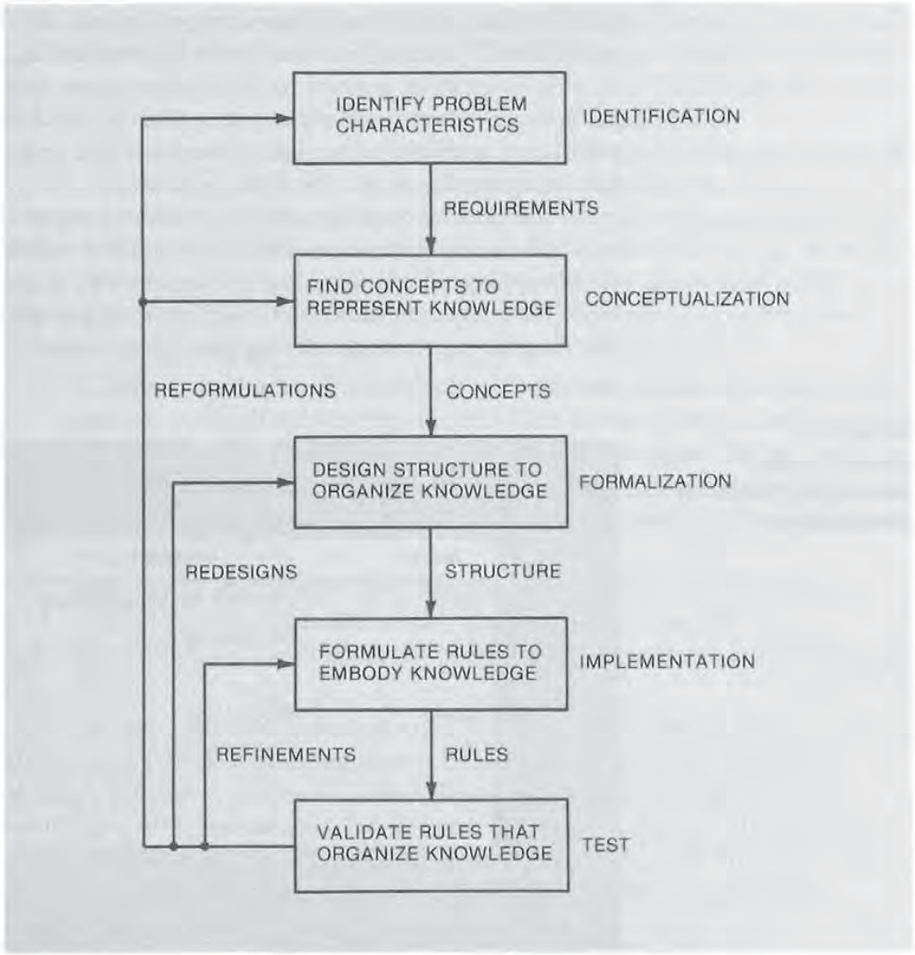
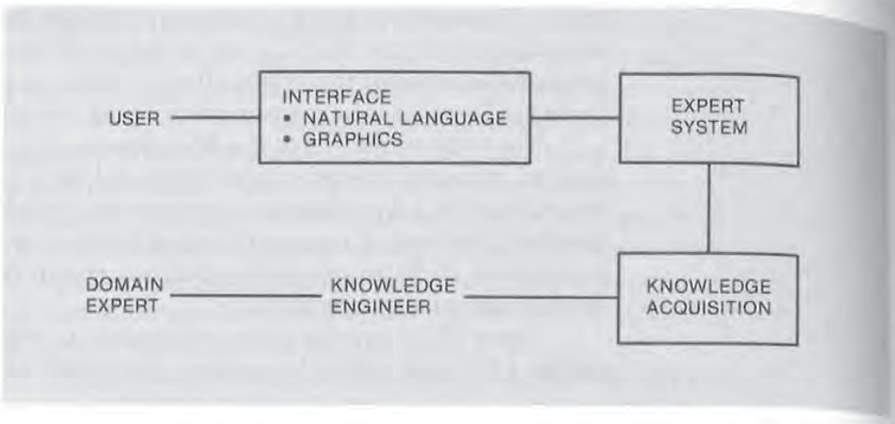


Figure 10.13 Stages of Knowledge Acquisition

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Figure 10.14 Environment of an Expert System



development work. A summary of expert system development tools that are applicable for a mainframe computer is presented in Table 10.3.

It is common practice to think of an expert system as having two major portions. The portion of the expert system in which the logical operations are performed is known as the *inference engine.* The various relationships and basic knowledge are known as the *knowledge base.*

The general diagnostic field to which an expert system is applicable is one in which the procedures used by the recognized experts can be expressed in a set of rules or logical relationships. The automotive diagnosis area is clearly such a field. The diagnostic charts that outline repair procedures (as outlined earlier in this chapter) represent good examples of such rules.

Table 10.3 Expert System Developing Tools for Mainframes

Name	Company	Machine
Ops5	Carnegie Mellon University	VAX
S.1	Teknowledge	VAX
		Xerox 1198
Loops	Xerox 1108	
Kee	Intelligenetics	Xerox 1198
Art	Inference	Symbolics

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

To clarify some of the ideas embodied in an expert system, consider the following example of the diagnosis of an automotive repair problem. This particular problem involves failure of the car engine to start. It is presumed in this example that the range of defects is very limited. Although this example is not very practical, it does illustrate some of the principles involved in an expert system.

A typical expert system formulates expertise in IF-THEN rules.

The fundamental concept underlying this example is the idea of condition-action pairs that are in the form of IF-THEN rules. These rules embody knowledge that is presumed to have come from human experts (e.g., experienced mechanics or automotive engineers).

The expert system of this example consists of three components:

1. A rule base of IF-THEN rules
2. A database of facts
3. A controlling mechanism

Each rule of the rule base is of the form of "if condition A is true, then action B should be taken or performed." The IF portion contains conditions that must be satisfied if the rule is to be applicable. The THEN portion states the action to be performed whenever the rule is activated (fired).

The database contains all of the facts and information that are known to be true about the problem being diagnosed. The rules from the rule base are compared with the knowledge base to ascertain which are the applicable rules. When a rule is fired, its actions normally modify the facts within the database.

The controlling mechanism of this expert system determines which actions are to be taken and when they are to be performed. The operation follows four basic steps:

1. Compare the rules to the database to determine which rules have the IF portion satisfied and can be executed. This group is known as the *conflict set* in AI parlance. A conflict set is a type of set, as in set theory.
2. If the conflict set contains more than one rule, resolve the conflict by selecting the highest priority rule. If there are no rules in the conflict set, stop the procedure.
3. Execute the selected rule by performing the actions specified in the THEN portion, and then modify the database as required.
4. Return to step 1 and repeat the process until there are no rules in the conflict set.

In the present simplified example, it is presumed that the rule base for diagnosing a problem starting a car is as given in Figure 10.15. Rules R2 through R7 draw conclusions about the suspected problem, and rule R1 identifies problem areas that should be investigated. It is implicitly assumed that the actions specified in the THEN portion include "add this fact to the database." In addition, some of the specified actions have an associated

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Figure 10.15
Simple Automobile Diagnostic Rule Base

```
R1: IF starter turns engine but it fails to start
    THEN suspect no fuel reaches engine OR
         suspect there is no spark OR
         suspect too much fuel is reaching engine

R2: IF suspect no fuel reaches engine AND
       gas gauge works AND
       gas gauge is on empty
    THEN gas tank is empty (0.95)

R3: IF suspect no fuel reaches engine AND
       gas gauge is not on empty AND
       temperature is less than 32 degrees Fahrenheit
    THEN fuel line is frozen (0.75)

R4: IF suspect no fuel reaches engine AND
       can smell gas
    THEN break in fuel line (0.65)

R5: IF suspect no fuel reaches engine AND
       gas gauge is not on empty AND
       do not smell gas
    THEN water in gas tank (0.5) OR
       gas gauge broken (0.6)

R6: IF suspect too much fuel is reaching engine AND
       can smell gas
    THEN mixture is too rich (0.7)

R7: IF suspect there is no spark AND
       gas gauge not on empty AND
       (weather is damp OR weather is rainy)
    THEN spark plug wires are wet (0.6)
```

fractional number. These values represent the confidence of the expert who is responsible for the rule that the given action is true for the specified condition.

Further suppose that the facts known to be true are as shown in Figure 10.16. The controlling mechanism follows step 1 and discovers that only R1 is in the conflict set. This rule is executed, deriving these additional facts in performing steps 2 and 3:

Suspect there is no spark.

Suspect too much fuel is reaching the engine.

At step 4, the system returns to step 1 and learns that the conflict set includes R1, R4, and R6. Since R1 has been executed, it is dropped from the conflict set. In this simplified example, assume that the conflict is resolved by selecting the lowest-numbered rule (i.e., R4 in this case). Rule R4 yields the additional facts after completing steps 2 and 3 that there is a break in fuel line (0.65). The value 0.65 refers to the confidence level of this conclusion.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Figure 10.16 Starting Database of Known Facts

```
gas gauge works
starter turns engine but it fails to start
gas gauge is not on empty
can smell gas
```

The procedure is repeated with the resulting conflict set R6. After executing R6, the system returns to step 1, and finding no applicable rules, it stops. The final fact set is shown in Figure 10.17. Note that this diagnostic procedure has found two potential diagnoses: a break in fuel line (confidence level 0.65), and mixture too rich (confidence level 0.70).

The previous example is intended merely to illustrate the application of artificial intelligence to automotive diagnosis and repair.

To perform diagnosis on a specific car using an expert system, the mechanic identifies all of the relevant features to the mechanic's terminal including, of course, the engine type. After connecting the data link from the electronic control system to the terminal, the diagnosis can begin. The terminal can ask the mechanic to perform specific tasks that are required to complete the diagnosis, including, for example, starting or stopping the engine.

The mechanic uses the expert system interactively in diagnosing problems.

The expert system is an interactive program and, as such, has many interesting features. For example, when the expert system requests that the mechanic perform some specific task, the mechanic can ask the expert system why he or she should do this, or why the system asked the question. The expert system then explains the motivation for the task, much the way a human expert would do if he or she were guiding the mechanic. An expert system is frequently formulated on rules of thumb that have been acquired through years of experience by human experts. It often benefits the mechanic in his or her

Figure 10.17 Final Resulting Database of Known Facts

```
gas gauge works
starter turns engine but it fails to start
gas gauge is not on empty
can smell gas
suspect no fuel reaching engine
suspect there is no spark
suspect too much fuel is reaching engine
break in fuel line (0.65)
mixture too rich (0.7)
```


PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

task to have requests for tasks explained in terms of both these rules and the experience base that has led to the development of the expert system.

The general science of expert systems is so broad that it cannot be covered in this book. The interested reader can contact any good engineering library for further material in this exciting area. In addition, the Society of Automotive Engineers has many publications covering the application of expert systems to automotive diagnosis.

From time to time, automotive maintenance problems will occur that are outside the scope of the expertise incorporated in the expert system. In these cases, an automotive diagnostic system needs to be supplemented by direct contact of the mechanic with human experts. The GM-CAMS system, for example, has incorporated this feature into its customer support center.

Vehicle off-board diagnostic systems (whether they are expert systems or not) continue to be developed and refined as experience is gained with the various systems, as the diagnostic database expands, and as additional software is written. The evolution of such diagnostic systems is heading in the direction of fully automated, rapid, and efficient diagnoses of problems in cars equipped with modern digital control systems.

OCCUPANT PROTECTION SYSTEMS

Occupant protection during a crash has evolved dramatically since about the 1970s. Beginning with lap seat belts, and motivated partly by government regulation and partly by market demand, occupant protection has evolved to passive restraints and airbags. We will discuss only the latter since airbag deployment systems can be implemented electronically, whereas other schemes are largely mechanical.

Conceptually, occupant protection by an airbag is quite straightforward. The airbag system has a means of detecting when a crash occurs that is essentially based on deceleration along the longitudinal car axis. A collision that is serious enough to injure car occupants involves deceleration in the range of tens of gs (i.e., multiples of 10 of the acceleration of gravity), whereas normal driving involves acceleration/deceleration on the order of 1 g.

Once a crash has been detected, a flexible bag is rapidly inflated with a gas that is released from a container by electrically igniting a chemical compound. Ideally, the airbag inflates in sufficient time to act as a cushion for the driver (or passenger) as he or she is thrown forward during the crash.

On the other hand, practical implementation of the airbag has proven to be technically challenging. Considering the timing involved in airbag deployment it is somewhat surprising that they work as well as they do. At car speeds that can cause injury to the occupants, the time interval for a crash into a rigid barrier from the moment the front bumper contacts the barrier until the final part of the car ceases forward motion is substantially less than a second. Table 10.4 lists required airbag deployment times for a variety of test crash conditions.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Table 10.4
Airbag Deployment Times

Test Library Event	Required Deployment Time (msec)
9 mph frontal barrier	ND
9 mph frontal barrier	ND
15 mph frontal barrier	50.0
30 mph frontal barrier	24.0
35 mph frontal barrier	18.0
12 mph left angle barrier	ND
30 mph right angle barrier	36.0
30 mph left angle barrier	36.0
10 mph center high pole	ND
14 mph center high pole	ND
18 mph center high pole	ND
30 mph center high pole	43.0
25 mph offset low pole	56.0
25 mph car-to-car	50.0
30 mph car-to-car	50.0
30 mph 550 hop road, panic stop	ND
30 mph 629 hop road, panic stop	ND
30 mph 550 tramp road, panic stop	ND
30 mph 629 tramp road, panic stop	ND
30 mph square block road, panic stop	ND
40 mph washboard road, medium braking	ND
25 mph left-side pothole	ND
25 mph right-side pothole	ND
60 mph chatter bumps, panic stop	ND
45 mph massoit bump	ND
5 mph curb impact	ND
20 mph curb dropoff	ND
35 mph belgian blocks	ND

Note: ND = nondeployment

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

A typical airbag will require about 30 msec to inflate, meaning that the crash must be detected within about 20 msec. With respect to the speed of modern digital electronics, a 20 msec time interval is not considered to be short. The complicating factor for crash detection is the many crashlike accelerations experienced by a typical car that could be interpreted by airbag electronics as a crash, such as impact with a large pothole or driving over a curb.

The configuration for an airbag system has also evolved from electromechanical implementation using switches to electronic systems employing sophisticated signal processing. One of the early configurations employed a pair of acceleration switches SW1 and SW2 as depicted in Figure 10.18a. Each of these switches is in the form of a mass suspended in a tube with the tube axis aligned parallel to the longitudinal car axis. Figure 10.18b is a circuit diagram for the airbag system.

The two switches, which are normally open, must both be closed to complete the circuit for firing the squib. When this circuit is complete, a current flows through the squib ignitor that activates the charge. A gas is produced (essentially explosively) that inflates the airbag.

The switches SW1 and SW2 are placed in two separate locations in the car. Typically, one is located near the front of the car and one in or near the front of the passenger compartment (some automakers locate a switch under the driver's seat on the floor pan).

Referring to the sketch in Figure 10.18a, the operation of the acceleration-sensitive switch can be understood. Under normal driving conditions the spring holds the movable mass against a stop and the switch contacts remain open. During a crash the force of acceleration (actually deceleration of the car) acting on the mass is sufficient to overcome the spring force and move the mass. For sufficiently high car deceleration, the mass moves forward to close the switch contacts. In a real collision at sufficient speed, both switch masses will move to close the switch contacts, thereby completing the circuit and igniting the squib to inflate the airbag.

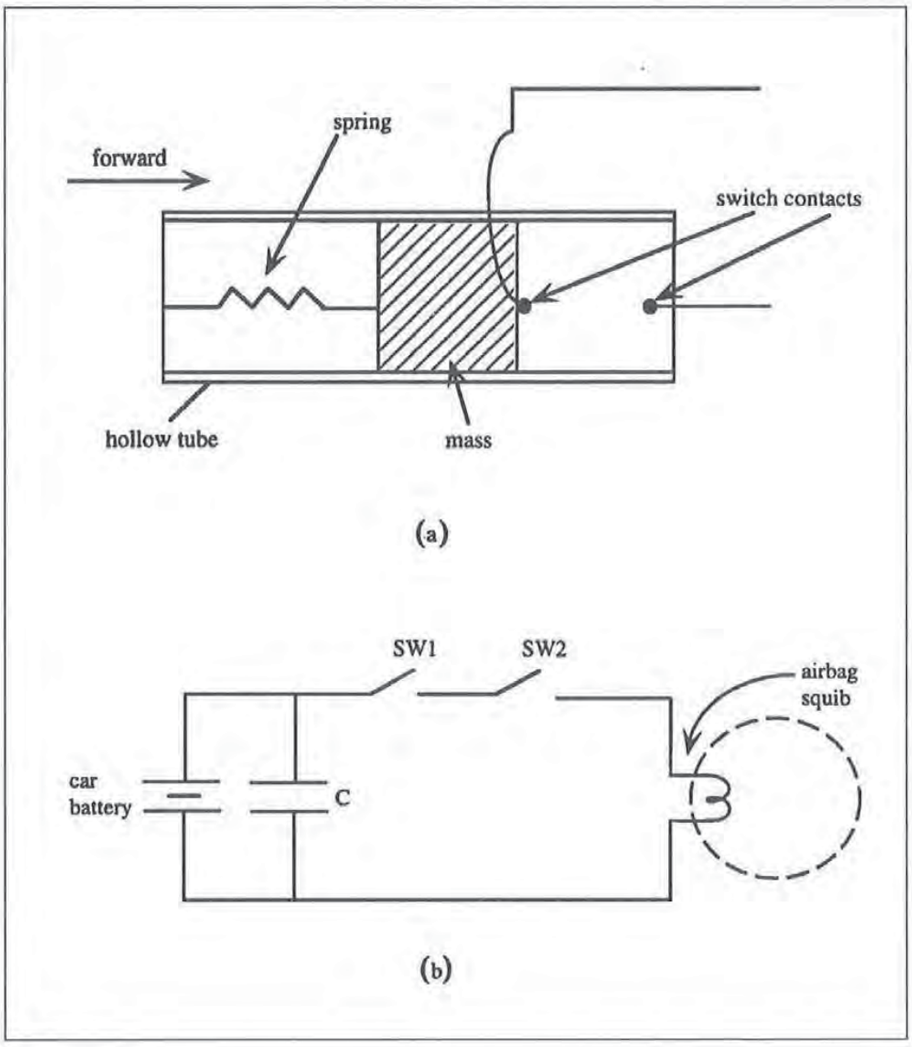
Figure 10.18b also shows a capacitor connected in parallel with the battery. This capacitor is typically located in the passenger compartment. It has sufficient capacity that in the event the car battery is destroyed early in the crash, it can supply enough current to ignite the squib.

In recent years there has been a trend to implement electronic airbag systems. In such systems the role of the acceleration-sensitive switch is played by an analog accelerometer along with electronic signal processing, threshold detection, and electronic driver circuit to fire the squib. Figure 10.19 depicts a block diagram of such a system.

The accelerometers a1 and a2 are placed at locations similar to where the switches SW1 and SW2 described above are located. Each accelerometer outputs a signal that is proportional to acceleration (deceleration) along its sensitive axis.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Figure 10.18
Airbag Deployment System

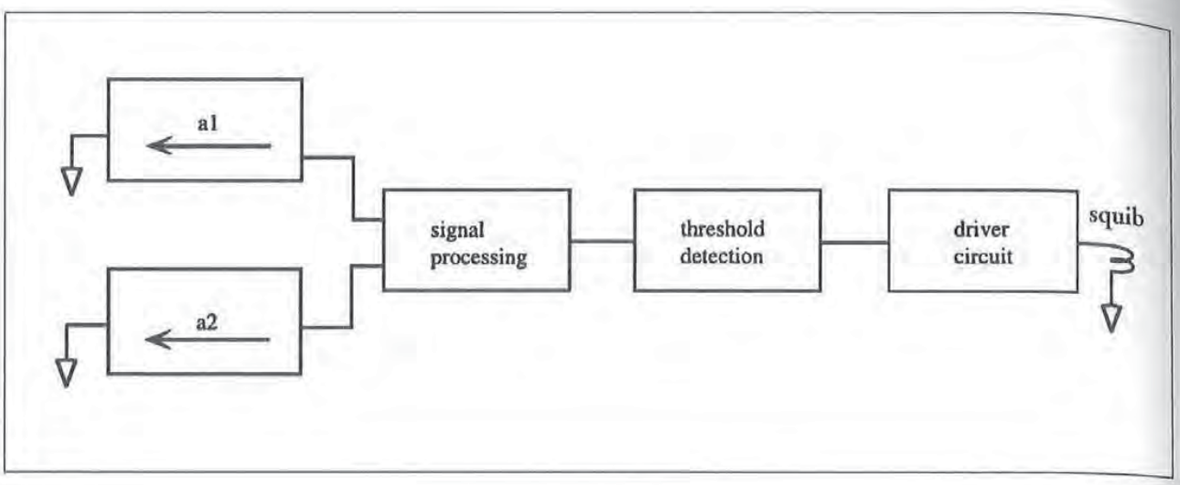


Under normal driving conditions the acceleration at the accelerometer locations is less than 1 g. However, during a collision at a sufficiently high speed the signal increases rapidly. Signal processing can be employed to enhance the collision signature in relation to the normal driving signal. Such signal processing must be carefully designed to minimize time delay of the output relative to the collision deceleration signal.

After being processed, the deceleration signal is compared with a threshold level. As long as the processed signal is less than this threshold the driver circuit remains deactivated. However, when this signal exceeds the

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Figure 10.19
Accelerometer-Based Airbag System



threshold, the driver circuit sends a current of sufficient strength to activate the squib and inflate the airbag.

Typically, the threshold is set so that airbag deployment occurs for a crash into a barrier at or above a specific speed. Depending on the system design, this speed can be anywhere between 8 and 12 mph. This speed range is chosen by the manufacturer to optimize the protection offered the car occupants while minimizing false deployment (that is, deployment when there is no crash).

There will continue to be new developments in airbag technology in order to improve performance. Complicating this task is the fact that the signature of a crash differs depending on the crash configuration. For example, there is one class of signature for a crash into a rigid barrier (i.e. a nonmoving and incompressible object) and another for a crash between a pair of cars (particularly when vehicle curb weights are different). In spite of technical difficulties in implementation, the airbag is finding broad application for occupant protection and seems destined to continue to do so.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Quiz for Chapter 10

1. In a microprocessor-based digital electronic engine control system, diagnosis
   - **a.** is not really required
   - **b.** can be accomplished with a voltmeter
   - **c.** can be accomplished with a multimeter
   - **d.** is best accomplished with a computer-based system
2. A timing light is useful for
   - **a.** locating timing marks in the dark
   - **b.** adjusting ignition timing
   - **c.** checking dwell
   - **d.** reading the clock on the instrument panel in the dark
3. An engine analyzer has been used to
   - **a.** set ignition points in cars equipped with them
   - **b.** measure intake fuel flow rate
   - **c.** set the choke
   - **d.** none of the above
4. In modern engines incorporating computer-based control systems, diagnosis is performed
   - **a.** with a timing light only
   - **b.** with a timing light and voltmeter
   - **c.** in the digital control system
   - **d.** none of the above
5. Diagnosis of intermittent failures
   - **a.** is routinely accomplished with the on-board diagnostic capability of the engine control system
   - **b.** is readily found using standard service bay equipment
   - **c.** is accomplished by displaying fault codes to the driver at the time of the failure
   - **d.** none of the above
6. A fault code is
   - **a.** a numerical indication of failure in certain specific engine components
   - **b.** displayed to the mechanic during diagnostic mode
   - **c.** registered in memory whenever a failure in a component occurs
   - **d.** all of the above
7. Failures can be detected by a computer-based control system in the following components:
   - **a.** O_2 sensor
   - **b.** MAP sensor
   - **c.** brake switch on cars equipped with cruise control
   - **d.** all of the above and more

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

8. An expert system is
   - **a.** a computer program that incorporates human knowledge to solve problems normally solved by humans
   - **b.** an organization of automotive engineers
   - **c.** a digital computer
   - **d.** none of the above

9. An expert system is applicable to automotive diagnosis because
   - **a.** automobiles are designed by experts
   - **b.** the diagnostic procedures used can be expressed in a set of rules or logical relationships
   - **c.** modern automobiles incorporate complex digital computers
   - **d.** all of the above

10. In addition to displaying fault codes, the example on-board diagnostic system explained in this chapter can
    - **a.** tell the mechanic where to locate the faulty component on the engine
    - **b.** measure certain engine parameters
    - **c.** detect failures in the catalytic converter
    - **d.** all of the above

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Future Automotive Electronic Systems

Up to this point, this book has been discussing automotive electronic technology of the recent past or present. This chapter speculates about the future of automotive electronic systems. Some concepts are only in the laboratory stage and may not, at the time of this writing, have had any vehicle testing at all. Some of the system concepts have been or are currently being tested experimentally. Some are operating on a limited basis in automobiles. Some of the concepts that were included in the corresponding chapter of the previous editions of this book are now in production automobiles.

Whether or not any of the concepts discussed here ever reaches a production phase will depend largely on its technical feasibility and marketability. Some will simply be too costly to have sufficient customer appeal and will be abandoned by the major automobile manufacturers.

On the other hand, one or more of these ideas may become a major market success and be included in many models of automobiles. Some of these systems may even prove to be a significant selling point for one of the large automobile manufacturers.

The following is a summary of the major electronic systems that have been considered and that may be considered for future automotive application. For convenience, these ideas are separated into the following categories:

1. Engine and drivetrain
2. Safety
3. Instrumentation
4. Navigation
5. Diagnosis

ENGINE AND DRIVETRAIN

The first edition of this book described electronic engine control technology that had been developed up to about the 1981 model-year cars. Considerable technical innovations have evolved in the interval since then. Some of these technological developments include

1. Knock control
2. Linear solenoid idle speed control
3. Sequential fuel injection
4. Distributorless ignition

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

5. Self-diagnosis for fail-safe operation
6. Back-up MPU
7. Crankshaft angular position measurement for ignition timing
8. Direct mass air flow sensor

Although these technological changes have improved the performance and reliability of the electronically controlled engine, the fundamental control strategy for fuel metering has not changed. The fuel metering strategy has been and will probably continue to be (at least for the short term) to provide a stoichiometric mixture to the engine. This strategy will remain intact as long as a three-way catalytic converter is used to reduce undesirable tailpipe exhaust gas emissions. However, within the constraint of stoichiometric mixture control strategy, there will be some technological improvements in engine control. These improvements will occur in mechanical and electrical components as well as in software that is optimized for performance and efficiency.

In the area of mechanical components, research is being done in the area of variable parameter intake structures. New mechanisms and electromechanical actuators are being developed that will permit

1. Induction systems with variable geometry
2. Variable valve timing
3. Variable nozzle turbochargers
4. Throttle actuators

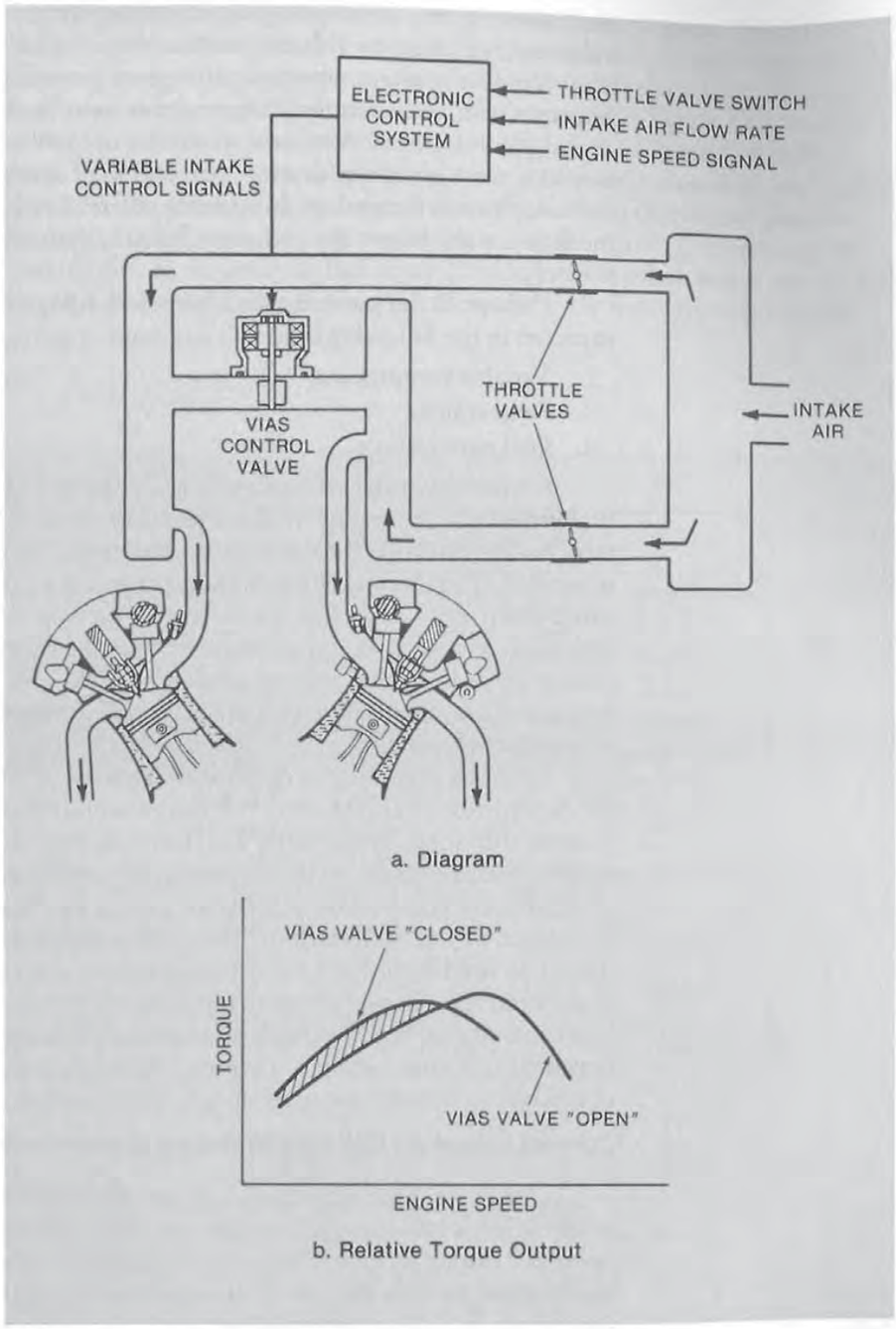
The performance and efficiency of any engine are markedly influenced by the intake system. The intake system configuration directly affects the volumetric efficiency of the engine, which is a measure of engine performance as an air pump. The design of an intake system in the past has involved many compromises and trade-offs that were made to enable high volumetric efficiency over the entire engine operating range. Variable geometry is achieved through the use of new electromechanical mechanisms or actuators that can change the shape and dimensions of intake system components.

One such system is illustrated in Figure 11.1 for an experimental V-6 engine. This system has two separate intake systems, each of which has a throttle valve. In a traditional engine, the intake manifold is tuned to achieve maximum torque at a particular RPM. The system of Figure 11.1, which is known as a variable impedance aspiration system (VIAS), has two separate intake pipes leading from a plenum chamber to the cylinder banks, with a butterfly valve connecting the two sides. By suitable opening and closing of this valve, the effective dimensions of the intake pipes are changed, thereby tuning the intake. Figure 11.1b shows the relative torque output for an open and closed valve. Note the improved torque at low RPM.

An important aspect of volumetric efficiency is the valve timing (see Chapter 1). Valve timing and valve lift profile are designed with many constraints to ensure the best possible volumetric efficiency over a wide range of engine operations. In

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Figure 11.1 Configuration of Variable-Geometry Intake System



PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

the future, variable valve timing will provide significant improvement in volumetric efficiency by reducing the constraints on valve timing.

Variable intake components offer great potential for engine performance improvement. However, these components must be controlled by the engine's digital control system. A control system for optimal use of a variable intake system is currently under development and is, of course, equally as important as the components themselves. In addition, there is an increasing trend to apply modern control theory (i.e., adaptive learning systems) to automotive engine control.

Perhaps in the more distant future, technological improvements can be expected in the following areas:

1. Variable compression
2. Swirl control
3. Fuel atomization

Compression ratio directly affects the thermal efficiency and, hence, performance of the engine. It also affects knocking. A variable compression ratio has the potential for significant performance improvement when suitably controlled. The thermal efficiency of an engine is increased with increased compression ratio. However, excessively high compression ratio can lead to knocking. In a variable compression ratio engine the maximum compression ratio must be limited to prevent excessive knock. The development of actuator mechanisms and control strategies for variable compression are important future research areas.

Swirl is a term used to describe the motion of intake gases as they enter the combustion chamber. Swirl influences combustion speed and, thereby, thermal efficiency. Swirl control can theoretically be achieved by using a variable intake system. There is research currently being done in this area.

Efficient combustion of all of the energy that is available in the fuel is influenced by fuel atomization. When fuel is mixed with air, the droplets should be sized such that air and gasoline molecules can readily be combined. The atomization of fuel to optimally-sized droplets is influenced by the fuel injector configuration. Research into new fuel injectors that can provide improved fuel atomization is underway. Also being researched is the use of ultrasonics to increase atomization after injection has occurred.

Control Based on Cylinder Pressure Measurements

One of the more interesting new control concepts currently under investigation is based on cylinder pressure measurements. Cylinder pressure developed during the power stroke has long been recognized as the most fundamental variable that can be monitored to determine the operating state of the engine. Cylinder pressure measurements provide real-time combustion process feedback that can be used for control of engine variables of individual cylinders.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Figure 11.2 is a block diagram of an engine control system that obtains the required feedback signal from a cylinder pressure sensor. An example of fuel control strategy using cylinder pressure is based on the relationship between air/fuel ratio and the cyclic fluctuation in cylinder pressure. Figure 11.3 is a graph of the fluctuation in peak cylinder pressure (θ_{pmax}) as a function of air/fuel ratio. This fluctuation remains relatively low for air/fuel ratios of approximately 13 to 20. For leaner mixtures, the random fluctuations in cylinder pressure increase. Such fluctuations are equivalent to rough engine operation and are undesirable. In the example fuel control strategy, the air/fuel ratio is maintained near 20 and is reduced whenever the measured cycle fluctuation in cylinder pressure exceeds a threshold value.

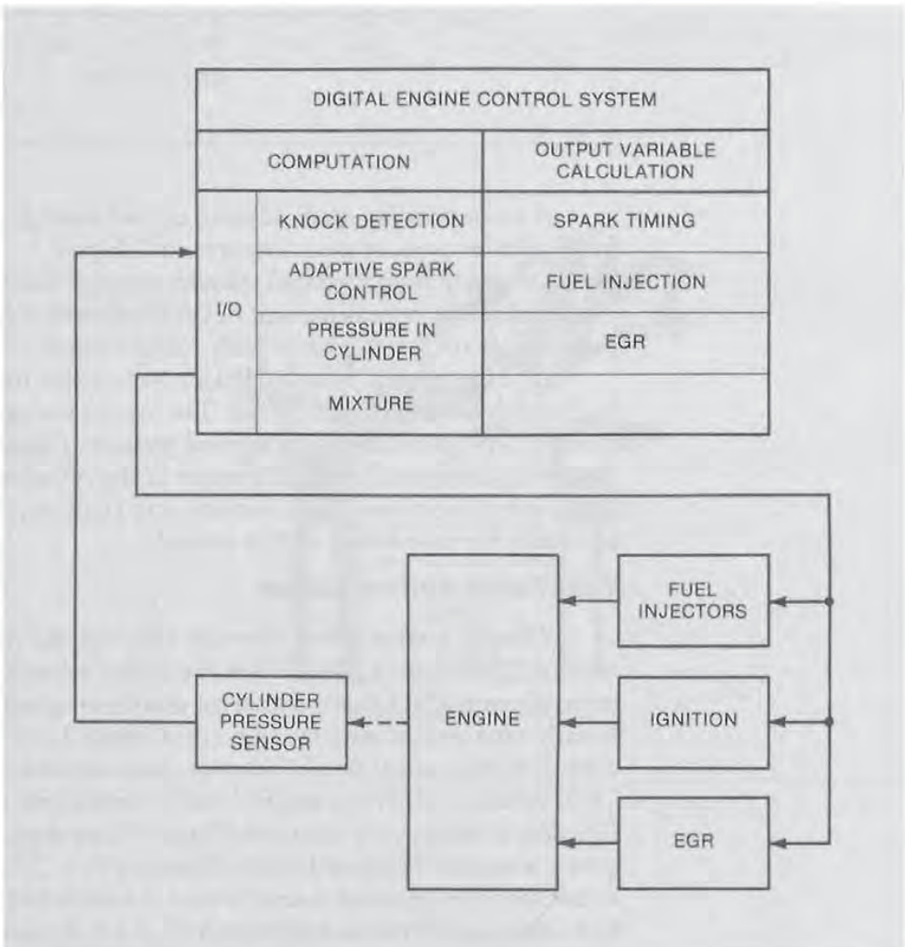


Figure 11.2 Engine Control System Based on Cylinder Pressure Measurements

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

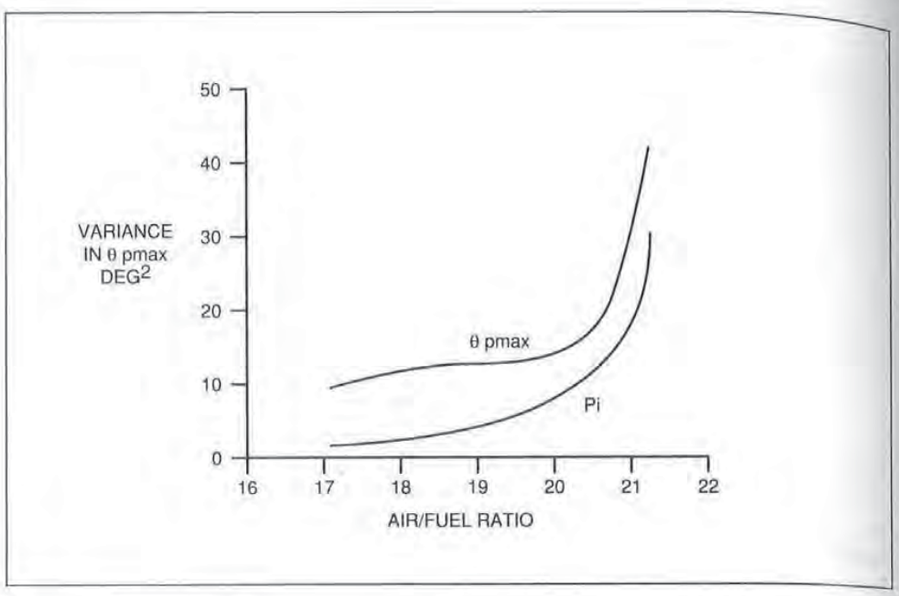


Figure 11.3 Variation in Cylinder Pressure with Air/Fuel Ratio

A corresponding spark-advance control strategy can be similarly derived from cylinder pressure measurements. In Chapter 7, a scheme for measuring knock intensity from the rapid cylinder pressure fluctuations near TDC is explained. Thus, a measurement of cylinder pressure has the potential to provide fuel and spark control from a single sensor.

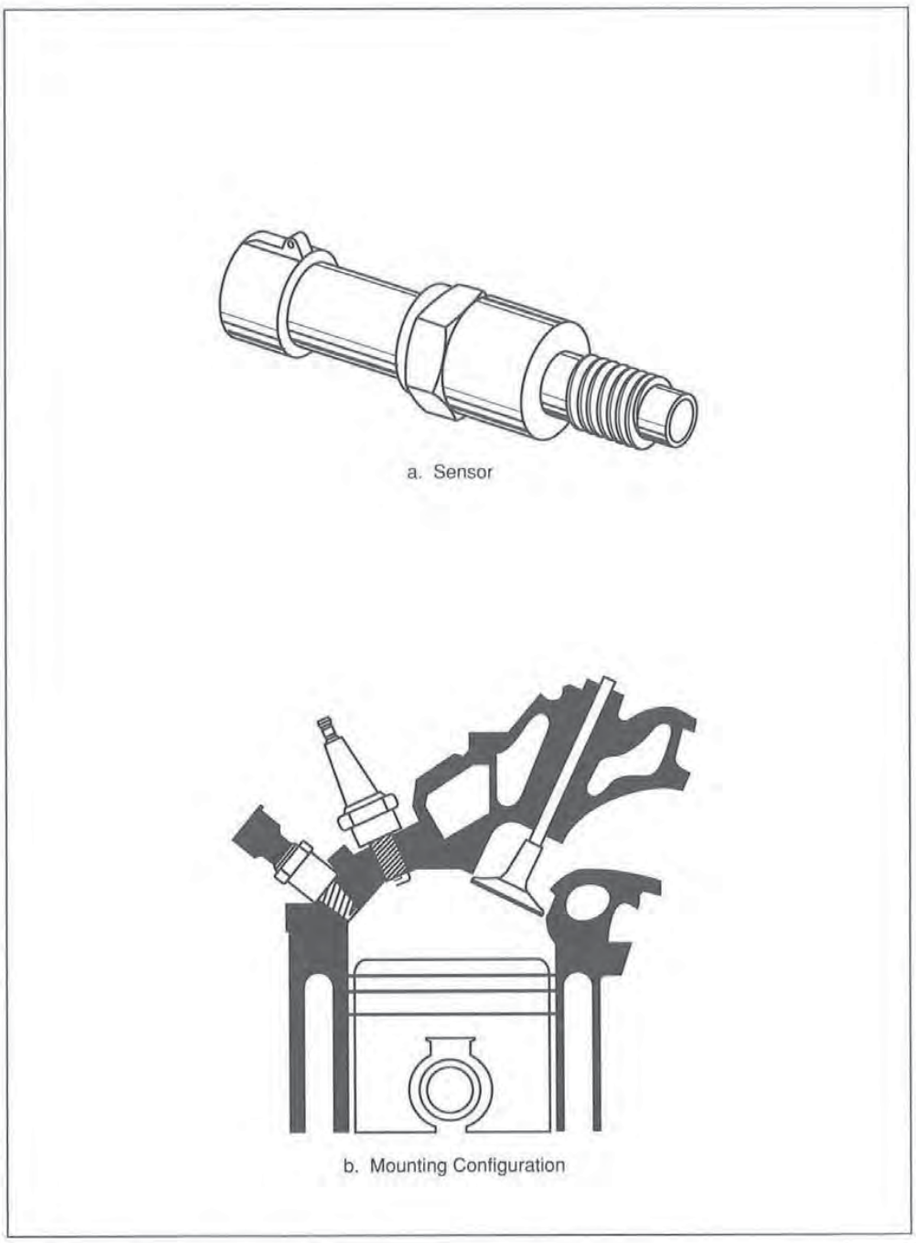
An experimental cylinder pressure sensor that uses a piezoelectric element has been developed (Figure 11.4a). The output voltage from the piezoelectric element is proportional to the applied pressure. Figure 11.4b is a sketch of the mounting configuration for this sensor in the cylinder head. Cylinder pressure is applied to the piezoelectric element, and an output voltage is generated that is suitable for closed-loop engine control.

Wide Range Air/Fuel Sensor

There is another sensor that may influence the trend of future fuel control systems. This sensor is mounted in the engine exhaust pipe similarly to the presently used EGO sensor. However, this sensor generates an output that varies linearly with air/fuel ratio over a range of about 12 to 22. The importance of a control strategy based on air/fuel ratio measurements is illustrated in Figure 11.5, in which relative power, fuel consumption rate, and NO_x emissions as a function of equivalence ratio (see Chapter 5) are depicted. Note that engine power is reduced compared to stoichiometry ($\lambda = 1$) for relatively high values of λ, but that the reduction is smaller than the reduction in NO_x emission. The fuel consumption rate is minimum for $\lambda \cong 1.5$. In contrast, these variables are shown versus the output of a standard O_2 (EGO) sensor.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Figure 11.4
Cylinder Pressure Sensor



a. Sensor

b. Mounting Configuration

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

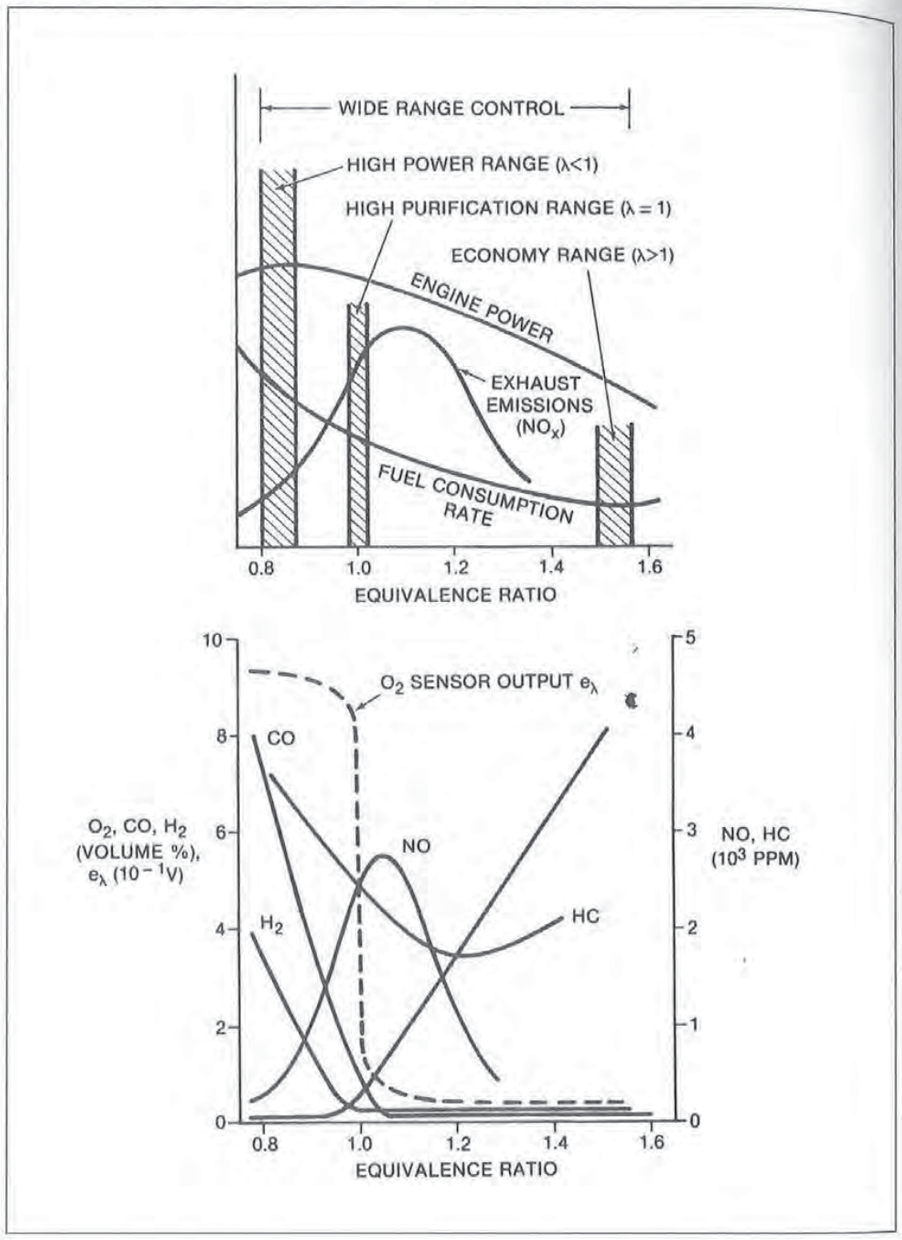


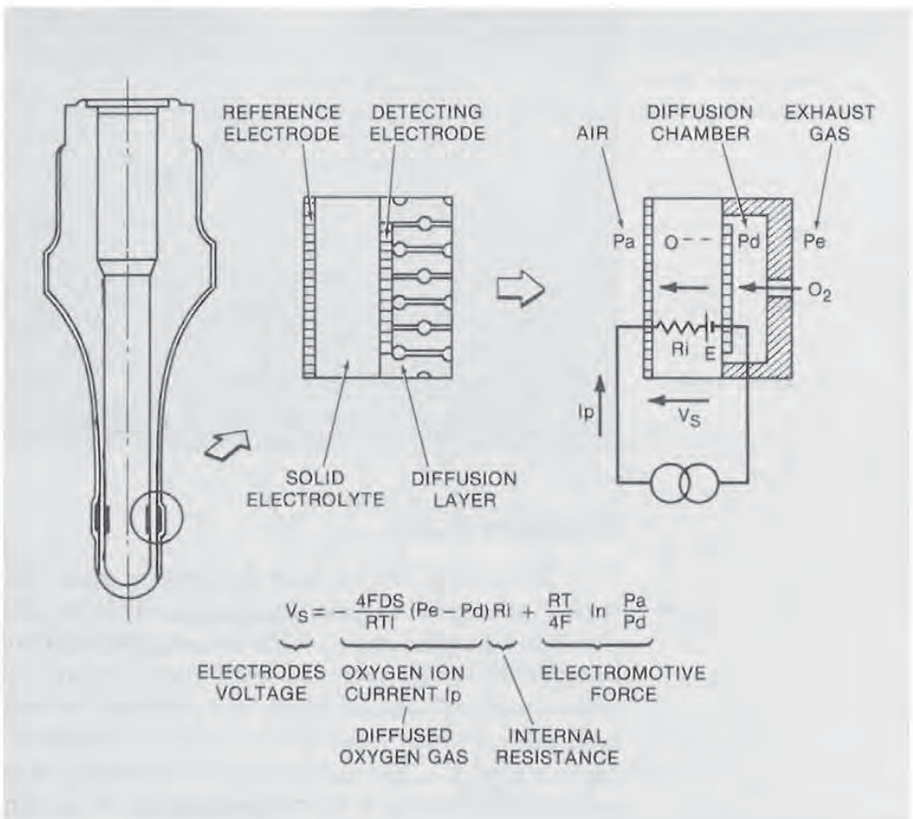
Figure 11.5 Engine Performance versus Equivalence Ratio

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

The sensor configuration is shown in Figure 11.6. This sensor uses yttria (Y_2O_3)-stabilized zirconia (ZrO_2) as a diffusion element that is preheated to a desired operating temperature. In actual operation, a voltage, V_s, is applied across this element, and a current, I_p, flows. The theory of operation is beyond the scope of this book, though it is based on the diffusion of various ions through the element. Nevertheless, current I_p varies linearly with λ, as shown in Figure 11.7. A measurement of the current (which is straightforward) yields a measurement of λ.

Whether this sensor concept will be broadly applied in engine control is yet to be determined. However, the control strategy based on air/fuel ratio measurements has the benefit of providing emission control without requiring a three-way catalytic converter, and at the same time achieves relatively good fuel economy.

Figure 11.6 Linear Air/Fuel Sensor Configuration



PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

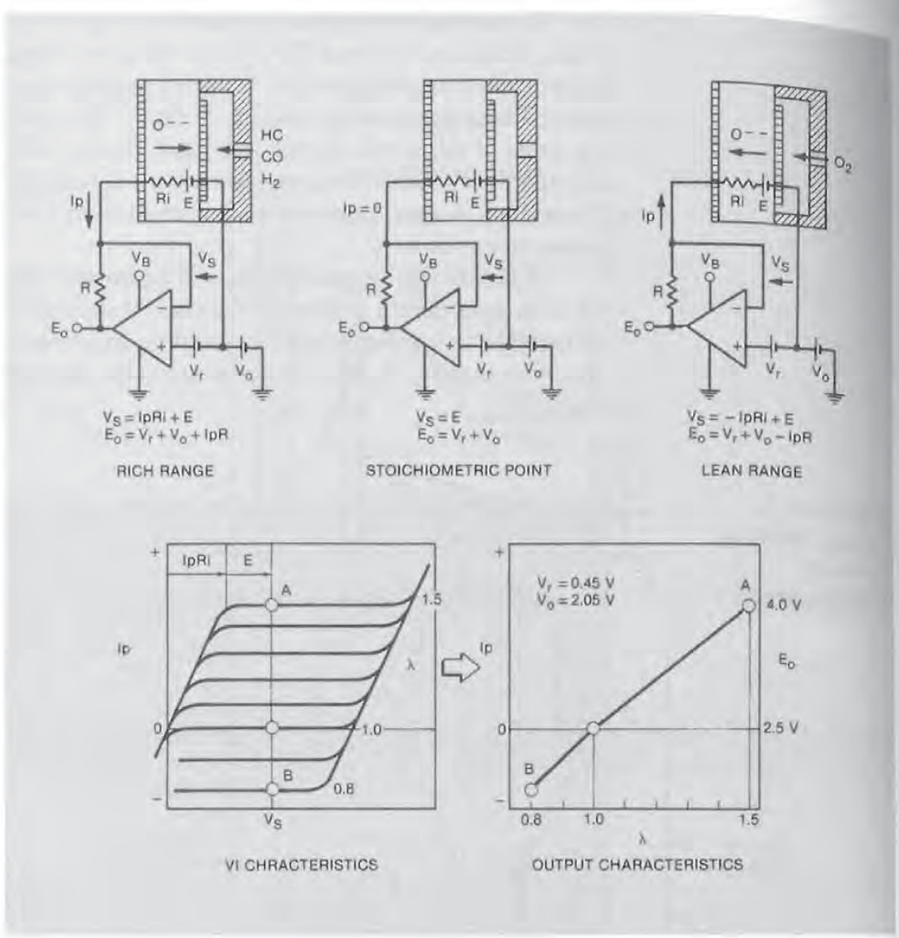


Figure 11.7 Functional Operation of Lambda Sensor

Alternative Engine

The engine that has been discussed in detail throughout this book is a 4-stroke/cycle, gasoline-fueled, spark-ignited (SI) engine (see Chapter 1). An alternative gasoline engine is the 2-stroke/cycle engine. This type of engine has been used for many years as a small marine engine, as motorcycle and lawnmower engines, and briefly as a passenger car engine. Unlike the 4-stroke/cycle engine, which requires two complete crankshaft revolutions for each power stroke, the 2-stroke/cycle engine delivers power during each crankshaft revolution. This engine has the potential to be more compact and lightweight for a given power output and to require fewer parts than a comparable 4-stroke/cycle engine. Great potential fuel economy benefits can be achieved using this engine compared with a 4-stroke/cycle engine due to reduced vehicle weight and improved vehicle shape for drag reduction.

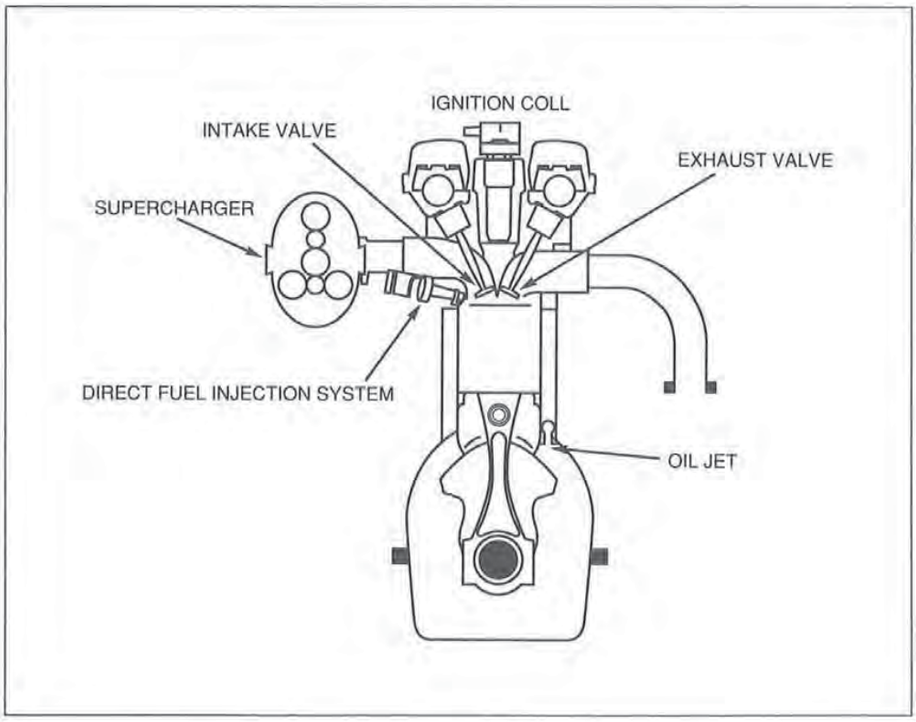
PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

In the past, the 2-stroke/cycle engine was virtually eliminated as a passenger car power plant due to the emission regulations of the Clean Air Act. Poor emission performance results, in part, from less efficient combustion than the 4-stroke/cycle engine. In addition, the traditional 2-stroke/cycle engine requires mixing lubricating oil with gasoline, resulting in poor emissions.

The potential for this engine in cars may be returning due to recent developments in technology, including electronic fuel control. Figure 11.8 is a schematic cross-sectional drawing of a 2-stroke/cycle engine. Some of the new technology on this engine that is missing from the traditional 2-stroke/cycle engine includes the intake and exhaust valves, supercharger, direct fuel injection, and oil injector jet for lubrication. In at least one engine configuration under development, there are four valves per cylinder that assist in scavenging (i.e., removing exhaust and charging the cylinder with intake air). In addition, a Roots-type supercharger helps in scavenging and mixture distribution.

The direct fuel injection provides highly atomized fuel droplets. The control of fuel droplet size to very small droplets improves the surface/volume ratio of fuel, resulting in reduced emissions and improved fuel economy.

Figure 11.8 2-Stroke/Cycle Engine Configuration



PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Other keys to optimal emission control include precise mixture distribution and ignition control. Mixture distribution is controlled by regulating (under electronic control) the fuel injection timing. Electronic controls have proved to be the only cost-effective means of mixture distribution and ignition timing control.

Should the highly sophisticated fuel control system for the 2-stroke/cycle engine meet all emissions and performance goals, the engine should have a great future in passenger car applications.

Alternative-Fuel Engines

In order to reduce dependence on imported oil, there has been a considerable development effort devoted to finding alternatives to gasoline fuels. The two leading candidates are natural gas and alcohol fuels (methanol and ethanol). The latter fuel is made from grain and is a renewable fuel source. Brazil has operated large fleets of ethanol-fueled cars for years, though at great government subsidy. For the foreseeable future, ethanol does not appear to be a practical alternative to replace gasoline in the United States (although it is often mixed with gasoline, forming so-called gasohol).

Methanol is an alcohol fuel that is potentially available at relatively low cost and can replace gasoline as a motor fuel. It can be manufactured from coal, which is in abundant supply in the United States. It is routinely used as a fuel for racing cars because it has a relatively high octane rating.

Unfortunately, methanol has a number of disadvantages for passenger use. For example, it has roughly half the energy of an equivalent amount of gasoline. Thus, for a given range, the fuel tank must be roughly double the size of a fuel tank for gasoline. In addition, methanol-fueled cars do not start readily in cold weather, which is an obvious disadvantage in the northern United States. Moreover, methanol is toxic and highly corrosive. The entire fuel system must be made from stainless steel in order to cope with the severe corrosion.

Yet another disadvantage of methanol is the lack of a distribution system (including gas stations equipped to sell this fuel). This latter problem can be potentially overcome with the advent of engines that can operate on either gasoline, methanol, or a mixture of the two. Vehicles that are so equipped are called *flexible fuel vehicles* (FFV).

Electronic fuel controls are vital to the success of any FFV. Fundamental to any FFV is a sensor that can measure the alcohol content of the fuel. There are two types of practical alcohol sensors available at the present time. One of these measures alcohol content optically by sensing the index of refraction for the mixture, which is a unique function of the alcohol content. The other senses alcohol with a capacitive sensor. This latter sensor is based on the differences in dielectric constant (see Chapter 5) of gasoline and methanol.

Once the alcohol content of fuel has been measured, the electronic fuel control system can properly regulate fuel delivery to stoichiometric mixture

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

ratio. The quantity of fuel required for a given mass air flow rate increases as the alcohol content increases. For neat methanol (100% methanol), the fuel flow rate is roughly double that for neat gasoline.

Figure 11.9 is a schematic of an FFV system. This system configuration is virtually identical to the fuel control system explained in Chapters 6 and 7. The only significant difference is the alcohol sensor (and the need for stainless steel fuel delivery hardware).

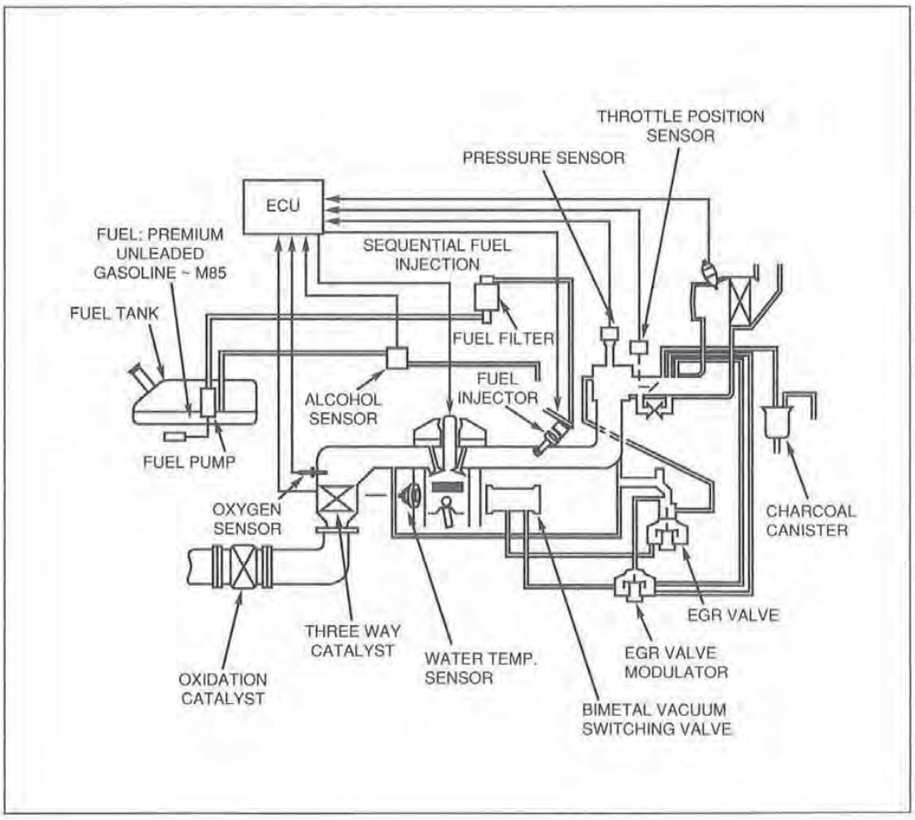
Transmission Control

Electronic control of an automotive transmission could provide maximum performance by matching engine controls and transmission gear ratios.

The automatic transmission is another important part of the drivetrain that must be controlled. Traditionally, the automatic transmission control system has been hydraulic and pneumatic. However, there are some potential benefits to the electronic control of the automatic transmission.

The engine and transmission work together as a unit to provide the variable torque needed to move the car. If the transmission were under control of the electronic engine control system, then optimum performance for the

Figure 11.9
FFV System



PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

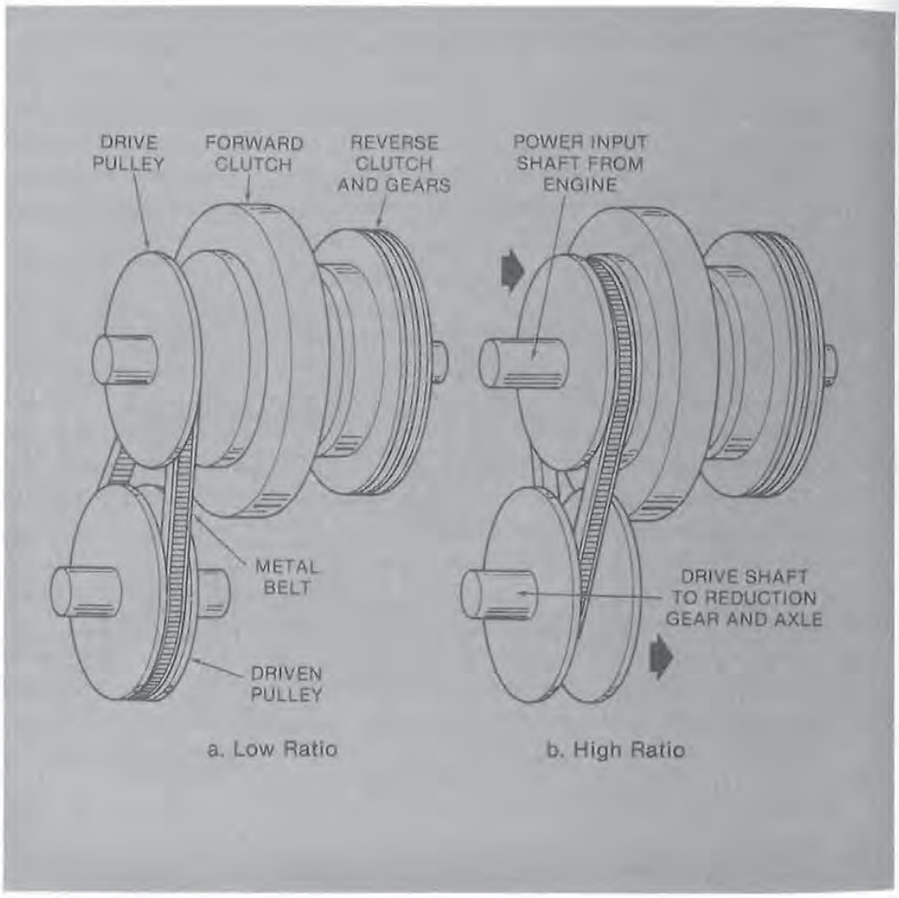
entire drivetrain could be obtained by coordinating the engine controls and transmission gear ratio.

Continuously Variable Transmission

One concept having great potential for integrated engine/power train control involves the use of a continuously variable transmission. Instead of being limited to three, four, or five gear ratios, this transmission configuration has a continuous range of gear ratios from a minimum value to a maximum value as determined by the design parameters for the transmission.

The continuously variable transmission (CVT) is an alternative to the present automatic transmission. It is being developed presently and will likely see considerable commercial use in production cars. The principle of the CVT is shown in Figure 11.10.

Figure 11.10 Continuously Variable Transmission



PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Power is transmitted from the driving shaft to the driven shaft by a belt that couples a pair of split pulleys. The effective gear ratio is the ratio of pulley radii at the contact point of the belt. The radii vary inversely with the spacings of the split pulleys. The spacings are controlled by a pair of hydraulic cylinders that push the left half of each pulley in or out.

The control strategy for an integrated engine and CVT system is relatively complicated and involves measuring vehicle speed and load torque. Considerable research effort has been and will continue to be expended to develop a suitable control system, the technology of which will, undoubtedly, be digital electronic controls.

SAFETY

Collision Avoidance Radar Warning System

Collision avoidance radar systems use low-power radar to sense objects and provide warnings of possible collisions.

An interesting safety-related electronic system having potential for future automotive application is the anticollision warning system. An on-board low-power radar system can be used as a sensor for an electronic collision avoidance system to provide warning of a potential collision with an object lying in the path of the vehicle. As early as 1976, at least one experimental system was developed that could accurately detect objects up to distances of about 100 yards. This system gave very few false alarms in actual highway tests.

For an anticollision warning application, the radar antenna should be mounted on the front of the car and should project a relatively narrow beam forward. Ideally, the antenna for such a system should be in as flat a package as possible, and should project a beam that has a width of about 2° to 3° horizontally and about 4° to 5° vertically. Large objects such as signs can reflect the radar beam, particularly on curves, and trigger a false alarm. If the beam is scanned horizontally for a few degrees, say 2.5° either side of center, false alarms from roadside objects can be reduced.

In order to test whether a detected object is in the same lane as the radar-equipped car traveling around a curve, the radius of the curve must be measured. This can be estimated closely from the front wheel steering angle for an unbanked curve. Given the scanning angle of the radar beam and the curve radius, a computer can quickly perform the calculations to determine whether or not a reflecting object is in the same lane as the protected car.

For the collision warning system, better results can be obtained if the radar transmitter is operated in a pulsed mode rather than in a continuous-wave mode. In this mode, the transmitter is switched on for a very short time, then it is switched off. During the off time, the receiver is set to receive a reflected signal. If a reflecting object is in the path of the transmitted microwave pulse, a corresponding pulse will be reflected to the receiver. The round trip time, t, from transmitter to object and back to receiver is proportional to the range, R,

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

to the object, as illustrated in Figure 11.11 and expressed in the following equation:

$$t = \frac{2R}{c}$$

where c is the speed of light (186,000 miles per second). The radar system has the capability of accurately measuring this time to determine the range to the object.

It is possible to measure the vehicle speed, V, by measuring the Doppler frequency shift of the pulsed signal reflected by the ground. (The Doppler frequency shift is proportional to the speed of the moving object. The Doppler shift is what causes the pitch of the whistle of a moving train to change as it passes.) This reflection can be discriminated from the object reflection because the ground reflection is at a low angle and a short, fixed range.

A collision avoidance system compares the time needed for a microwave signal to be reflected from an object to the time needed for a signal to be reflected from the ground. By comparing these times with vehicle speed data, the computer can calculate a "time to impact" value and sound an alarm if necessary.

The reflection from an object will have a pulse shape that is very nearly identical to that of the transmitted pulse. As noted, the radar system can detect this object reflection and find R to determine the distance from the vehicle to the object. In addition, the relative speed of closure between the car and the object can be calculated by adding the vehicle speed, V, from the ground reflected pulses and the speed of the object, S, which can be determined from the change in range of the object's reflection pulses. A block diagram of an experimental collision warning system is shown in Figure 11.12. In this system, the range, R, to the object and the closing speed, $V + S$, are measured.

The computer can perform a number of calculations on this data. For example, the computer can calculate the time to collision, T. Whenever this time is less than a preset value, a visual and audible warning is generated. The system could also be programmed to release the throttle and apply the brakes, if automatic control were desired.

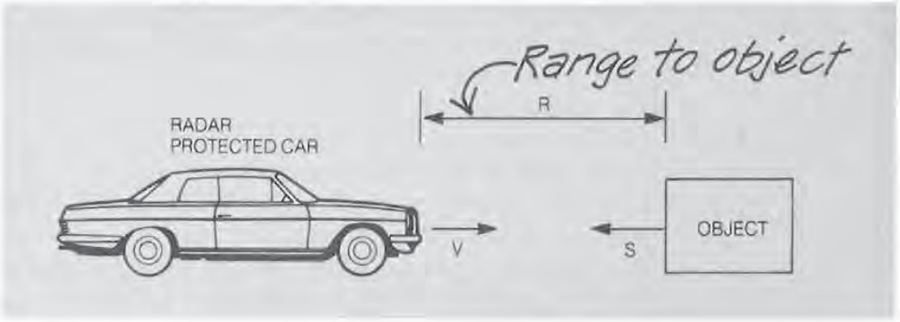


Figure 11.11 Range to Object for Anticollision Warning System

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

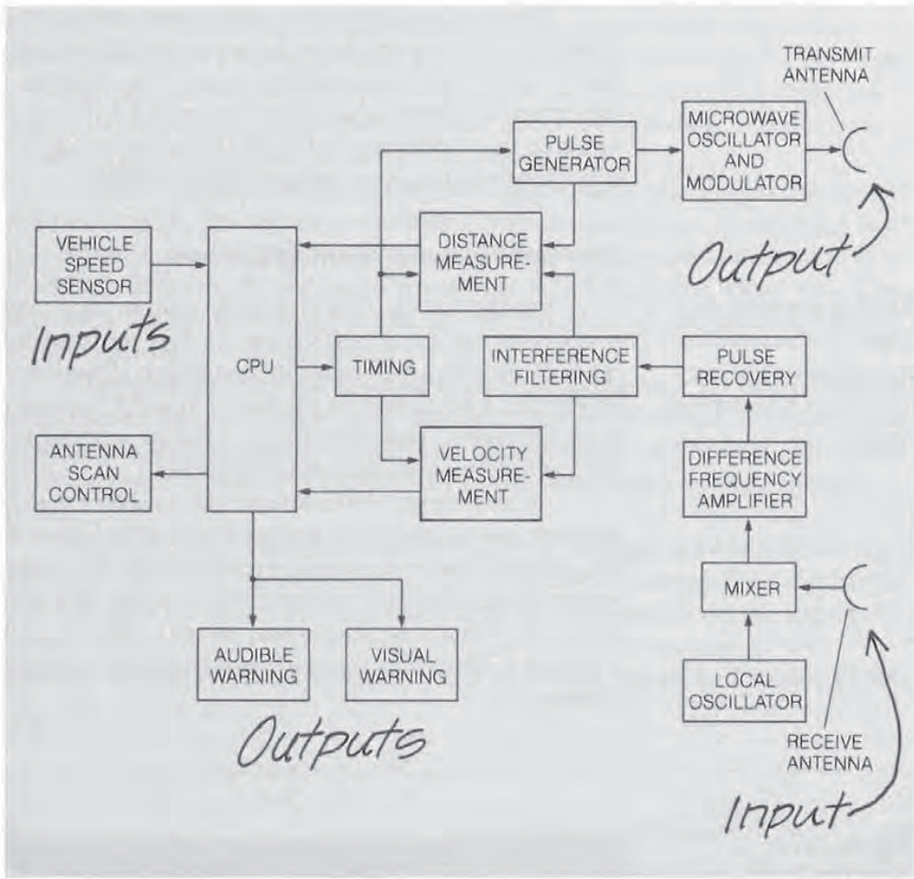


Figure 11.12
Collision Avoidance Warning System

If the object is traveling at the same speed as the radar-equipped car and in the same direction, $S = -V$, and T is infinite. That is, a collision would never occur. If the object is stationary, $S = 0$ and the time to collision is:

$$T = \frac{R}{V}$$

Note that this system can give the vehicle speed, which is applicable for antilock braking systems. If the object is another moving car approaching the radar-equipped car head-on, the closing speed is the sum of the two car speeds. In this case, the time to closure is

$$T = \frac{R}{V+S}$$

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

This concept already has been considerably refined since its inception. However, there are still some technical problems that must be overcome before this system is ready for production use. Nevertheless, the performance of the experimental systems that have been tested is impressive. It will be interesting to watch this technology improve and to see which, if any, of the present system configurations becomes commercially available.

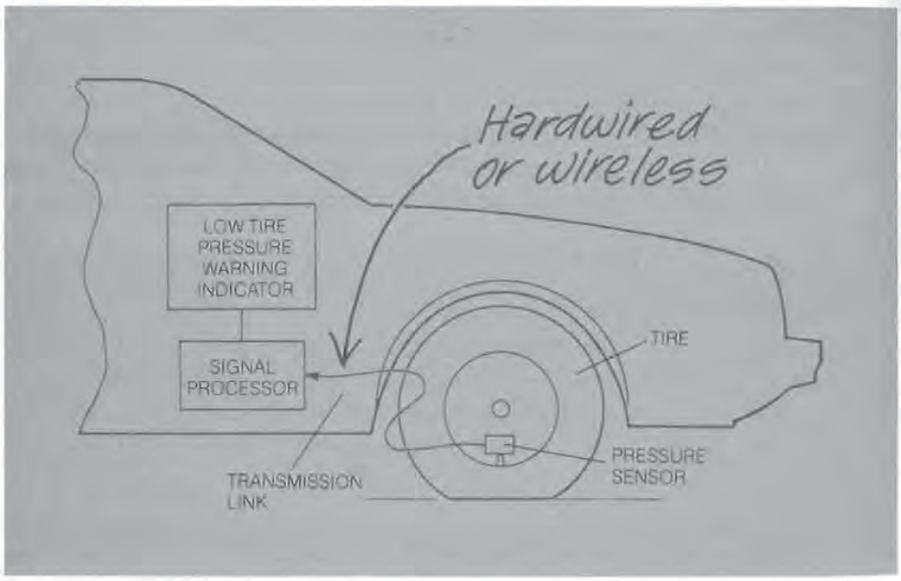
Low Tire Pressure Warning System

Another potential application of electronics to automotive safety is a low tire pressure warning system.

Another interesting electronic system that may be used on future automobiles is a warning system for low tire pressure that works while the car is in motion. A potentially dangerous situation could be avoided if the driver could be alerted to the fact that a tire has low pressure. For example, if a tire develops a leak, the driver could be warned in sufficient time to stop the car before control becomes difficult.

There are several pressure sensor concepts that could be used. A block diagram of a hypothetical system is shown in Figure 11.13. In this scheme, a tire pressure sensor continually measures the tire pressure. The signal from the sensor mounted on the rolling tire is coupled by a link to the electronic signal processor. Whenever the pressure drops below a critical limit, a warning signal is sent to a display on the instrument panel to indicate which tire has the low pressure.

Figure 11.13
Low Tire Pressure Warning System



PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

A low tire pressure warning system utilizes a tire-mounted pressure sensor. The pressure sensor signals a loss in tire pressure.

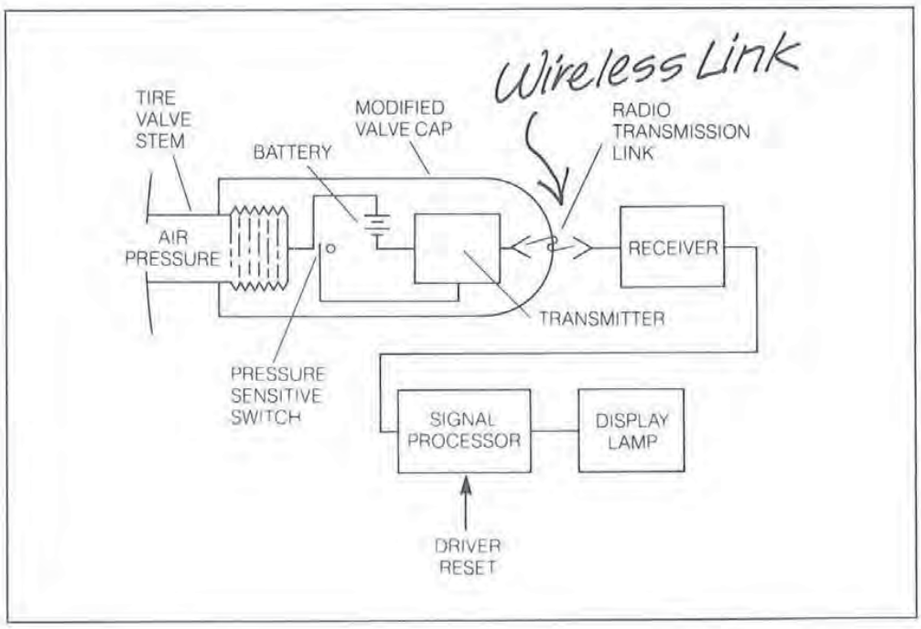
The difficult part of this system is the link from the tire pressure sensor mounted on the rotating tire to the signal processor mounted on the body. Several concepts have the potential to provide this link. For example, slip rings, which are similar to the brushes on a dc motor, could be used. However, this would require a major modification to the wheel-axle assembly and does not appear to be an acceptable choice at the present time.

Another concept for providing this link is to use a small radio transmitter mounted on the tire. By using modern solid-state electronic technology, a low-power transmitter could be constructed. The transmitter could be located in a modified tire valve cap and could transmit to a receiver in the wheel well. The distance from the transmitter to the receiver would be about one foot, so only very low power would be required.

One problem with this method is that electrical power for the transmitter would have to be provided by a self-contained battery. However, the transmitter need only operate for a few seconds and only when the tire pressure falls below a critical level. Therefore, a tiny battery could theoretically provide enough power.

The scheme is illustrated schematically for a single tire in Figure 11.14. The sensor switch is usually held open by normal tire pressure on a diaphragm mechanically connected to the switch. Low tire pressure allows the spring-loaded switch to close, thereby switching on the microtransmitter. The receiver, which is directly powered by the car battery, receives the transmitted

Figure 11.14 Low-Pressure Sensor Concept



PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

signal and passes it to the signal processor, also directly powered by the car battery. The signal processor then activates a warning lamp for the driver, and it remains on until the driver resets the warning system by operating a switch on the instrument panel.

One reason for using a signal processing unit is the relatively short life of the transmitter battery. The transmitter will remain on until the low-pressure condition is corrected or until the battery runs down. By using a signal processor, the low-pressure status can be stored in memory so the warning will still be given even if the transmitter quits operating. The need for this feature could arise if the pressure dropped while the car was parked. By storing the status, the system would warn the driver as soon as the ignition was turned on.

Many other concepts have been proposed for providing a low tire pressure warning system. The future of such a system will be limited largely by its cost and reliability.

INSTRUMENTATION

The reduced cost of VLSI and microprocessor electronics is resulting in advanced instrumentation and the use of voice synthesis in warning systems.

It is very likely that some interesting advances in automotive instrumentation will be forthcoming, such as certain functions, new display forms including audible messages by synthesized speech, and interactive communication between the driver and the instrumentation. These advances will come about partly because of increased capability at reduced cost for modern solid-state circuits, particularly microprocessors and microcomputers.

One of the important functions that an all-electronic instrumentation system can have in future automobiles is continuous diagnosis of other on-board electronic systems. In particular, the future computer-based electronic instrumentation may perform diagnostic tests on the electronic engine control system. This instrumentation system might display major system faults and even recommend repair actions.

Another function that might be improved in the instrumentation system is the trip computer function. The system probably will be highly interactive; that is, the driver will communicate with the computer through a keyboard or maybe even by voice.

The full capabilities of such a system are limited more by human imagination and cost than technology. Most of the technology for the systems discussed is available now and can be packaged small enough for automotive use. However, in a highly competitive industry where the use of every screw is analyzed for cost-effectiveness, the cost of these systems still limits their use in production vehicles.

Heads Up Display

In the first edition of this book, it was speculated that CRT displays would appear in production cars. This has, in fact, occurred, and there is a

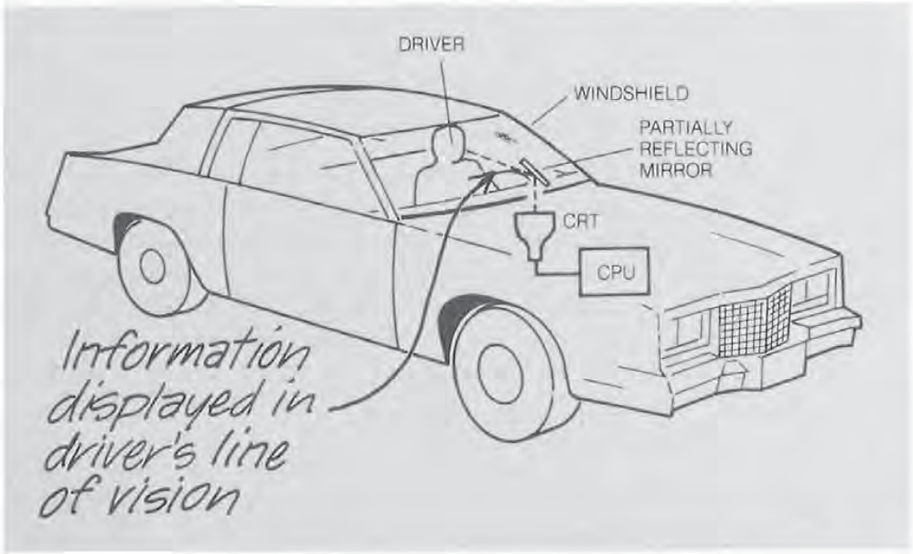
PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

description of the CRT display in Chapter 9. It was also speculated that the CRT might be used in conjunction with a heads up display (HUD). There is no clear sign, however, that the basic display source will be a CRT. In fact, any light-emitting display device can be used with a HUD. A heads up display of the speed is now available on certain models of automobiles.

The CRT, when combined with a partially reflective mirror, results in a HUD. Information is displayed on the CRT in the form of a reversed image. The image is reflected by the mirror and viewed normally by the driver.

It is convenient to describe a HUD by presuming that the display source is a CRT, keeping in mind that many other display sources can be substituted for the CRT. Figure 11.15 illustrates the concept of a HUD. In this scheme, the information that is to be displayed appears on a CRT that is mounted as shown. A partially reflecting mirror is positioned above the instrument panel in the driver's line of sight of the road. In normal driving, the driver looks through this mirror at the road. Information to be displayed appears on the face of the CRT upside down, and the image is reflected by the partially reflecting mirror to the driver right side up. The driver can read this data from the HUD without moving his or her head from the position for viewing the road. The brightness of this display would have to be adjusted so that it is compatible with ambient light. The brightness of this data image should never be so great that it inhibits the driver's view of the road, but it must be bright enough to be visible in all ambient lighting conditions. Fortunately, the CRT brightness can be automatically controlled by electronic circuits to accommodate a wide range of light levels.

Figure 11.15
Heads Up Display



PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Speech Synthesis

Speech synthesizers use phoneme synthesis, a method of imitating the basic sounds used to build speech. Computers rely on an inventory of phonemes to build the words for various automotive warning messages.

One really exciting new display device, information provided by synthesized speech, has great potential for future automotive electronic instrumentation. Important safety or trip-related messages could be given audibly so the driver doesn't have to look away from the road. In addition to its normal function of generating visual display outputs, the computer generates an electrical waveform that is approximately the same as a human voice speaking the appropriate message. The voice quality of some types of speech synthesis is often quite natural and similar to human speech.

The speech synthesis considered here must be distinguished from production voice message systems that have already appeared in production cars. In these latter systems only "canned," or preplanned, messages have been available. In the true speech synthesis system, relatively complex messages can be generated in response to outputs from various electronic subsystems. For example, the trip computer could give fuel status in relationship to the car's present position and known fueling stations (both of the latter being available from the navigation system). By combining information from several subsystems on board the car it is possible to inform the driver of trip status at any preprogrammed level of detail.

There are several major categories of speech synthesis that have been studied experimentally. Of these, phoneme synthesis is probably the most sophisticated. A *phoneme* is a basic sound that is used to build speech. By having an inventory of these sounds in computer memory and by having the capability to generate each phoneme sound, virtually any word can be constructed by the computer in a manner similar to the way the human voice does. Of course, the electrical signal produced by the computer is converted to sound by a loudspeaker.

Synthesized speech is being used to automatically provide data over the phone from computer-based systems and is available on some production cars.

MULTIPLEXING IN AUTOMOBILES

One of the high-cost items in building and servicing vehicles is the electrical wiring. Wires of varying length and diameter form the interconnection link between each electrical or electronic component in the vehicle. Virtually the entire electrical wiring for a car is in the form of a complex, expensive cable assembly called a *harness*. Building and installing the harness requires manual assembly and is time consuming. The increased use of electrical and electronic devices has significantly increased the number of wires in the harness.

Sensor Multiplexing

The use of microprocessors for computer engine control, instrumentation computers, etc., offers the possibility of significantly reducing the complexity of the harness. For example, consider the engine control system. In the present configuration, each sensor and actuator has a separate wire connection to the

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

CPU. However, each sensor only communicates periodically with the computer for a short time interval during sampling.

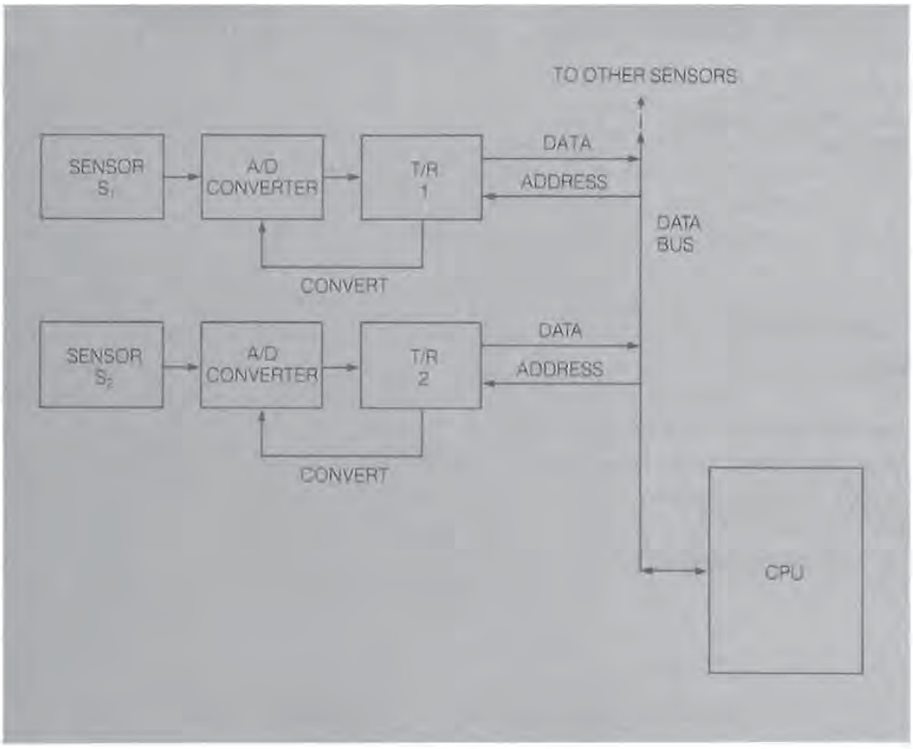
Sensor multiplexing can reduce the necessary wiring in an electrical harness by using time division multiplexing.

It is possible to connect all the sensors to the CPU with only a single wire (with ground return, of course). This wire, which can be called a data bus, provides the communication link between all of the sensors and the CPU. Each sensor would have exclusive use of this bus to send data (i.e., measurement of the associated engine variable or parameter) during its time slot. A separate time slot would be provided for each sensor.

This process of selectively assigning the data bus exclusively to a specific sensor during its time slot is called *time division multiplexing* (or sometimes just multiplexing—MUX). Recall that multiplexing was discussed as a data selector for the CPU input and output in a digital instrumentation system as described in Chapter 9. Limited use of multiplexing already exists in some production cars, but the concept considered here is for data flow throughout the entire car between all electronic subsystems.

To understand the operation of time division multiplexing of the data bus, refer to the system block diagram in Figure 11.16. The CPU controls the use of the data bus by signaling each sensor through a transmitter/receiver

Figure 11.16 Sensor Multiplexing Block Diagram



PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

(T/R) unit. Whenever the CPU requires data from any sensor, it sends a coded message on the bus, which is connected to all T/R units. However, the message consists of a sequence of binary voltage pulses that are coded for the particular T/R unit. A T/R unit responds only to one particular sequence of pulses, which can be thought of as the address for that unit.

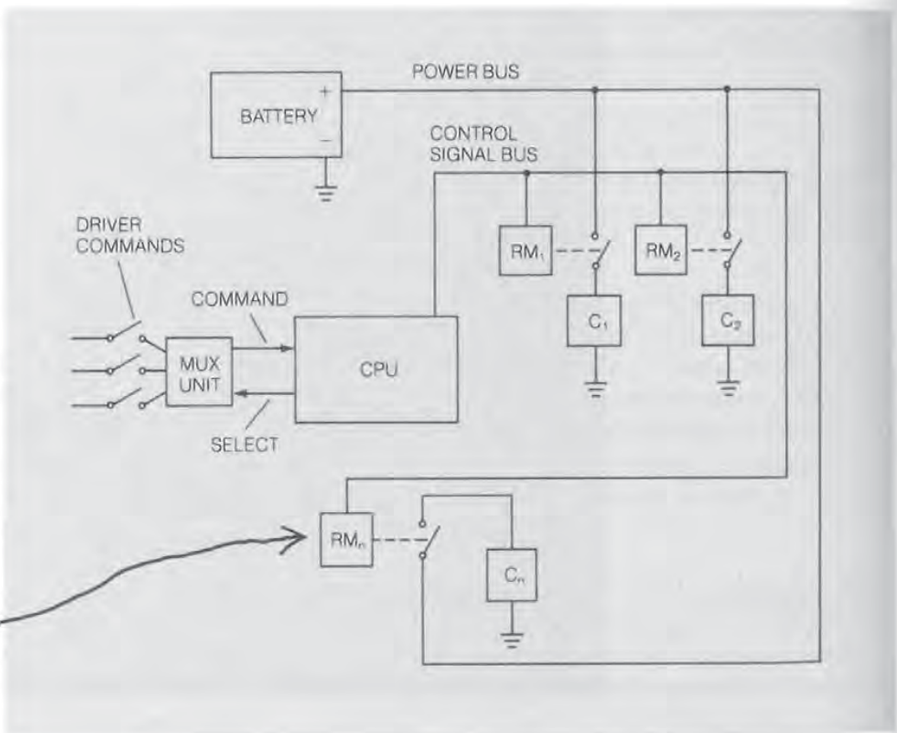
Each sensor in a multiplexing system sends its individual data over a common bus. The computer identifies the sensor by signaling each sensor with a unique address.

Whenever a T/R unit receives data corresponding to its address, it activates an analog-to-digital converter. The sensor's analog output at this instant is converted to a digital binary number as already discussed. This number and the T/R unit's address are included so that the CPU can identify the source of the data. Thus, the CPU interrogates a particular sensor and then receives the measurement data from the sensor on the data bus. The CPU then sends out the address of the next T/R unit whose sensor is to be sampled.

Control Signal Multiplexing

It also is possible to multiplex control signals to control switching of electrical power. Electrical power must be switched to lights, electric motors, solenoids, and other devices. The system for multiplexing electrical power control signals around the vehicle requires two buses—one carrying battery power and one carrying control signals. Figure 11.17 is a block diagram of such

Figure 11.17 Control Signal Multiplexing Block Diagram



Receiver module activates its related component or subsystem.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

a multiplexing system. In a system of this type, a remote switch applies battery power to the component when activated by the receiver module (RM). The receiver module is activated by a command from the CPU that is transmitted along the control signal bus.

A multiplexed system can also control switching of electrical power for lights, motors, and similar devices. Each RM would switch power to the appropriate device in response to a CPU command.

This control signal bus operates very much like the sensor data bus described in the multiplexed engine control system. The particular component to be switched is initially selected by switches operated by the driver. (Of course, these switches can be multiplexed at the input of the CPU.) The CPU sends an RM address as a sequence of binary pulses along the control signal bus. Each receiver module responds only to one particular address. Whenever the CPU is to turn a given component on or off, it transmits the coded address and command to the corresponding RM. When the RM receives its particular code, it operates the corresponding switch, either applying battery power or removing battery power, depending on the command transmitted by the CPU.

Fiber Optics

Signal buses using fiber optics transmit data and control signals in the form of light pulses along thin fiber "wires." Such systems are relatively immune from noise interference.

It is possible, maybe even desirable, to use an optical fiber for the signal bus. For such a system, the address voltage pulses from the CPU are converted to corresponding pulses of light that are transmitted over an optical fiber. An *optical fiber,* which is also known as a *light pipe,* consists of a thin transparent cylinder of light-conducting glass about the size of a human hair. Light will follow the light pipe along its entire path, even around corners, just as electricity follows the path of wire. A big advantage of the optical fiber signal bus for automotive use is that external electrical noise doesn't interfere with the transmitted signal. The high-voltage pulses in the ignition circuit, which are a major potential source of interference in automotive electronic systems, will not affect the signals traveling on the optical signal bus.

For such a system, each component has an RM that has an optical detector coupled to the signal bus. Each detector receives the light pulses that are sent along the bus. Whenever the correct sequence (i.e., address) is received at the RM, the corresponding switch is either closed or opened.

A variety of multiplexing systems have been experimentally studied. It seems very likely that one form or another of multiplexing system will be used in the near future whenever the cost of such a system becomes less than that of the harness that it is to replace. It is possible that the move to multiplexing will occur in stages. For example, one experimental system incorporates a multiplexing system for switches located in the door only.

NAVIGATION

One of the more interesting potential future developments in the application of electronics to automobiles is navigation. Every driver who has

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

taken a trip to an unfamiliar location understands the problem of navigation. The driver must first obtain maps having sufficient detail to locate the destination. Along the trip the driver must be able to identify the car location in relationship to the map and make decisions at various road intersections about the route continuation.

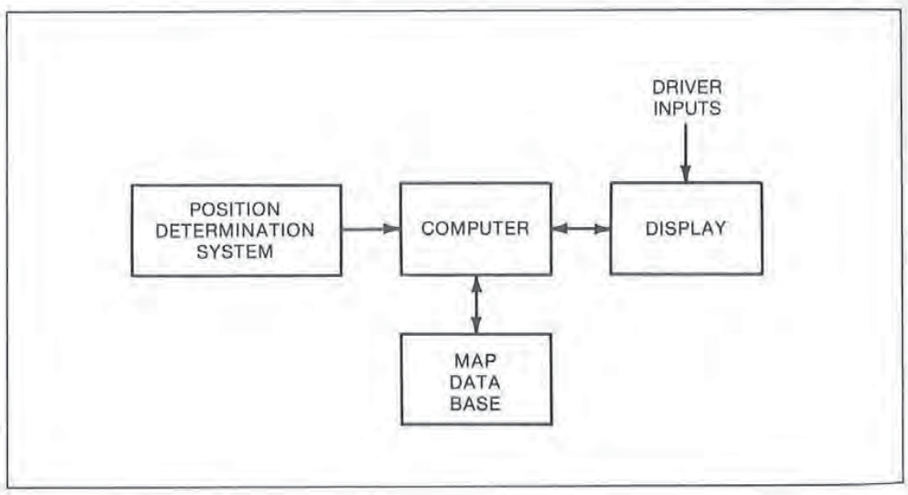
There has been considerable research done into the development of an electronic automatic navigation system, which may someday lead to the widespread commercial sale of such a system. Although stand-alone electronic navigation systems with multiscale electronic maps have been commercially available for some time, these are somewhat less complex than the concept considered here. The present concept assumes a multisensor system that optimally integrates position and car motion data from the various sensors to obtain the best possible estimate of present position.

Figure 11.18 is a block diagram showing the major components of a generic automatic navigation system. The display portion of a research system is typically a CRT. This display depicts one of many maps that are stored in memory.

Ideally, the display device should have the capability of displaying maps with various levels of magnification. As the car approaches its destination, the map detail should increase until the driver can locate his or her position within an accuracy of about half a block.

The map database must be capable of storing sufficient data to construct a map of an entire region. For example, data could be stored on floppy disks (one for each region of the country) that are read into computer

Figure 11.18 Generic Automatic Navigation System



PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

RAM as desired for a particular trip. Alternatively, a CD (compact disc) player could be used for large-scale data storage. In this case, the CD player would be part of the entertainment system. If the vehicle electronic system is integrated, the CD player can function as a large-scale memory for on-board navigation data.

The computer portion of the generic navigation system obtains signals from various position sensors and calculates the correct vehicle position in relationship to the map coordinates. The computer also controls the map display, accounting for magnification (called for by the driver) and displaying the vehicle position superimposed on the map. The correct vehicle position might, for example, be shown as a flashing bright spot.

Navigation Sensors

The most critical and costly component in the generic navigation system is the position-determining system, that is, the position sensor. Among the concepts presently being considered for automotive navigation are inertial navigation, radio navigation, signpost navigation, and dead reckoning navigation. Each of these has relative advantages in terms of cost and performance.

An inertial navigation sensor has been developed for aircraft navigation, but it is relatively expensive. The aircraft inertial navigation sensor consists of three gyros and accelerometers. Figure 11.19 is a block diagram of a typical navigation system using inertial navigation.

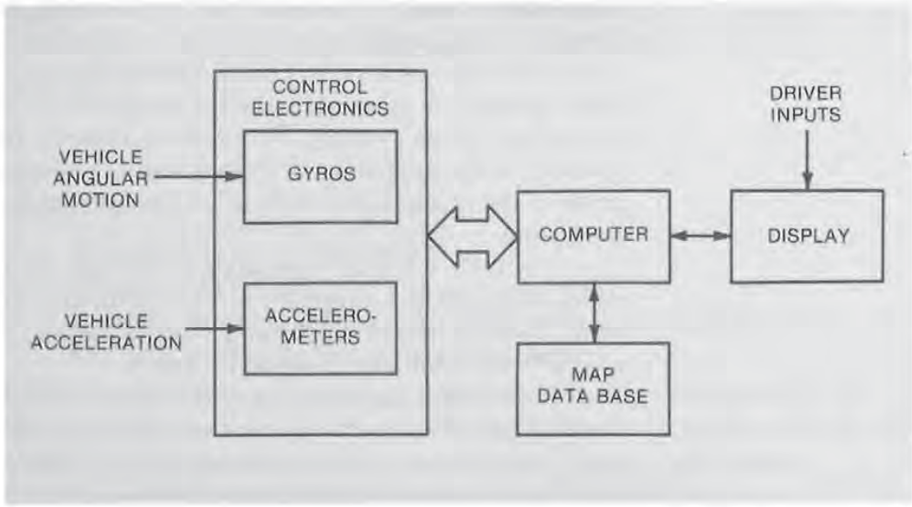


Figure 11.19 Automotive Inertial Navigation System

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

An inertial navigation system locates the vehicle position relative to a known starting point by integrating acceleration twice with respect to time. For example, along the x direction, vehicle position at time t is $x(t)$:

$$x(t) = x_o + \int_o^t \int_o^t a(y)\, dy\, dt$$

where

x_o is the initial x position
a is the acceleration along x direction

A similar integration is performed along the two orthogonal directions.

An inertial navigation system has position errors due to initial gyro alignment errors, uncompensated gyro drift, and accelerometer errors. A typical high-quality commercial navigation system (e.g., Carousel IV) has a position error of about 3000 feet for each hour of flight. Position errors generated at this rate in an automotive environment imply a trip of no more than a half hour before the error exceeds the half-block limit. This error, in combination with the system's relatively high cost (about $120,000), renders the inertial navigation system unfeasible for automotive use for the foreseeable future. On the other hand, updated measurement of a car's present position can be obtained using radio navigation sensors.

Radio Navigation

A radio-based automotive navigation system uses either land- or satellite-based transmitters and automotive receivers for position location. Land-based transmitter systems that are potentially applicable include Decca, Loran-C, VOR, and Omega. The only satellite-based system that is potentially applicable is the Global Positioning System (GPS). The land-based systems are primarily intended for aircraft or ship navigation and have somewhat limited coverage. For example, Loran-C has no coverage for large portions of the southwestern United States. Nevertheless, research is being done on the applicability of these land-based systems to automotive navigation.

The GPS, when fully operational, will have 24 orbiting satellites, of which there will be a minimum of four within line of sight of any location on earth. This is sufficient for position location. Figure 11.20 is a block diagram of a GPS-based automotive navigation system.

In final operational service, there will be two classes of user service available for GPS: the Precise Positioning Service (PPS), which is available only to the military, and the Standard Position Service (SPS), which is available for automotive navigation. Each satellite transmits clock pulses that

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

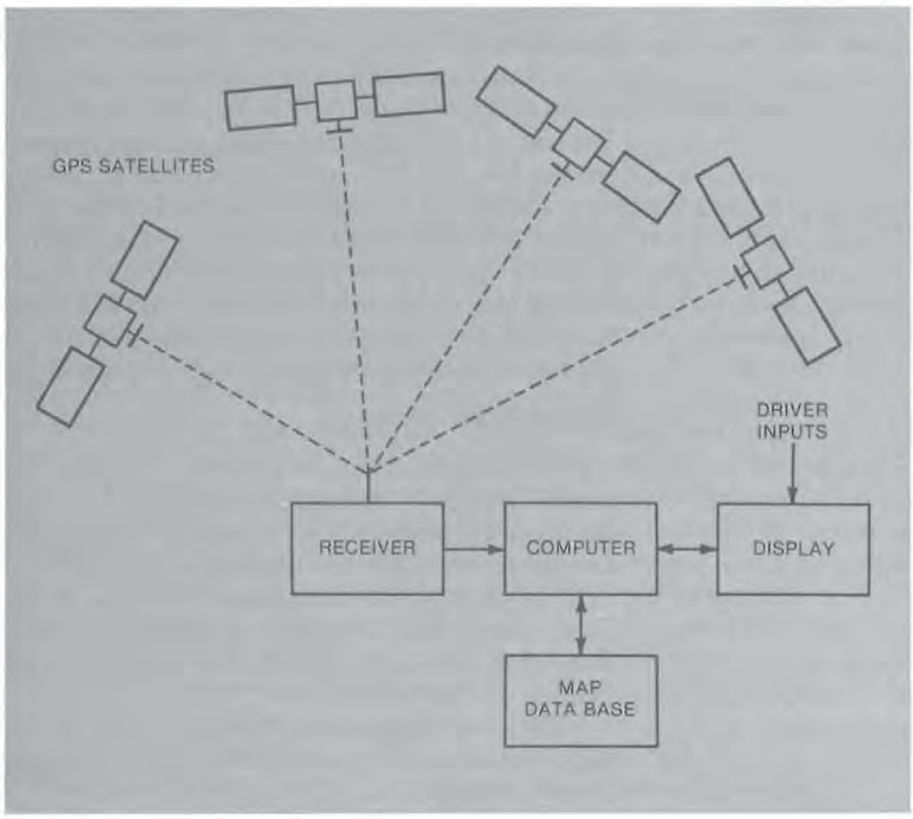


Figure 11.20 Automotive GPS Navigation System

give the time of transmission. The distance to any satellite is known by the relationship

$$R_i = c(t_i - t_t)$$

where

R_i is the distance to any satellite
c is the speed of light
t_i is the time that the clock pulse is transmitted from satellite to car
t_r is the time that the car receives the pulses

The measurement of the propagation time from satellite to receiver $(t_i - t_r)$ requires highly accurate (and expensive) clocks in both the satellite and the car. Position is determined (in three dimensions and time) by solving four equations involving the range to four satellites. In GPS service, an accuracy of

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

100 meters is quoted. In experiments, absolute accuracies of 30 meters have been achieved.

There are a number of problems associated with GPS-based navigation systems, including cost, time to fix position, and propagation considerations. The cost of a GPS receiver is determined partly by its precise clock. However, produced in sufficient quantities, the receiver cost could be brought into a commercially viable range. The time to fix initial position is on the order of two to three minutes, which is inconvenient but possibly acceptable. Once initial position is fixed, updated position is available in about two-second intervals. In addition, it is necessary to maintain a direct line of sight. This can be a problem in areas of tall buildings or in mountainous terrain. Nevertheless, GPS is potentially viable for future automotive navigation and has many advocates.

Signpost Navigation

In signpost navigation, a number of information stations (signposts) are located throughout the road network. In one scheme, the signpost continuously transmits data concerning its geographic location. The on-board navigation system converts this data to map coordinates, which are displayed.

Figure 11.21 is a block diagram of a typical signpost navigation system. This system requires an augmented database to convert the transmitted data to map coordinates. This system has the capability to provide position to an accuracy of a few meters.

There are drawbacks to the signpost system, however, including an inability to determine position between signposts, inability to show a turn until

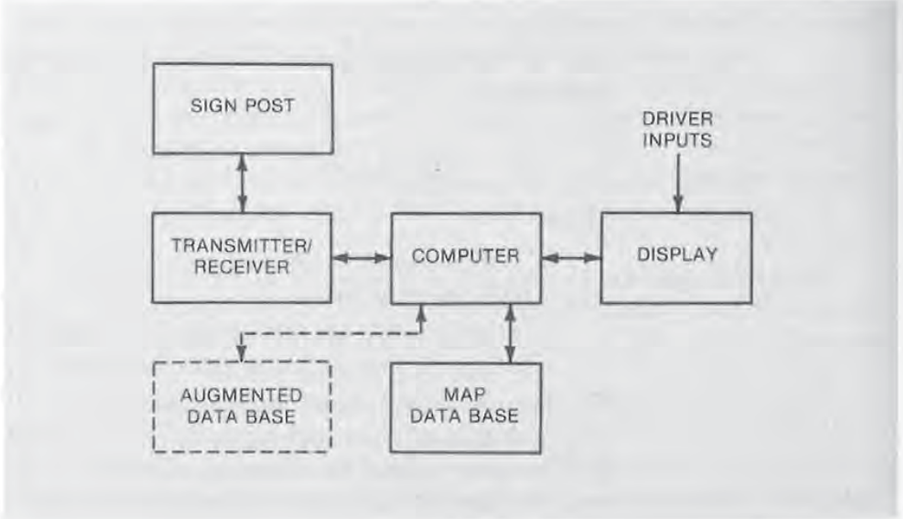


Figure 11.21 Signpost Navigation System

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

the next signpost is reached, the need for signposts at every intersection, and the requirement for a large number of codes. Thus, in spite of the high accuracy of this system, it inherently requires a huge investment in infrastructure.

Dead Reckoning Navigation

Dead reckoning navigation is a method of determining present position from a known earlier position and information about vehicle motion. Figure 11.22 is a block diagram for such a system. The sensor components of this system include a heading sensor and a wheel speed sensor. Navigation systems of this type have been commercially available for some time. However, integration of this dead reckoning navigation system into a multisensor navigation system has not been available (the combined system being potentially a future electronic feature). The use of heading and speed information is illustrated in Figure 11.23. Experimental systems have used a form of magnetic compass, known as a flux gate, to measure heading. Wheel speed sensors have already been explained in Chapter 8. Although this system is conceptually simple, it suffers from poor accuracy. It is estimated that a position error of about half a block would accrue for trips of less than six miles.

Typically, an electronic dead reckoning system employs a CRT (see Chapter 9) as a display device for presenting a map of the relevant geographic region. In at least one commercial system (ETAK), there are eight different levels of resolution. The maps are generated from digital data that is stored on a magnetic tape cassette. A compact disk read-only memory data storage (CD-ROM) is also suitable for map data storage. Using the stored data, the

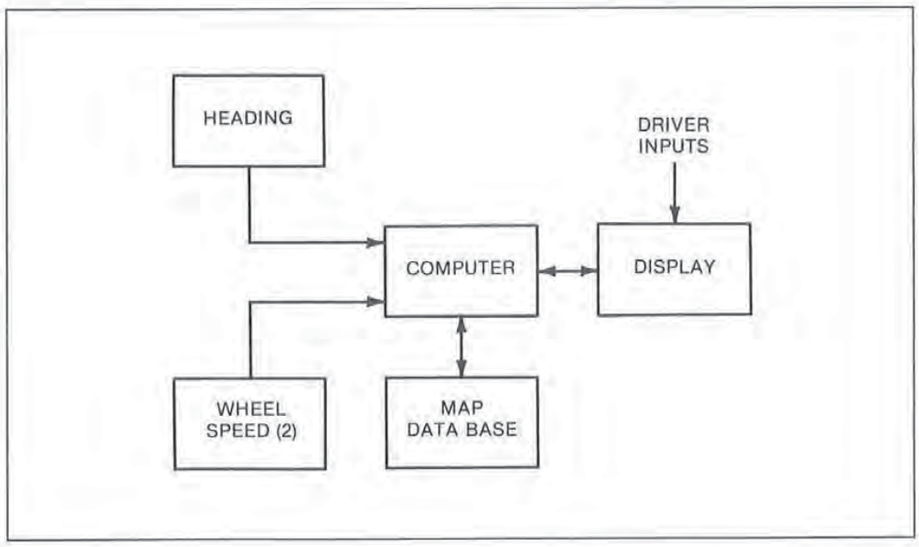


Figure 11.22 Dead Reckoning Navigation System

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

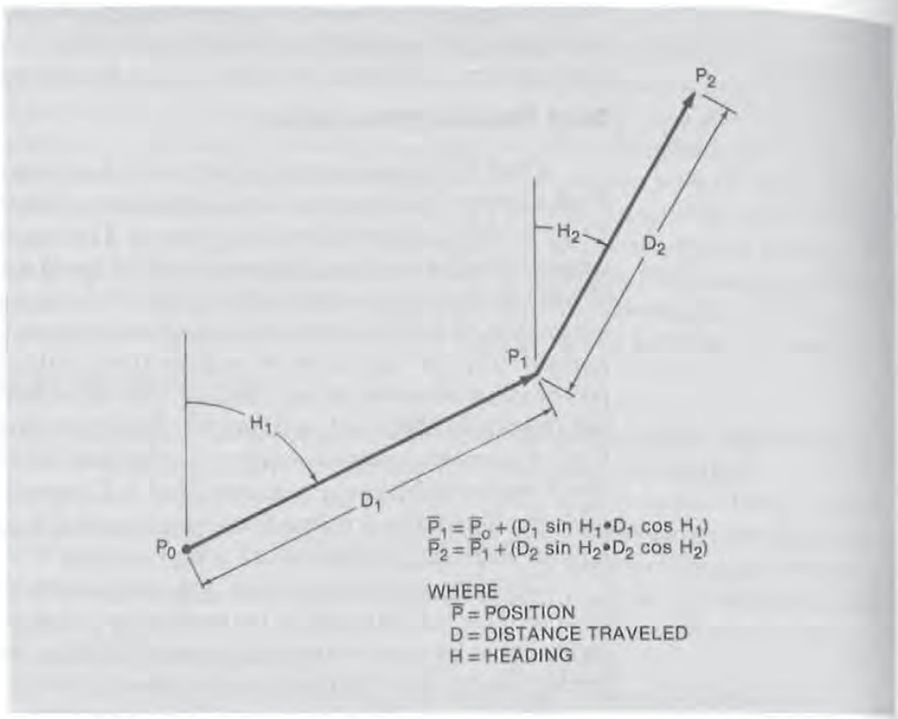


Figure 11.23 Dead Reckoning Navigation Computation

electronic map is displayed on the CRT, identifying the present position of the car as well as its destination. Using the present position (P_o of Figure 11.23), the new position (P_1) is calculated.

Errors occur in any dead reckoning navigation system after a time. However, in automotive navigation systems, such errors can be readily bounded. It is presumed that the car is on a road (or in a driveway or parking lot) at all times. The coordinates of the road are known as part of the navigation database. Wherever the estimated position (P_1) is off the road, the computer adjusts the car position to the nearest point on the road. This correction procedure is known as *map matching* and results in extremely accurate navigation.

FUTURE TECHNOLOGY

A potential area for future technological development is an extension of the radar collision-avoidance scheme. In at least one proposed configuration, the areas behind and on either side of the vehicle are scanned by a combination of laser radar and ultrasonic sensing system. The data from these sensors will be analyzed by a computer running some very sophisticated algorithms. The purpose of these systems is to warn drivers of a potential

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

collision with approaching vehicles (e.g., before lane changes are made). Warnings to the driver can be made by synthesized voice or visual HUD display.

Still another potential technical development in automotive electronics involves the application of artificial intelligence to voice recognition. In such a system the driver can activate electronic functions by simply speaking to the car. A microphone will pick up his speech, recognize what is spoken, and take action accordingly. Such a system has the advantage that the driver can enter commands or data without looking away from the road while keeping both hands safely on the steering wheel.

Another interesting technical development that is likely to occur in the future involves the use of electronically controlled window transparency. Using advanced electrochromic material it is possible to reduce window transparency on very bright sunny days or to increase transparency on darker days. This has the advantage of reducing glare and improving the heat load on the air conditioning system within the vehicle.

OFFICE ON WHEELS

The development of cellular telephones for cars has greatly expanded the ability to conduct business on the road. Not only is it possible to conduct ordinary phone conversations while driving, but it is also now possible to exchange information from home offices to the automobile via the cellular phone. Since its introduction in 1984, the sale of cellular phones has increased dramatically, with the total in service at roughly 4 million in mid-1991, and has continued to expand exponentially since then.

A cellular phone is linked via radio to a two-way (duplex) fixed station servicing a specific geographic region, or cell. The radio link carrier frequency is sufficiently high that coverage for any cell is limited to the line of sight for the fixed station antenna.

At the present time, cellular service is available within urban areas and along high traffic interstate roads. As the car moves across the boundary of a cell into another cell, a computer selects the particular cell for best coverage at each location. Any cellular phone within a given cell can be connected to any phone in the world using services of the cellular phone utility that operates that cell and all fixed telephone utilities in the world.

Virtually any information service that is available in a fixed office through telephones is now available in a car via the cellular phone. These extraordinary capabilities have led to the term *office on wheels* for cars that are so equipped. For example, a facsimile machine is readily operated through a cellular phone link to any other facsimile machine.

In addition to facsimile machines, the office on wheels can readily accommodate an answering machine and a portable computer with printer and, of course e-mail. Clearly, the driver cannot simultaneously operate a

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

computer and drive a car. However, a rear-seat installation of a computer, which is perhaps coupled via modem and the cellular phone to other computers, is technically feasible now. In one configuration the computer, answering machine, and facsimile are standard office devices that receive power through a special adapter via the cigarette lighter.

Integration of the office into the vehicle electronics is also possible. For example, we have already shown in Chapter 9 that a CRT is available in certain car models. This CRT can play several roles as a display device. In addition to its original application, it serves as input/output for heating/cooling and entertainment systems. It can serve as the display device for an electronic navigation system. It can also be converted to serve as the monitor for an automotive computer. Of course, a keyboard assembly is also required along with the main computer structure as a feature of the office on wheels automobile.

It can be anticipated that the computer would only be operable when the transmission selector is in Park. This feature provides assurance that the car is not actually on the road when in computer mode. A printer could also be provided for receiving hard copy of the computer output.

The applications of such an automotive built-in computer are many. For example, a salesman could transmit orders directly from the field to headquarters. Alternatively, contract modifications could be made and transmitted to a remote site instantaneously. The extension of these ideas to an office on wheels is limited only by the ingenuity of the users of such a system.

Voice Recognition Cell Phone Dialing

As beneficial as cellular phone systems are, they do have a potential safety disadvantage. For most people, dialing a number on a cell phone requires looking at the key pad while entering the digits. If the car is moving (and particularly if it is moving in heavy traffic), the momentary distraction of dialing the phone can potentially divert the driver's attention and an accident can occur.

A scheme for dialing the phone without diverting the driver's attention from driving involves speech recognition technology. There are already cell phones available that can accept verbal dialing such that the driver simply speaks the telephone number to be dialed. When the connection is made the phone conversation can be completed without the driver having to physically hold the phone to his or her ear and mouth.

However, the majority of such hands-free cell phones can recognize only one or two individual's voices. Normally such a system is trained to recognize the individual speakers. In the future it is likely that cell phone systems will be available that can recognize essentially any speaker. Using such systems, phone conversations can be completed without the driver ever having to divert his or her attention from the road.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

ADVANCED DRIVER INFORMATION SYSTEM

One of the areas having the greatest potential payoff for electronics in automobiles is in the relationship of the car and driver to the road. Improvements in traffic flow in congested areas might be possible if the driver has information concerning traffic problems on the road ahead.

In an attempt to improve traffic flow, particularly on congested routes near large metropolitan areas, a government program has been established that has come to be known as the *intelligent transportation system* (ITS). As of the time of this writing, roughly $1 billion has been invested with cooperative investment from the transportation industry. The general aim of this project has been to improve the safety, efficiency, capacity, and environmental quality of the existing highway transportation system.

The concept involves building an infrastructure supported by on-board vehicle electronics to evaluate traffic flow in an area and to communicate to drivers recommendations for improved routing as well as timely messages concerning traffic tie-ups and safety-related warnings. Included in the required hardware for the system are sensors for measuring existing traffic flow, very large, high-power computers for processing data and for generating the appropriate messages, as well as communications systems and automotive displays.

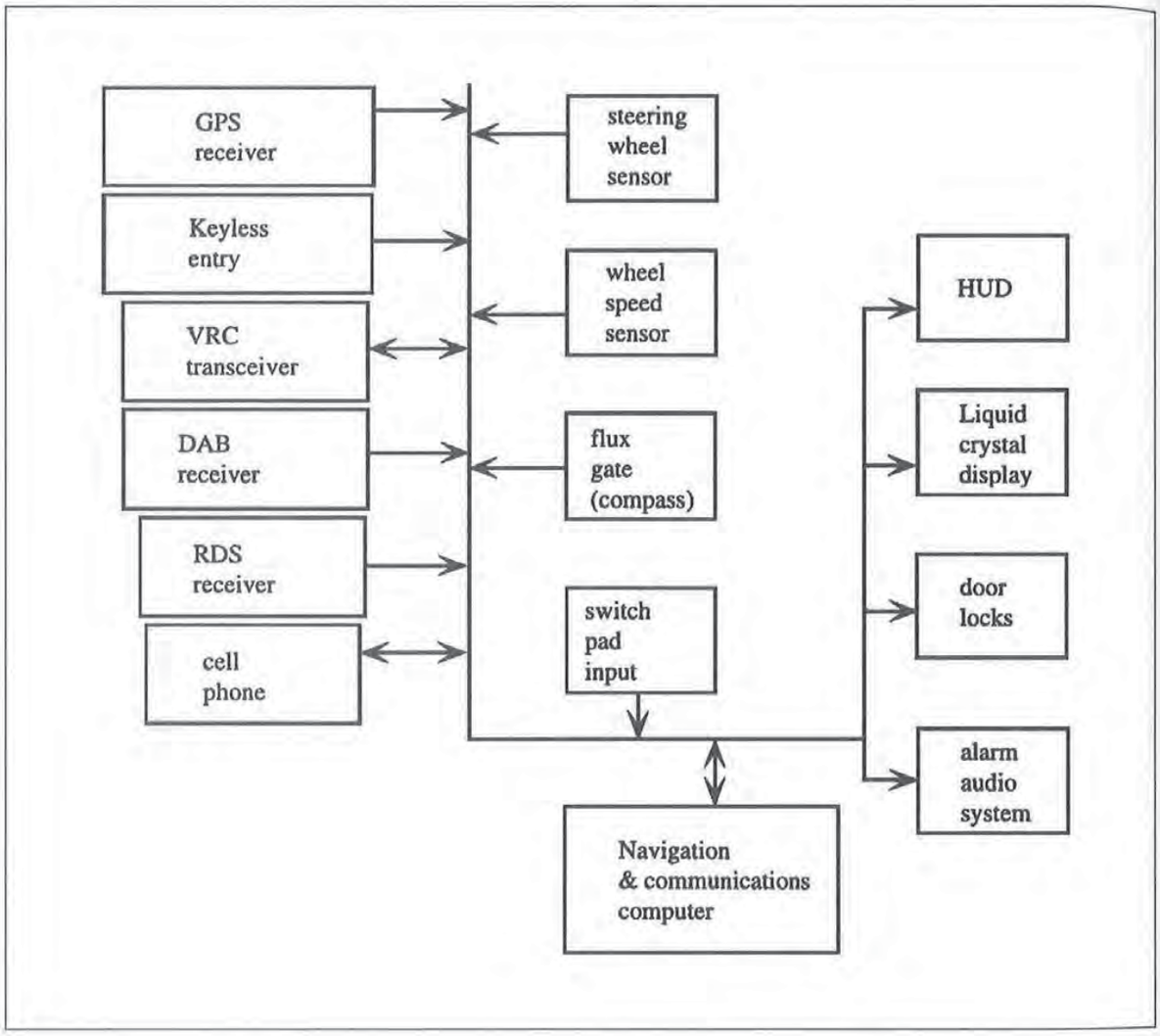
Although the long-term capabilities for ITS are unclear, the short-term application of technology will probably be in the form of an advanced driver information system. One of the most likely candidates is a radio message service system utilizing a portion of the bandwidth allotted to commercial FM radio stations (in the same spectrum used to transmit Muzak). This system requires a special FM receiver equipped with a decoding system. Whenever it is appropriate (e.g., for road emergencies or traffic congestion), a message is transmitted by the FM stations in the area. In one scheme, the radio receiver is automatically retuned to a special frequency on which voice messages are transmitted identifying the problem to the driver.

One very interesting experimental system having great potential for future ITS application is the system called TELEPATH that was developed by Delco. This system serves as an example of an ITS system in that it is representative of features that are likely to be found in future cars, although the exact architecture for any particular vehicle could well be different than the present example.

A block diagram of this system, shown in Figure 11.24, is built around the digital data bus described in Chapter 9. This system supports a number of subsystems, including Global Positioning System (GPS) navigation, a keyless entry, vehicle-to-roadside communication (VRC), a digital audio broadcast (DAB) entertainment system, and a radio data system (RDS) that also serves as a communication link for a differential GPS augmentation data channel and a cellular phone. Other inputs to the navigation and communications computer

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Figure 11.24
The TELEPATH Intelligent Transportation System



include a switch pad for data/command input, a compass, antilock braking, and wheel steering sensors. This system is to have an active matrix liquid crystal display (AMLCD) as well as a heads up display (HUD).

The GPS navigation system has already been discussed. The keyless entry system is in common use today and involves transmission of a digital code via a radio frequency link from a miniature (hand-held) transmitter that is received

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

in the car and decoded. If there is a code match, a signal is sent to the door lock actuator, which can be solenoids or motors.

The vehicle-to-roadside communication (VRC) system provides a means of transmitting messages from a road information system (via radio). The latter requires an infrastructure of low-power transmitters and receivers located adjacent to highways at strategic locations, as well as a message-generating system. The latter can be an internal preprogrammed fixed message (e.g., specific road closure) or it can be a digital data link to a computer-controlled master controller capable of generating variable messages (e.g., warning of congested traffic on a given route at a specific time). The infrastructure can also be used to automatically interrogate passing vehicles via an on-board transponder. The transponder is a special transceiver that receives coded messages from a master controller requesting that certain data be transmitted back to the master. Transponders are commonly used in aircraft to report position and altitude to an air traffic control radar interrogator. In the VRC system, data can be collected from moving vehicles. A form of VRC is in use today for automatic toll collection as well as to read truck weights while the truck is in motion.

The VRC concept includes a transponder on board the vehicle that has an output for relaying messages to the driver. These messages are routed along the data bus to either the HUD display or to an audio warning message system, or both. Message complexity is limited by the system's maximum data rate and by the time interval in which the moving vehicle is within the limited range of the roadside transmitter. The message is repetitively transmitted by the roadside transmitter at intervals sufficient for all passing vehicles to receive the entire message. In an experimental implementation developed by Delco, the data rate is roughly 50 kbits/sec for a 5-second repetition period. Uses of the VRC system can include roadsign-type information to warn drivers of hazardous road conditions, speed limit changes (e.g., for work crews), services available, weighing of commercial vehicles while in motion, and, as indicated above, toll collections from vehicles traveling at highway speed without requiring stops at toll collection booths.

The digital audio broadcast system (DBS) is a radio broadcast entertainment system that has the potential to achieve CD-quality audio and reliable data services over a broadcast radio channel. The nonaudio message should have a capacity of the order of 10 kbits/sec. An experimental system has been tested that operates with a carrier frequency of 1.5 GHz and uses a form of phase-shift keying modulation.

The radio data system (RDS) utilizes an auxiliary channel (subcarrier) on a commercial FM radio signal. A special receiver is required to obtain the data from the auxiliary data channel. Uses of RDS include paging, traffic congestion messages, and warnings of hazardous conditions (rock slides, icy bridges, etc.). An interesting potential use for RDS is to relay corrections to GPS signals appropriate for a local receiving area. These corrections provide greatly

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

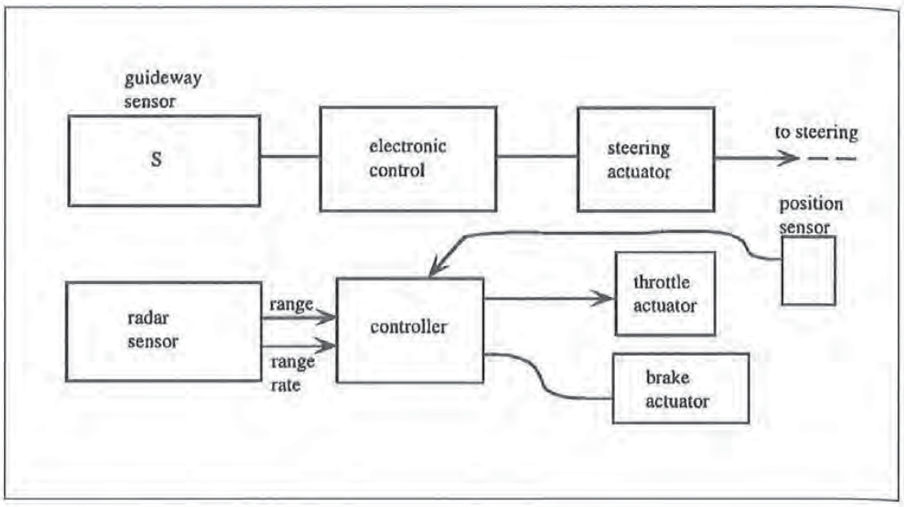


Figure 11.25
Automatic Driving Control System

improved accuracy (reducing errors from about 100 meters to less than about 5 meters). The corrected GPS is known as differential GPS, or DGPS.

The technology for such service exists today. Implementation requires only the infrastructure for sending emergency messages. Advanced forms of such a service are in the experimental stages of development now and can be implemented as soon as this infrastructure exists. These extensions include providing alternate route suggestions to drivers to help them avoid serious traffic delays. The further extensions of such a service are limited only by the system infrastructure and have great potential for easing traffic flow problems.

AUTOMATIC DRIVING CONTROL

Another rather interesting (but probably pretty far in the future) technology is the vehicle guideway system. This is a purely experimental system at the time of this writing that is envisaged as an automatic driving system. The concept involves automatic steering and automatic vehicle speed control. The concept leads to a system of multiple-vehicle automatic driving called *platooning*. In a platooning system a group of cars is automatically controlled to maintain a set highway cruise speed with a fixed nominal intercar spacing.

Steering control is via a signal radiated from a wire buried in the center of the roadway. Distances between cars and vehicle speeds are maintained with the aid of measurements made by an on-board radar system.

A simplified block diagram for automatic control is shown in Figure 11.25. In this figure, a sensor (S) is located on the bottom front of the car that picks up the signal radiated by the buried wire. This sensor signal is the input to

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

a tracking controller that outputs a control signal to a steering actuator. Steering commands guide the vehicle to maintain the sensor over the guideway wire.

Vehicle speed control is accomplished using an on-board radar sensor. This sensor is located in front of the vehicle and directs a narrow radar beam forward. The radar sensor system obtains a measurement of the range to a car in front of the given car as well as the rate of change of that range. The sensor can also measure vehicle ground speed via Doppler shift of radar signals reflected from the ground.

The control system is a multiple-input/multiple-output controller that generates control signals for a throttle actuator and a braking actuator. Normally the controller will only activate the throttle; however, if the range to the vehicle is decreasing even with a closed throttle, then braking is required. The braking actuator pressurizes the brake lines automatically to slow the vehicle as required. This action could occur if the platoon of cars were driving down a long, relatively steep mountain or slope. It could also be required if an obstacle were encountered that was stationary (as in the case of a car with a breakdown). Panic-stop braking could actually be required in extreme cases.

Whenever manual control is required (e.g., when a given vehicle exits the highway in order to reach a given destination), the driver takes control by operating a control release switch.

There are many variations on the concept described above. Some will prove to be feasible; others will not. At this time the automatic vehicle guideway is an interesting experimental system with great potential for maintaining optimum traffic flow on otherwise busy or congested highways.

It should be emphasized that many of the topics included in this final chapter have an uncertain future in terms of production automobiles. Each idea discussed here has had at least an experimental confirmation of its technical feasibility. However, the final arbiter of the viability of each subsystem will be the automobile consumer, who will vote with his or her dollars on whether any given subsystem or feature is worth the incremental purchase price.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Quiz for Chapter 11

1. Engine performance may be improved in the future by
   a. tuning the intake manifold
   b. use of variable compression ratio
   c. variable valve timing
   d. all of the above
2. One potential engine control strategy based on a feedback signal from cylinder pressure may incorporate
   a. a piezoelectric cylinder pressure sensor
   b. a new MAP sensor
   c. an exhaust air/fuel sensor
   d. none of the above
3. An airbag is
   a. a mechanism for occupant protection in a car
   b. a container for use in case of airsickness
   c. an impact sensor
   d. all of the above
4. One concept for automotive collision avoidance involves
   a. braking rapidly in dangerous situations
   b. measuring the round-trip time of a radar pulse from protected car to collision object
   c. aircraft surveillance of highways
   d. wheel speed sensors
5. Doppler shift has potential automotive application for
   a. measuring the speed of passing trains
   b. automatic gear changing
   c. measuring vehicle speed over the road
   d. none of the above
6. The major problem associated with a practical low tire pressure sensor is
   a. developing a means of getting the electrical signal from the rotating sensor to the car body
   b. developing a sensor that can measure relative pressure
   c. absolute pressure calibration
   d. measuring tire pressure when the vehicle is stopped
7. A CRT has potential automotive application for
   a. controlling vehicle motion
   b. recording vehicle transient motion
   c. monitoring entertainment systems
   d. displaying information to the driver
8. The term HUD refers to
   a. housing and urban development
   b. heads up display
   c. heads up driver
   d. none of the above

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

9. Speech synthesis is
   - **a.** a system that automatically recognizes human speech
   - **b.** an automatic checkbook balancing system
   - **c.** a visual display of speech waveforms
   - **d.** a means of electronically generating human speech

10. An optical fiber is
    - **a.** a tiny beam of light
    - **b.** an optical waveguide that is often called a light pipe
    - **c.** an optical switch
    - **d.** none of the above

11. An inertial navigation system incorporates the following sensors
    - **a.** radio receivers
    - **b.** Doppler radar
    - **c.** gyros and accelerometers
    - **d.** none of the above

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565



PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Glossary

A/F: *See* Air/Fuel Ratio.
Accumulator: The basic work register of a computer.
Actuator: A device which performs an action in response to an electrical signal.
A/D (also ADC): Analog-to-digital converter; a device which is proportional to the analog voltage level input.
Analog Circuits: Electronic circuits which amplify, reduce, or otherwise alter a voltage signal which is a smooth or continuous copy of some physical quantity.
Assembly Language: An abbreviated computer language which humans can use to program computers. Assembly language eventually is converted to machine language so that a computer can understand it.
BDC: Bottom dead center; the extreme lowest position of the piston during its stroke.
Bit: A binary digit; the smallest piece of data a computer can manipulate.
Block Diagram: A system diagram which shows all of the major parts and their interconnections.
BSCO: Brake specific fuel consumption; the ratio of the rate at which fuel is flowing into an engine to the brake horsepower being generated.
BSHC: Brake specific HC; the ratio of the rate at which hydrocarbons leave the exhaust pipe to the brake horsepower.
BSNO$_x$: Brake specific NO$_x$; the ratio of the rate at which oxides of nitrogen leave the exhaust pipe to the brake horsepower.
Byte: 8 bits dealt with together.
CAFE: Corporate-Average-Fuel-Economy. The government mandated fuel economy which is averaged over the production for a year for any given manufacturer.
Capacitor: An electronic device which stores charge.
Catalytic Converter: A device which enhances certain chemical reactions which help to reduce the levels of undesirable exhaust gases.
Closed-Loop Fuel Control: A mode where input air/fuel ratio is controlled by metering the fuel response to the rich-lean indications from an exhaust gas oxygen sensor.
CO: Carbon monoxide; an undesirable chemical combustion product due to imperfect combustion.
Combinational Logic: Logic circuits whose outputs depend only on the present logic inputs
Combustion: The burning of the fuel-air mixture in the cylinder.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Comparator, Analog: An electronic device which compares the voltages applied to its inputs.
Compression Ratio: The ratio of the cylinder volume at BDC to the volume at TDC.
Control Variable: The plant inputs and outputs which a control system manipulates and measures to properly control it.
Conversion Efficiency (Catalytic Converter): The efficiency with which undesirable exhaust gases are reduced to acceptable levels or are converted to desirable gases.
CPU: Central processing unit; the calculator portion of a computer.
Cutoff: A transistor operating mode where very little current flows between the collector and emitter.
D/A (also DAC): Digital-to-analog converter; a device which produces a voltage which is proportional to the digit input number.
Damping Coefficient: A parameter which affects a system's time response by making it more or less sluggish.
DEMUX: Demultiplexer; a type of electronic switch uses to select one of several output lines.
Diesel: A class of internal combustion engine in which combustion is initiated by the high temperature of the compressed air in the cylinder rather than an electrical spark.
Digital Circuits: Electronic circuits whose outputs can change only at specific instances and between a limited number of different voltages.
Diode: A semiconductor device which acts like a current check valve.
Display: Advice which indicates in human readable form the result of measurement of some variable.
Drive Train: The combination of mechanisms connecting the engine to the driving wheels including transmission, driveshaft, and differential.
Dwell: The time that current flows through the primary circuit of the ignition coil for each spark generation.
Dynamometer: A device for loading the engine and measuring engine performance.
EGO: Exhaust gas oxygen; the concentration of oxygen in the exhaust of an engine. An EGO sensor is used in closed-loop fuel control systems to indicate rich or lean A/F.
EGR: Exhaust gas recirculation; a procedure in which a portion of exhaust is introduced into the intake of an engine.
Electronic Carburetor: A fuel metering actuator in which the air/fuel ratio is controlled by continual variations of the metering rod position in response to an electronic control signal.
Engine Calibration: The values for air/fuel, spark advance, and EGR at any operating condition.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Engine Crankshaft Position: The angular position of the crankshaft relative to a reference point.
Engine Mapping: A procedure of experimentally determining the performance of an engine at selected operating points and recording the results.
Equivalence Ratio: Actual air/fuel ratio divided by the air/fuel ratio at stoichiometry.
Evaporative Emissions: Evaporated fuel from the carburetor or fuel system which mixes with the surrounding air.
Foot-Pound: A unit of torque corresponding to a force of one pound acting on a one foot level arm.
Frequency Response: A graph of a system's response to different frequency input signals.
Gain: The ratio of a system's output magnitude to its input magnitude.
HC: Hydrocarbon chemicals, such as gasoline, formed by the union of carbon and hydrogen.
Ignition Timing: The time of occurrence of ignition measured in degrees of crankshaft rotation relative to TDC.
Inductor: A magnetic device which stores energy in a magnetic field produced by current flowing in it.
Instrumentation: Apparatus (often electronic) which is used for measurement or control, and for display of measurements or conditions.
Integral Amplifier: A control system component whose voltage output changes at a rate proportional to its input voltage.
Integrated Circuit: A semiconductor device which contains many circuit functions on a single chip.
Interrupts: An efficient method of quickly requesting a computer's attention to a particular external event.
Lead Term: A control system component which anticipates future inputs based on the current signal trend.
Limit Cycle: A mode of control system operation in which the controlled variable cycles between extreme limits with the average near the desired value.
Linear Region: A transistor operating mode where the collector current is proportional to the base current.
Logic Circuits: Digital electronic circuits which perform logical operations such as NOT, AND, OR, and combinations of these.
Lookup Table: A table in the computer memory which is used to convert an important value into a related value from the table.
MAP: Manifold absolute pressure; the absolute pressure in the intake manifold of an engine.
Mathematical Model: A mathematical equation which can be used to numerically compute a system's response to a particular input.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Microcomputer: A small computer which uses an integrated circuit which contains a central processing unit and other control electronics.
MUX: Multiplexer; a type of electronic switch used to select one of several input lines.
NO_x :The various oxides of nitrogen.
Op Code: A number which a computer recognizes as an instruction.
Open-Loop Fuel Control: A mode where engine input air/fuel ratio is controlled by measuring the mass of input air and adding the proper mass of fuel to obtain a 14.7 to 1 ratio.
Operational Amplifier: A standard analog building block with two inputs, one output, and a very high voltage gain.
Optimal Damping: The damping which produces the very best time response.
Peripheral: An external input-output device which is connected to a computer.
Phase Shift: A measure of the delay in degrees between the time a signal enters a system and the time it shows up at the output as a fraction of a full cycle of 360°.
Plant: A system which is to be controlled.
Proportional Amplifier: A control system component which produces a control output proportional to its input.
Qualitative Analysis: A study which reveals how a system works.
Quantitative Analysis: A study which determines how well a system performs.
RAM: Random access memory; read/write memory.
Random Error: A measurement error which is neither predictable nor correctable, but has some statistical nature to it.
ROM: Read only memory; permanent memory used to store permanent programs.
RPM: Revolutions per minute; the angular speed of rotation of the crankshaft of an engine or other rotating shaft.
Sample and Hold: The act of measuring a voltage at a particular time and storing that voltage until a new sample is taken.
Sampling: The act of periodically collecting or providing information about a particular process.
Semiconductor: A material which is neither a good conductor nor a good insulator.
Sensor: An energy conversion device which measures some physical quantity and converts it to an electrical quantity.
Sequential Logic: Logic circuits whose output depends on the particular sequence of the input logic signals.
SI Engine: Abbreviation for spark-ignited, gasoline-fueled, piston-type, internal-combustion engine.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Signal Processing: The alteration of an electrical signal by electronic circuitry; used to reduce the effects of systematic and random errors.
Skid: A condition in which the tires are sliding over the road surface rather thin rolling; usually associated with braking.
Slip: The ratio of the angular speed of the driving element to the angular speed of the driven element of a torque converter; also, the condition in which a driven tire loses traction so that the driving torque does not produce vehicle motion.
Software: The computer program instructions used to tell a computer what to do.
Spark Advance: The number of degrees of crankshaft rotation before TDC where the spark plug is fired. (*See* ignition timing.)
Spark Timing: The process of firing the spark plugs at the proper moment to ignite the combustible mixture in the engine cylinders.
Stoichiometry: The air/fuel ratio for perfect combustion; it enables exactly all of the fuel to burn using exactly all of the oxygen in the air.
System: A collection of interacting parts.
Systematic Error: A measurement error in instrumentation system which is predictable and correctable.
TBFI: Throttle-body-fuel-injector; a fuel metering actuator in which the air/fuel ratio is controlled by injecting precisely controlled spurts of fuel into the air stream entering the intake manifold.
TDC: Top dead center; the extreme highest point of the piston during its stroke.
Throttle Angle: The angle between the throttle plate and a reference line; engine speed increases as the angle increases.
Torque Converter: A form of fluid coupling used in an automatic transmission which acts like a torque amplifier.
Torque: The twisting force of the crankshaft or other driving shaft.
Transfer Function: A mathematical equation which, when graphed, produces a system's frequency response plot.
Transistor: An active semiconductor device which operates like a current valve.
Transport Delay: The time required for a given miss of fuel and air to travel from the intake manifold through the engine to the EGO sensor in the exhaust manifold.
Volumetric Efficiency: The pumping efficiency of the engine as air is drawn into the cylinders.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565



Index

A

absolute atmospheric pressure sensors, 194
acceleration enrichment, 235-237
accelerator, 153, 206, 261
accelerometers, 291, 362-363
accumulator (A) register, 106, 110, 119-125, 409
active matrix liquid crystal display (AMLCD), 402
active region, transistor, 75, 81
active suspension system, 285-286
actuators, 30, 32, 34, 52, 58, 60, 155, 215-220, 261, 368, 405, 409. *See also* fuel injection; throttle actuator
  abnormal responses, 252
  automotive applications of, 187-189
  fuel control, 172-173, 181
  stepper motor, 273-274
  suspension system, 289-290
  vacuum-operated, 274-277
A/D converter. *See* analog-to-digital converter (ADC)
adder circuits, 86-88
address bus (AB), 103, 110, 133, 321
address offset, 112-113
addressing peripherals, 105
air charge, 176
air flow. *See* mass air flow (MAF)
air intake. *See* intake air
air mass, measuring, 176-181
airbags, 360-364
air/fuel ratio, 9, 147, 153-155, 175, 176, 208-209, 227, 229, 253-255, 371. *See also* stoichiometry
  actuators to control, 215
  lean mixture, 161, 171-173, 209, 211, 212, 217, 235, 237, 238, 255, 371
  performance, effect on, 160-161
  rich mixture, 161, 171-173, 209, 211, 212, 217, 226, 235-237
  wide range air/fuel sensors, 372-375
alcohol fuels, 378-379
algorithms, 53-54, 135
amplifiers. *See also* error amplifiers; operational amplifiers
  integral, 271, 276, 411
  transistor, 76-77
analog accelerometers, 362-363
analog circuits, 53, 77, 102, 409
analog computer, 80, 99
analog control systems, 58, 275-276
analog filters, 137
analog instrumentation display, 300-303, 307, 311, 312, 313
analog sensors, 135
analog signals
  digital-to-analog converter (DAC), 127-129, 130, 132
  processing, 54-55
  sampling, 130
analog systems, 32-35
analog-to-digital converter (ADC), 37, 129-130, 135, 207, 300, 307, 309, 311, 328, 409
  interrupts, 132
  polling, 130-131
AND function, 83, 84, 116-125, 274
anode, 72
antilock braking system (ABS), 24, 277-285
arbitration, 338

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

arithmetic and logic unit (ALU), 92-93, 110, 125
assembly language, 118-120, 409
assembly line data link (ALDL), 352
automatic driving control, 404-405
automatic transmission, 19, 379-381

B

bandpass filters, 137
bandwidth, 39-40, 46, 49-52
base pulse width, 231, 234
base-emitter diode, 75
beam, 319-320
before top dead center (BTDC), 17, 161
binary circuits, 80-81
binary counters (BC), 190-192, 269, 274, 311
binary numbering system, 36, 81-83, 107
bits, 83, 86-88, 103, 409
block, engine, 7
block diagrams, 31-32, 409
  digital instrumentation system, 53
boost, steering, 25, 292
boot program, 110-111
bore, piston, 156
bottom dead center (BDC), 9, 156, 409
brakes, 3, 23-24
  antilock braking system, 24, 277-285
  power, 158
  pressure modulator, 281-284
  turnoff, cruise control, 277
brake-specific fuel consumption (BSFC), 159, 160, 161, 409
brake-specific HC (BSHC), 409
brake-specific NOx (BSNOx), 409
braking actuator, 405
braking torque, 281
branches (computer program), 107-108, 111-113
breaker points, 15-16
buffers, 117-118, 126-127
buses (computer), 103-105, 133, 321-322, 391
bypass air, 237
bytes, 103, 409

C

CAFE (corporate average fuel economy), 148, 150, 409
calibration, 155, 160, 410
  conversion, 141
  measurement, 47, 52
  parameters, 163, 223, 224
  set by control system, 164
  shift, 50
  stability, 152
California Air Resources Board (CARB), 351-352
caliper, 23
cams, on distributor shaft, 16
camshaft, 7, 156
  crankshaft angular position, sensing, 196
  measuring position of, 200
camshaft position sensors, 226, 228
capacitors, 15-16, 30, 62, 362, 409
  cruise control systems, 276
  half-wave rectifier circuit, 73
carbon monoxide (CO), 148, 150, 164-166, 169, 227, 234, 237, 250, 409
carburetor, 11, 410
carry circuit, 86
catalytic converter, 155, 164-166, 168, 173, 254. *See also* three-way catalyst (TWC)
  definition, 409
  monitoring, 352

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

cathode, 72
cathode ray tube (CRT), 352, 386-387, 392, 400
cellular telephones, 399-400
central processing unit (CPU), 99-100, 103, 125, 410
  registers, 106-110
  sensors connected to, 389, 391
centrifugal spark advance, 17
chassis, 3
chassis dynamometer, 149-150
"Check Engine" light, 342
clock
  digital, 90
  electronic, 167
  frequencies, 255
  microcomputer, 104
closed-loop control systems, 58, 59-60, 139, 155, 254. *See also* limit-cycle control
  cylinder pressure sensors and, 372
  exhaust gas oxygen sensors, 256-257
  fuel control, 168-175, 170-175, 212, 227, 233-235, 409
  ignition timing, 243-248
  knock sensors, 213-214
  operation, 171-175
  spark advance correction, 250
clutch, torque converter locking, 251-252
collector-base diode, 75
collision avoidance radar warning system, 381-384
collision (LAN), 338
combinational logic, 409
combinatorial logic circuits, 83-88
combustion, 409
command input, 139
communication
  block diagram of system, 32
  diagnostic, 338-339
  interactive, 386
compact disc (CD) player, 393
comparator, analog, 410
compression, variable, 370
compression ratio, 156, 410
compression stroke, 9
computer. *See also* microcomputer
  analog, 80, 99
  languages, 118-119
computer programs, 38, 101-102, 413
  branches, 107-108, 111-113
  control, 135, 224
  cruise control, 271
  AND function, 121-123
  modification, 152, 223, 305
  suspension system, 289-290
Computerized Automotive Maintenance System (CAMS), 352-354
condition code (CC) register, 107-108
constant velocity (CV), 19
continuously variable transmission (CVT), 380-381
continuous-time, 137, 223. *See also* analog control systems
control application electronic system
  block diagram for, 32
control bus (CB), 133
control law, 58
control logic, 139, 141
control modes, 225-238, 253-255
control section, microprocessor, 109-110
control signal, 60
  bus, 391
  multiplexing, 390-391
control systems, 56-60. *See also* actuators; electronic control systems; sensors
  closed-loop (*See* closed-loop control systems)
  feedback, 139-141
  limit-cycle (*See* limit-cycle control)

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

control systems, *(continued)*
microcomputers in, 138-143
multivariable systems, 141
objectives, 56-57
control variable, 410
Controller Area Network (CAN), 338-339
controllers, 56. *See also* microcontroller
frequency and deviation of, 173-175
inputs to, 157
multimode, 223
outputs from, 157-158
proportional, 60-66, 263-265, 271-272
serial digital link from, 339
conversion efficiency (catalytic converter), 410
coolant temperature (CT), 157, 189, 229, 253
failure, 229-230
measuring, 308-309
sample period, 305
sensors, 167, 207-208, 226, 228
spark timing and, 242
counter circuits, 200
crankshaft, 7, 10
angular velocity, measurement of, 194
throw, 156
crankshaft angular position, 167, 189, 411
ignition timing and, 337, 368
sensors (CPS), 194-206, 226, 228
critical damping, 45, 264, 266
CRT (cathode ray tube) display, 318-327
CRT controller, 321
cruise control system, 261-277
digital, 266-269
electronics, 271-277
speed response curves, 265-266
throttle actuator, 261-263, 267, 269-272, 276-277
cutoff, transistor, 75, 81, 410
cylinder head, 7-8
cylinder pressure
measurements, control based on, 370-372
sensors, 372
cylinders, 7, 155, 156, 170, 182
ignition sparking and, 240
shock absorber, 22

D

D/A converter. *See* digital-to-analog converter (DAC)
damping, 43-45, 285-291
coefficient, 410
high, 291
low, 286, 288, 291
optimal, 412
ratio, 264-266
data bus (DB), 104, 110, 111, 133, 321, 389
data latches. *See* flip-flop circuits
dead reckoning system, 397-398
deceleration, 254-255
deceleration leaning, 237, 238
demultiplexer (DEMUX), 303-304, 307, 311, 328, 410
diagnostics, 252, 335-366
electronic control system, 339-354
engine analyzer, 337-338
inputs, 298-299
instrumentation, 330-331
off-board, 338, 352-360
on-board, 252, 338, 339-352, 386
timing light, 335-337
diagrams, block. *See* block diagrams
diesel engines, 18, 410
differential, 19-20, 68

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

differential exhaust gas pressure, 189
differential GPS (DGPS), 404
differential pressure (DP), 233
differential pressure sensors (DPS), 228, 239
digital audio broadcast (DAB) entertainment system, 401, 403
digital buffer interface, 126
digital circuits, 80-83, 200, 410
  as integrated circuits, 92
  logic gates used to build, 86-88
digital clocks, 90
digital communications, 338-339
digital computer
  analog computer vs., 99
  multiple-bit numbers in, 86-88
  parts of, 99-100
digital control systems, 37, 58, 223-259. *See also* electronic control systems
  cruise control, 266-269
  exhaust gas recirculation (EGR), 239, 256-257
  features, 224-225
  fuel control, 225-238
  ignition control, 239-250
  integrated systems, 250-256
  suspension system, 289-290
digital data link, 325-326, 338-339
digital filters, 137-138, 308
digital instrumentation display, 300-303, 307, 311, 312, 327
digital proportional integral controller, 65-66
digital signal processing (DSP), 53-54
digital systems. *See also* digital control systems
  characteristics of, 35-37
  performance, 38
digital-to-analog converter (DAC), 37, 127-130, 132, 135, 300-301, 312, 313, 410
diodes, 30, 71-73, 75, 410
discrete-time systems. *See* digital control systems
disk brakes, 23
displacement, engine, 156
display devices, 32, 46, 49, 52, 297-298, 312-327
  analog or digital, conversion for, 300-303
  definition, 410
  multifunction, 299
distributor, 14-16, 240
distributorless ignition system (DIS), 182, 240-243, 367
disturbance response, proportional controller, 60-62, 64
Doppler frequency shift, 382
drive shaft, 19, 155
drive traction, 4
drive train, 18-20, 367-381, 410. *See also* power train
drive wheels, 4
driver electronics, 219, 274-275
driver information system, advanced, 401-404
driving control, automatic, 404-405
drum brakes, 23
duty cycle, 217, 219, 267, 271, 274
dwell, 15, 242, 337, 410
dynamic response, 48-52
dynamometer, 149-150, 158, 159, 241, 410

E

electric motors, 215, 292
electrical input/output, 32-33, 35, 51
electrical signals, 32-33, 35, 297
electrical wiring, 388
electron gun, 319
electronic control systems. *See also* digital control system; electronic engine control systems

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

electronic control systems. *(continued)*
antilock braking, 277-285
driving control, 404-405
steering control, 291-293
electronic controllers. *See* controllers
electronic engine control systems
automatic system adjustment, 252
basics, 147-185
concept of, 153-156
cost of, 153
cylinder pressure measurements, 370-372
diagnostics (*See* diagnostics)
drive train, 367-381
engine, 367-381
exhaust emissions (*See* exhaust emissions)
features, 224-225, 261
fuel control (*See* fuel control system)
ignition (*See* ignition system)
improvements, 255-257
integrated, 250-256, 393
microcomputer-based, 102
motivation for, 147-148
strategy, 162, 164-167
electronic systems. *See also* electronic control systems
block diagrams of, 31-32
components of, 30
concept of, 30-35
future, 367-407
history of, 2, 5, 29, 297-299
performance, 37-46
suspension system, 285-291
electronics, fundamentals of, 71-97
electro-optical display devices, 32, 312-327
emissions. *See* exhaust emissions
end of conversion (EOC), 135
engine analyzer, 337-338
engine block, 7
engine crank, 226-227, 229, 253
engine mapping, 160-164, 411
engine position sensors (EPS), 167
engine speed. *See* idle speed control; RPM
engine speed sensors, 200
engine warm-up, 226-227, 229-231, 253
engines, 5-10
alternative, 18, 376-378
alternative-fuel, 378-379
calibration (*See* calibration)
components of, 6
control, 11-12 (*See also* electronic engine control systems)
diesel, 18, 410
4-stroke cycle, 8-10
location of, 3-4
parameters, 156
performance, 158-164
2-stroke/cycle engine, 18, 376-378
variables, 156-157
Wankel, 18
entertainment system, 326
Environmental Protection Agency (EPA), 147, 152, 164, 235
equivalence ratio, 161, 411
error amplifiers, 60, 139, 271, 276. *See also* operational amplifiers
error signals, 139, 261
cruise control system, 267, 272, 274-276
fuel control systems, 168
errors
measurement, 47-49, 59, 60, 64-66
sources, 50-52
ethanol, 378-379
evaporative emissions, 411
evaporative emissions canister purge, 250-251
exhaust emissions, 147-148, 160
control, 161-164, 351-352, 375, 377-378

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

regulation, 147-153, 162, 164, 224, 235-237, 253-254, 377
2-stroke/cycle engine, 377-378
exhaust gas oxygen (EGO), 157, 169, 189, 410
exhaust gas oxygen (EGO) sensors, 167, 208-213, 226, 228, 352. *See also* heated EGO sensors (HEGO)
closed loop control/operation, 170-173, 234-235, 254
definition, 410
desirable characteristics, 211
improvements, 256-257
open loop mode, 175, 227, 253
secondary air management, 250
switching characteristics, 211-212
temperature dependence, 212
exhaust gas recirculation (EGR), 155, 157, 188, 224, 232-233, 253-255
actuators, 215, 218-219
control, 226, 228, 239
definition, 410
in integrated engine control system, 250
measuring air mass and, 180-181
performance and, 163-164
exhaust manifold, 165, 239, 253
exhaust pressure ratio (EPR), 226
exhaust system, 6, 155. *See also* catalytic converter
electronic control systems, 169
wide range air/fuel sensors for, 372-375
exhaust valve, 8, 10, 156
expert systems, 354-360

F

fault
codes, 299, 338, 340-350
hard, 343
intermittent, 327, 339, 343
federal government test procedures, 148-153
feedback, in operational amplifiers, 78-79
feedback control, 59, 139-141, 187. *See also* closed-loop control systems
cylinder pressure measurements, from, 370-372
sensors for, 208-214
fiber optics, 391
filters, 54, 137-138, 308, 312
firmware, 125
fixed messages, 318
flat-panel display, 318
flexible fuel vehicles (FFV), 378-379
flip-flop circuits, 89-91, 101
floats, fuel quantity, 300, 306
flywheel, 10, 194
foot-pound, 411
forward biased condition, 72
4-cylinder engine, 240, 257
4-stroke cycle, 8-10
four-wheel steering systems (SWS), 292-293
frame, 3
frequency response, 38-39, 55, 411
front wheel drive, 4, 19
fuel
alternative, 378-379
atomization, 370, 377
lead-free, 166
fuel consumption. *See also* fuel economy
brake-specific (BSFC), 159, 160
rate, 305, 372
fuel control system, 6, 147, 153-155, 157, 167-175, 368, 377. *See also* fuel injection
acceleration enrichment, 235-237
closed-loop (*See* closed-loop control system)
control modes, 225-238, 253-255

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

fuel control system, *(continued)*
deceleration leaning, 237, 238
frequency and deviation of controller, 173-175
in integrated engine control system, 250
open-loop (*See* open-loop fuel control system)
sequence, 169
variables, 168-169
fuel delivery timing sensors, 200-201
fuel economy, 148-153, 235-237, 253-255, 328-329, 375, 376
fuel flow rate, 157, 225
fuel flow sensors, 168
fuel injection, 11-12, 167, 169, 187, 188, 216-218, 234, 367
alternative engine, 377-378
quantity of fuel to be injected, 225, 230-231
signals, 217
timing, 170, 173, 194, 195, 257
fuel level sensors, 137-138
fuel metering actuators, 181. *See also* fuel injection
fuel metering system. *See* fuel control system
fuel quantity
measurement, 306-308
sample period, 305
sensors, 306-307
full adder circuits, 86-88

G

gain, 411
gates, 83-88, 91, 119
gear ratio, 19
General Motors CAMS diagnostic system, 352-354, 360
glass cockpit, 327
Global Positioning System (GPS), 394-396, 401, 404
glossary, 409-413
government regulations, 2
exhaust emissions (*See* exhaust emissions)
federal test procedures, 148-153
fuel economy (*See* fuel economy)
occupant protection systems, 360

H

half adder circuits, 86
half-wave rectifier circuit, 72-73
Hall-effect position sensors, 202-204
handling, 285, 287
handshaking, 339
hardware
microcomputers, 125-133
multiply, 224
harness, electrical, 388
heads up display (HUD), 386-387, 399, 402, 403
heated EGO sensors (HEGO), 212-213, 228, 234, 256-257
high-pass filters, 137
high-speed digital data (HSDD) link, 325-326
high-voltage circuit, 12-15
hydrocarbons (HC), 147-148, 150, 161, 164-166, 169, 227, 234, 237, 238, 250-251, 411
hysteresis, 211, 248-249

I

idle speed control, 227, 237-238, 254-255, 367
IF-THEN rules, 357-359

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

ignition actuators, 215, 219-220
ignition coils, 12, 15, 181, 219, 240, 242-243, 337
ignition control module (IGN), 168
ignition controller, output from, 157
ignition points, 337
ignition system, 6, 12-16
  electronic ignition, 181-182, 188, 239-250
  fuel control system and, 167, 225
  as separate control system, 155
ignition timing, 17-18, 157, 194, 195, 224, 378
  closed-loop, 243-248
  crankshaft angular position and, 368
  definition, 411
  sensors, 200-201
  timing light, 335-337
indicated power, 158
inductor, 411
inertial navigation, 393-394
inference engine, 356
initialization, computer, 110-111
inlet air temperature, 192, 225
input/output (I/O). *See also* memory-mapped I/O (input/output)
  device, 104, 134-135, 135, 227
  interface, 126-127, 271
inputs, instrumentation, 54-55, 77-79, 298-303, 328-329. *See also* sensors
instruction register, 111
instrument panel (IP), 290-291, 342
instrumentation, 32, 46-49, 297-333, 411
  applications of microcomputers, 135-138
  computer-based, advantages of, 305-306
  coolant temperature measurement, 308-309
  display devices, 312-327
  energy extracted by, 48
  fuel quantity, 306-308
  future systems, 386-388
  glass cockpit, 327
  input and output signal conversion, 300-303
  oil pressure measurement, 309-311
  performance, 306
  sampling, 304-306
  trip information computer, 328-330
  vehicle speed measurement, 311-312
intake air, 11, 147, 170, 179, 238, 254-255
  absolute temperature (IAT), 179
  temperature, 189, 226, 231-232
intake manifold, 155, 170, 239, 368-370
intake manifold pressure, 17, 157, 181
  absolute pressure (*See* manifold absolute pressure (MAP))
  analysis of, 175-181
intake stroke, 9
intake system, 368-370
intake valve, 8-9, 156, 257
integral amplifiers, 271, 276, 411
integrated circuits (IC), 91-95, 99, 411
  central processing unit, 125
  operational amplifiers, 77
  video, 323
integrated engine control system, 250-256, 393
integration
  concept of, 62-64
  proportional (*See* proportional integral (PI) controller)
intelligent transportation system (ITS), 401
interactive communication, 386
interrupts, 132-133, 411

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

inverting input, 54-55, 77-79
I/O. *See* input/output

J

J-K flip-flop circuit, 90
jump instruction, 113
jump-to-subroutine instruction, 113-116
junction, 74-75, 313

K

keyboard, 325-326, 328, 352
keyless entry system, 401, 402-403
knock
  control, 367, 370
  sensors, 213-214
  spark advance and, 243-248
knowledge base, 356
knowledge engineer, 354-355

L

lambda sensors. *See* exhaust gas oxygen (EGO) sensors
LCD (liquid crystal display), 313, 402
lead term, 411
lead-free fuel, 166
LED (light-emitting diode), 205, 313, 387
limit-cycle control, 66-68, 139-141
  definition, 411
  fuel control, 171, 173-174, 211
linear circuits, 77
linear region, 75, 411
linear transfer characteristic, 51
loading errors, 48, 50
local area network (LAN), 338-339
logic circuits/functions, 83-91, 119, 411
lookup tables, 141-143, 225, 229, 232-233, 242, 252, 311, 411
Lorentz force, 202
low-pass filters, 54, 137-138

M

magnetic circuit, 197-198
magnetic field intensity, 197-198
magnetic flux, 198-200, 203
magnetic focusing system, 319
magnetic sensors, 194, 196, 200, 268
  angular speed, 55
  reluctance position, 197-201
magnetostriction, 214
manifold. *See also* intake manifold
  exhaust, 165, 239, 253
  pressure, 214, 270 (*See also* manifold absolute pressure (MAP))
  vacuum, 17, 270-271, 275
manifold absolute pressure (MAP), 179-180, 189, 192, 225, 231-233, 411
  sensors, 175-176, 192-194
  spark timing and, 242, 243
map matching, 398
masking, 123
mass air flow (MAF), 157, 181
  alcohol fuel and, 379
  indirect measurement of, 192-194
  rate, 154, 167, 189, 225, 230-232
  sensors, 167, 169, 177-181, 189-194, 225, 226, 228, 368
  spark timing and, 242
mass density equation, 231
master, 338
mathematical model, 411

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

mean best torque (MBT), 244
measurement
  basic system, 32, 49-53
  definition, 46
  issues, 47-49
memory, 90, 100, 103, 110
  program read into, 101-102
  RAM (*See* random access memory)
  read/write, 104, 125
  ROM (*See* read-only memory)
memory-mapped I/O (input/output), 105, 117
methanol, 378-379
microcomputer, 412. *See also* digital computer; microprocessor
  architecture, 133
  automotive systems, uses in, 133-143
  in control systems, 138-143
  example use of, 116-125
  fundamentals, 99-102
  hardware, 125-133
  instrumentation, uses in, 135-138, 298, 321
  lookup tables (*See* lookup tables)
  mainframe computers compared, 101
  operations, 103-105
  reading instructions by, 110-116
  tasks, 102
microcontroller, 187, 224-225, 271, 289
microelectronics, 2
microprocessor (MPU), 93-95, 99-100, 125, 133, 187, 223-225, 227, 255
  architecture, 109-110
  back-up, 368
  for cruise control, 266, 271-272
  diagnostics by, 339
  instrumentation use, 297, 321-322
  suspension system, 289
minimum advance for best timing (MBT), 161-162
motion control, 261-295
multimode controllers, 223
multiplexer (MUX), 301-304, 311, 328, 388-391, 412

N

NAND gate, 84-86, 89
natural gas, 378
navigation systems, 391-398
node, 338
noise, 52, 56-57
noninverting input, 54, 77-79
nonlinear behavior, 50
nonlinear sensors, 53
NOR gate, 84-86
NOT gate, 83, 84, 119
notched position sensors, 201
NOx, 148, 150, 161, 163, 164, 166, 169, 218, 234, 239, 250, 372, 412
NPN transistor, 74-75
Nyquist sampling theorem, 130, 138

O

occupant protection systems, 360-364
off-board diagnosis, 338-339, 352-360
office on wheels, 399-400
offset, 112-113
oil pressure management, 309-311
on-board diagnosis, 252, 338, 339-352, 386
open-loop fuel control system, 168, 169, 175, 212, 227, 231-231, 253-254

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

open-loop fuel control system, *(continued)*
definition, 58-59, 412
open-loop gain, 54
operation codes (op codes), 111, 412
operational amplifiers, 54-55, 77-80, 275-276, 412
analog computers, 80
feedback, 78-79
summing mode, 79-80
optical display devices, 312-327
optical fiber, 391
optical sensors, 194, 196, 205-206, 268-269
optimal damping, 412
OR gate, 83, 84, 119
output, 56, 139, 300-303. *See also* actuators; input/output (I/O)
overdamping, 264
overhead cam engine, 7
oxidizing catalytic converter, 165-166
oxygen partial pressure, 210
oxygen sensors
EGO (*See* exhaust gas oxygen (EGO) sensors)
O2, 342-343, 349-350, 372

P

parallel interface, I/O, 126-127, 271
parameters, 156
passive restraints, 360
peripherals, 100, 412
addressing, 105
temporary storage for inputs, 117
phase shift, 39, 412
phoneme, 388
phototransistor, 205
piezoelectric crystals, 214
piezoelectric element, 372
piezoelectric force generators, 215
piezoresistivity, 193
piston rings, 7
pistons, 7
diameter, 156
shock absorber, 22, 289
pixel, 323
plant, 32, 56-59, 261, 412
output, 60, 139
variables, measurements of, 187, 188
platooning, 404-405
PN junction, 74-75, 313
PNP transistor, 74-75
polling, 130-131
potentiometer, 206-207, 300, 307
power, 147, 155, 157, 158, 188
power steering system, 25
power stroke, 10
power train. *See also* drive train
control system, 299
controller, serial digital link from, 339
digital data line (PDDL), 299, 311
sensor and actuator applications, 187-188
precision, measurement, 47
pressure sensors, 33-34, 175-176, 192-194, 228, 239. *See also* manifold absolute pressure (MAP)
program counter, 110, 111, 114-116
programs. *See* computer programs
proportional amplifiers, 271, 276, 412
proportional control systems, 60-66, 263-265, 271-272
proportional integral differential (PID) controller, 66

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

proportional integral (PI) controller, 64-66, 263-265, 271-272
pulse width, 231, 234

Q

qualitative analysis, 412
quantitative analysis, 412
quantization, 35-37, 53

R

radar warning system, collision avoidance, 381-384
radio data system (RDS), 401, 403-404
radio navigation, 394-396
random access memory (RAM), 125, 134, 227, 412
  cruise control system, 271
  video (CRT), 321-324
random errors, 47, 412
  sensors, 52
readable interfaces, 126
reading (computer), 104, 110-116
read-only memory (ROM), 125, 134, 224-225, 227, 233, 412. *See also* lookup tables
  cruise control system, 271
  display (DROM), 322-323
  replacing, 305
read/write memory (RWM), 104, 125
real-time computing system, 133
receiver module (RM), 391
reconstruction filter, 137
rectifier circuit, 72-73
registers, 90, 103, 106-110, 109-110
reliability, measurement, 49
resistors, 30
return-from-subroutine (RTS) instruction, 116
reverse biased condition, 72
ride, 285-288
rotary engine, 18
RPM (revolutions per minute), 157, 159, 167, 189, 194, 200, 278
  control modes for fuel control and, 225, 226, 230-233, 253-255
  control of, 147
  definition, 412
  idle speed control, 237-238
  mass air flow measurement, 153, 192
  sensor disk, 200
  sensors, 228
  spark timing and, 181, 242, 243
  volumetric efficiency, 180
R-S flip-flop circuit, 89

S

safety, 381-386
sample and hold, 412
sample period, 304-305
sample time, 35
sampling, 35-36, 272, 304-306, 389, 412
saturation condition, transistor, 76, 81
sea level standard day (SLSD), 179
secondary air, 165, 250, 253-255
self-diagnosis, 299, 338, 368
semiactive suspension system, 285-286, 289
semiconductor devices, 71-76, 412
sensors, 30, 32, 35, 49-53, 155, 261, 297
  abnormal responses, 252
  air flow rate, 189-194

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

sensors, *(continued)*
automotive applications of, 187-189
camshaft position, 226, 228
coolant temperature, 167, 207-208, 226, 228
crankshaft angular position, 194-206
CRT display and, 321
cylinder pressure, 372
definition, 412
engine position, 181
errors in, 50-52
exhaust system (*See* exhaust gas oxygen (EGO) sensors)
feedback control, 208-214
filtering output of, 137
frequency response, 55
fuel delivery timing, 200-201
fuel flow, 168
fuel quantity, 306-307
Hall-effect position, 202-204
ignition timing, 200-201
instrumentation input from, 298
knock, 213-214
low tire pressure, 385
magnetic (*See* magnetic sensors)
manifold absolute pressure (MAP), 175-176, 192-194
mass air flow rate (*See* mass air flow (MAF))
multiplexing, 388-390
navigation, 393-394
noncontacting, 194, 196
optic, 268-269
shielded-field, 204
speed, 189, 200, 266-269, 271, 311
temperature, 190, 207-208, 226, 228, 352
throttle angle (*See* throttle angle)
transducer gain, 33
variable resistance, 309
wide range air/fuel, 372-375
sequential logic, 88-91, 412
serial operation (computer), 107
set point, 58
shielded-field sensors, 204
shift logical operations, 124
shock absorbers, 20-22, 43-45, 285-291
shot noise, 52
SI (spark-ignited) engine, 5-6, 8-10, 148, 412
signal processing, 32, 34, 49, 51-56, 297
for airbags, 362-363
definition, 413
fuel quantity management, 307-308
low tire pressure warning, 386
operations, 135
signpost navigation, 396-398
sinusoid, 38-44, 286
skid, 413
slaves, 338
slip, 413
software. *See* computer programs
solenoids, 215-216, 219, 239, 270, 274
lock-up, 252
suspension system, 290
solid state devices, 297. *See also* semiconductor devices; thermistors
CRT, 318-327
glass cockpit, 327
solid-state electronics, 2, 5, 29
spark advance, 17, 181, 243-250, 413
correction scheme, 248-250
cylinder pressure measurements to control, 372
excessive, 214
spark control, 155, 250
spark plugs, 12-13, 15, 188, 219, 240

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

spark pulse generation, 15-16
spark timing, 157, 160, 181, 241-242, 253-254
  advance mechanisms, 52
  definition, 413
  performance, effect on, 161-162
  regulation of, 147
spark-ignited engine. *See* SI (spark-ignited) engine
speech synthesis, 386, 388, 399
speed control, vehicle. *See also* cruise control system
  radar sensor, 405
  sample period, 305
speed response curves, 265-266
speed sensors, 189, 200, 266-269, 271, 311
speed set switch, 266
speed-density method, 192, 225, 231-233
spring rate, 21
springs, 20-21
sprung mass, 21, 41, 286-287, 289
square wave waveform, 51
stack pointer (SP), 115-116
stacks, 116
standards, measurement, 47
status register, 107-108
steering system, 3, 4, 24-26, 291-293
step response, of system, 45-46
stepper motor, 237, 270, 273-274
stoichiometry, 161, 162, 166-175, 209, 211, 224, 225, 231, 234, 255-256
  definition, 413
  future developments, 368, 372, 378-379
strain gauge MAP sensors, 192-194
stroke, 156, 182
struts, 21
subroutines, 114-116, 124
subsystems, 30, 338
summing amplifiers, 79-80, 271, 276
suspension system, 3, 20-22, 41-45, 285-291
swirl control, 370
switch tests, 344, 346-349
switches, 189, 298-299, 302
  acceleration-sensitive, 362
  closure of, 237
  cruise control systems, 276
  exhaust gas oxygen sensors, switching characteristics of, 211-212
  oil pressure management, 309-310
synchronizing pulses, CRT, 320
synchronous counter, 90-91
system plant. *See* plant
systematic errors, 47-49, 413
systems
  concept of, 30-35
  definition, 413

T

TDC. *See* top dead center (TDC)
technicians' terminal, 352
TELEPATH, 401
telephones, cellular, 399-400
temperature. *See also* coolant temperature (CT); intake air
  fuel metering and, 181
  inlet air, 192, 225
temperature sensors, 190, 207-208, 226, 228, 352
thermal efficiency, 159, 370
thermal noise, 52
thermistors, 207, 308-309
three-way catalyst (TWC), 166-167, 174-175, 224, 256
throttle actuator, 52, 261-263, 267, 269-272, 276-277, 405

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

throttle angle, 52, 153, 189, 206, 413
decrease in, 237
position sensors (TPS), 50, 157, 167, 188, 206-207, 226, 228, 236
throttle body fuel injectors (TBFI), 226, 413
throttle plate, 11, 277
angle (*See* throttle angle)
cruise control shutoff and, 277
intake air control, 175, 238
time division multiplexing, 389-390
time response, of system, 45
timed sequential port fuel injection (TSPFI), 226
timekeeping, interrupts for, 132
timer (computer), 132
timing. *See also* ignition timing; spark timing
fuel injection, 170, 257
light, 335-337
microcomputer operation, 104-105, 124-125
valves, 156, 368-370
tire pressure, low, warning system, 384-386
tire-slip control, 284-285
top dead center (TDC)
compression ratio and, 156
definition, 9, 413
fuel injection timing, 194-195, 257
ignition timing, 194-195, 197, 200, 240, 243-244, 337
spark advance measurement, 161
torque, 147
acceleration enrichment and, 235-236
air/fuel ratio variations and, 160, 161
braking, 281
definition, 159, 413
exhaust gas recirculation and, 163
ignition timing and, 241
maximum, 368
mean best, 244
restoring, 24-25
spark advance and, 243-244
wheel, 281, 285
torque converter, 413
torque converter locking clutch (TCC), 251-252
transaxle, 4, 19
transducer gain, of sensors, 33
transfer function, 413
transistors, 30, 71, 74-76, 220, 413
amplifiers, 76-77
digital circuits, 81
transmission, 18-19
continuously variable (CVT), 380-381
control, 379-381
gear selector position, 189
transmitter/receiver (T/R) unit, 390
transport delay, 413
trip computers, 328-330, 386
twisted nematic liquid crystal, 313-316
two's complement notation, 107
2-stroke/cycle engine, 18, 376-378

U

underdamping, 264
universal joints, 19
unsprung mass, 21, 41-42, 286-287, 289

V

vacuum spark advance, 17
vacuum-fluorescent display (VFD), 316-318

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

vacuum-operated actuator, 274-277
valves, 7, 8-9, 155. *See also* solenoids
  EGR, 239
  timing, 156, 368-370
variable impedance aspiration system (VIAS), 368
variable parameter intake, 368-370
variable resistance sensors, 309
variables, 56, 156-157, 188
  control, 410
  desired value of, 261
  fuel control systems, 168-169
  measurement of, 188, 189, 261, 297, 298
  status, display of, 297
vectored interrupts, 132-133
vehicle-to-roadside communication (VRC), 401, 403
very large scale integrated circuits (VLSI), 153
video voltage, 321
voltage-to-frequency (v/f) converter, 190
volumetric efficiency, 159, 180, 232-233, 368-370, 413

W

Wankel engine, 18
warning
  lights, 46, 312, 342
  messages, 298, 299, 309
  systems, 403
  tire pressure, low, 384-386
Wheatstone bridge, 190, 194
wheel torque, 281, 285
wide range air/fuel sensors, 372-375
word, 103
writable interfaces, 126
write, 104

X

XOR gate, 86-88

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Answers to Quizzes

Chapter 1

1. c
2. a
3. b
4. d
5. b
6. b
7. c
8. b
9. a
10. a
11. a
12. d

Chapter 2

1. e
2. b
3. b
4. a
5. b
6. c
7. b
8. d
9. d
10. d

Chapter 3

1. a
2. c
3. b
4. a
5. c
6. b
7. d
8. e
9. b
10. d
11. b
12. d
13. b
14. a
15. d
16. c
17. b
18. d
19. c
20. a

Chapter 4

1. d
2. d
3. c
4. a
5. e
6. b
7. d
8. c
9. b
10. a
11. b
12. c
13. d
14. b
15. a
16. b
17. b
18. d
19. d

Chapter 5

1. c
2. c
3. d
4. b
5. b
6. a
7. c
8. c
9. a
10. c
11. c
12. a
13. c
14. c
15. a
16. a
17. b
18. c
19. a

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

Chapter 6

1. b
2. c
3. a
4. b
5. b
6. d
7. c
8. a
9. a
10. b
11. d
12. a
13. c
14. b
15. c

Chapter 7

1. d
2. a
3. b
4. d
5. b
6. b
7. c
8. c
9. d
10. b
11. d
12. c
13. d
14. a

Chapter 8

1. b
2. c
3. a
4. b
5. d
6. a
7. b
8. a
9. a
10. a

Chapter 9

1. a
2. c
3. c
4. c
5. a
6. c
7. c
8. a
9. c
10. d
11. a
12. a
13. a
14. b
15. c
16. b
17. a
18. c
19. c

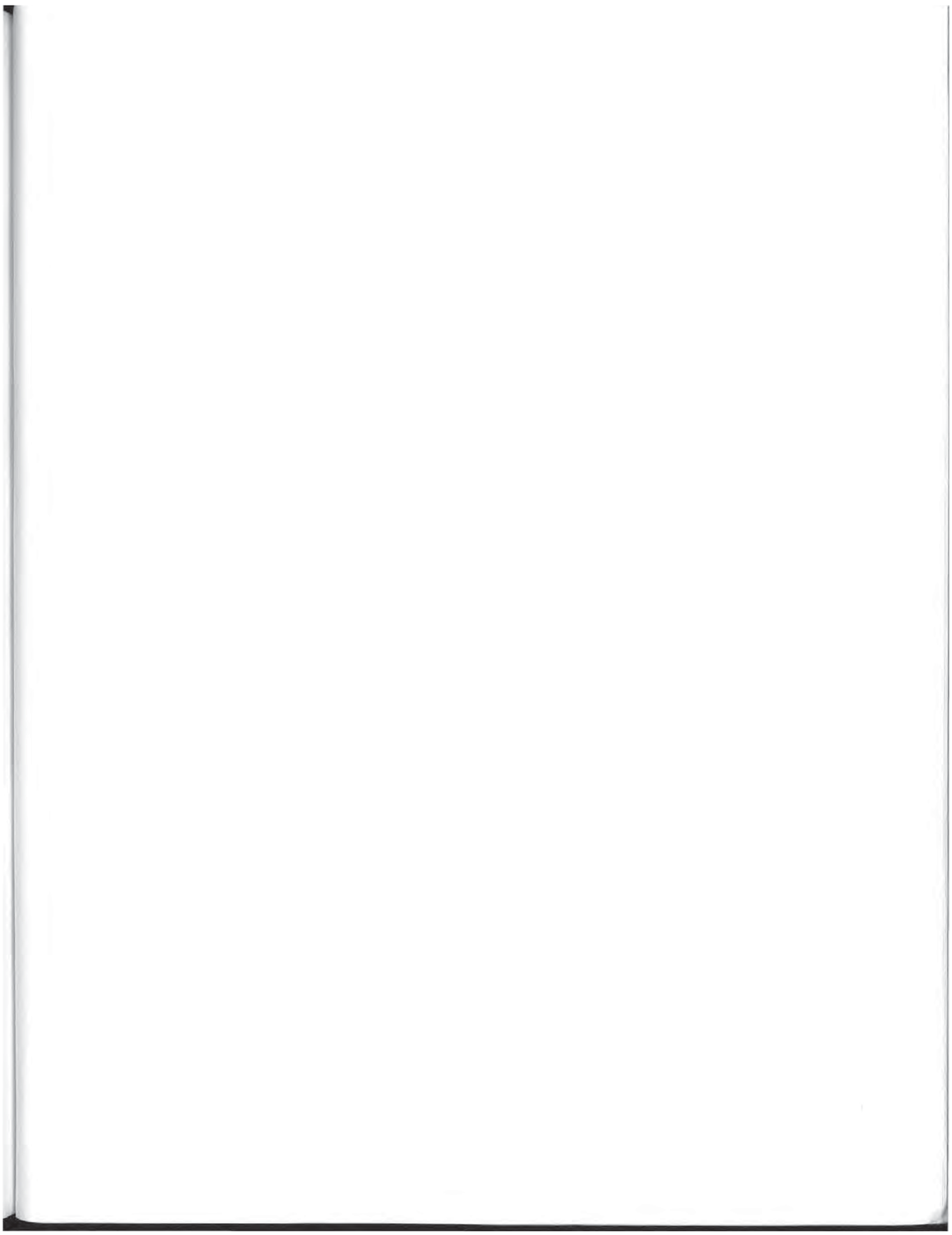
Chapter 10

1. d
2. b
3. d
4. c
5. d
6. d
7. d
8. a
9. b
10. b

Chapter 11

1. d
2. a
3. a
4. b
5. c
6. a
7. d
8. b
9. d
10. b
11. c

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565



PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

LOS ANGELES PUBLIC LIBRARY
3 7244 1112 0 1775

UNDERSTANDING Automotive Electronics

FIFTH EDITION

William B. Ribbens

In today's cars, the electronic
than simple electrical wiring. They now affect almost every operating aspect of the automobile. This edition of ***Understanding Automotive Electronics*** covers the most recent technological advances in operation and troubleshooting of electronic systems and components, including low-emission standards, on-board diagnostics and communications, digital instrumentation, and digital engine control. This is a practical text, suitable for the automotive technician, student or enthusiast.

The basis for understanding the fu
ubsystems is a good grasp of mechanical aut
tures and systems of late-1990s autos. In Ch
pecifically geared to automotive systems, is
eory, and concepts are illustrated with simple
detailed theory in later chapters.

Chapters 3-10 cover specific syste
ail, with many examples and illustrations.
omotive electronics technology, some curre
nay yet come to be.

- **Extensive revision of the po**
- **Overviews of basic automoti**
- **Electronic system, subsystem,**
- **Covers ultra-low emission ve**

ting

William B. Ribbens is a professor
g and Computer Science at the University

Related Newnes titles:
Auto Electronics Projects
Maplin Staff
ISBN 0-7506-2296-2, paperback, 208 pp

DATE DUE
NINETY-ONE
GAYLORD
PRINTED IN U.S.A.

ISBN 0-7506-7008-8
90000
9 780750 670081

Newnes
An imprint of Butterworth-Heinemann
http://www.bh.com

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

IN THE UNITED STATES DISTRICT COURT
FOR THE EASTERN DISTRICT OF MICHIGAN
SOUTHERN DISTRICT

MICHIGAN MOTOR TECHNOLOGIES LLC Plaintiff, v. VOLKSWAGEN AKTIENGESELLSCHAFT and VOLKSWAGEN GROUP OF AMERICA, INC., Defendant.	C.A. No. 2:19-cv-10485-DML-SDD **JURY TRIAL DEMANDED**

AMENDED COMPLAINT FOR PATENT INFRINGEMENT

Michigan Motor Technologies LLC ("MMT" or "Plaintiff"), for its Amended Complaint against Defendants Volkswagen Aktiengesellschaft ("VWAG" or "Defendant") and Volkswagen Group of America, Inc. ("VWGOA" or "Defendant") (collectively "Defendants"), alleges the following:

NATURE OF THE ACTION

1. This is an action for patent infringement arising under the Patent Laws of the United States, 35 U.S.C. § 1 et seq.

THE PARTIES

2. Plaintiff is a Limited Liability Company organized under the laws of the State of Michigan with a place of business at 2360 Orchard Lake Road, Suite 100, Sylvan Lake, Michigan 48320.

3. Upon information and belief, Volkswagen Aktiengesellschaft is a Corporation organized and existing under the laws of Germany, with its principal place of business at Berliner Ring 2, 38440 Wolfsburg, Germany.

4. Upon information and belief, Volkswagen Group of America, Inc. is a Corporation organized and existing under the laws of the State of New Jersey and a wholly

VW EX1029
U.S. Patent No. 6,581,565

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

owned subsidiary of Volkswagen Aktiengesellschaft. Volkswagen Group of America, Inc. has its principal place of business at 2200 Ferdinand Porsche Dr., Herndon, VA 20171.

JURISDICTION AND VENUE

5. This is an action for patent infringement arising under the Patent Laws of the United States, Title 35 of the United States Code.

6. This court has subject matter jurisdiction under 28 U.S.C. §§ 1331 and 1338(a).

7. Venue is proper in this judicial district under 28 U.S.C. § 1400(b). On information and belief, Defendants have committed acts of infringement in this District and have regular and established places of business within this District.

8. On information and belief, Defendant VWGOA has a place of business at 3800 Hamlin Road, Auburn Hills, MI 48326.

9. On information and belief, Defendants are subject to this Court's general and specific personal jurisdiction because Defendants have sufficient minimum contacts within the State of Michigan and this District, pursuant to due process and/or Michigan Long Arm Statute because Defendants purposefully availed themselves of the privileges of conducting business in the State of Michigan and in this District, because Defendants regularly conduct and solicit business within the State of Michigan and within this District, and because Plaintiff's causes of action arise directly from Defendants' business contacts and other activities in the State of Michigan and this District.

COUNT – I INFRINGEMENT OF U.S. PATENT NO. 6,588,260

10. The allegations set forth in the foregoing paragraphs 1-9 are incorporated into this First Claim for Relief.

11. On July 8, 2003, U.S. Patent No. 6,588,260 ("the '260 patent") entitled "Electronic Throttle Disable Control Test System," was duly and legally issued by the United

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

States Patent and Trademark Office. A true and correct copy of the ’260 patent is attached as Exhibit 1.

12. Plaintiff is the assignee and owner of the right, title and interest in and to the ’260 patent, including the right to assert all causes of action arising under said patents and the right to any remedies for infringement of them.

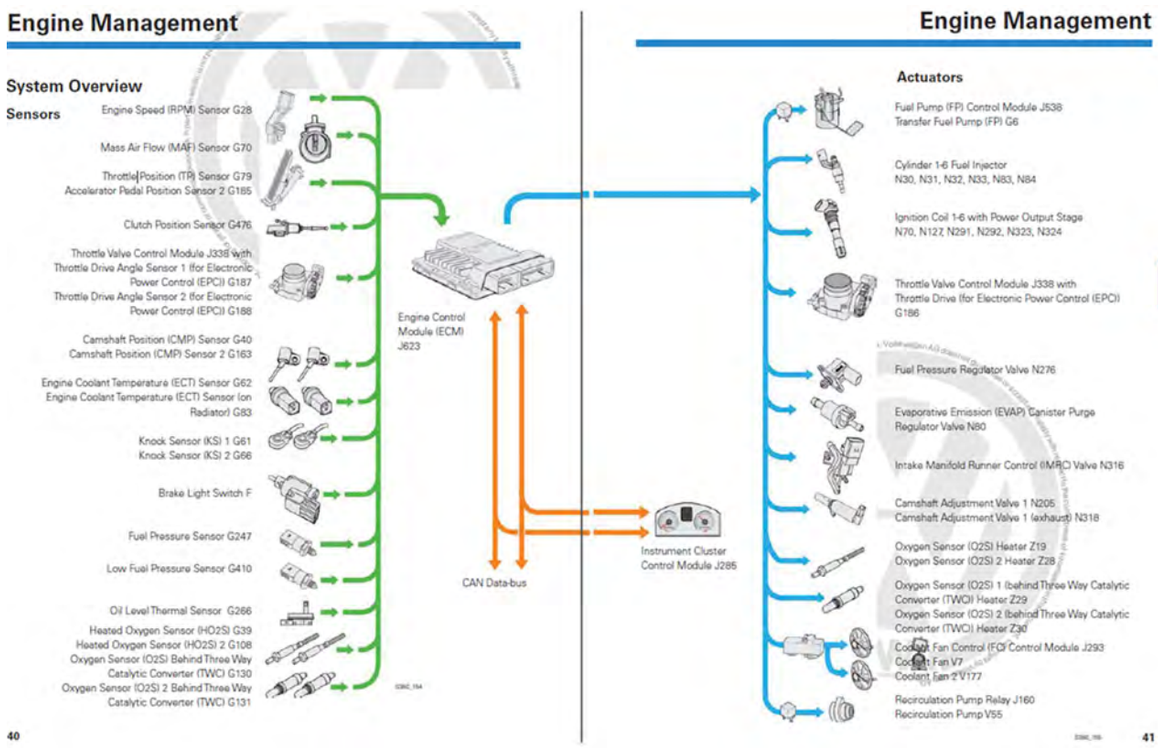
13. Upon information and belief, Defendants have directly infringed at least claim 1 of the ’260 patent by making, using, selling, importing and/or providing and causing to be used the at least the 2015-2018 3.6L Touareg (collectively the “’260 patent Accused Instrumentalities”).

14. In particular, claim 1 of the ’260 patent recites an electronic throttle control apparatus for testing integrity of a motor drive electronics disable feature comprising: a PCM having drive electronics for controlling a motor coupled to an electronic throttle plate, said PCM having control logic to disable said drive electronics and return said electronic throttle plate to a default position, determine a default throttle position sensor (TPS) output voltage corresponding to said default position, command a full closing motor voltage, compare a full closing TPS output voltage to said default TPS output voltage, and engage failure mode management when said full closing TPS output voltage and said default TPS output voltage are significantly different from each other.

15. Upon information and belief, the ’260 patent Accused Instrumentalities infringe at least claim 1 of the ’260 patent. The ’260 patent Accused Instrumentalities comprise an electronic throttle control apparatus (*Figure 1*) for testing integrity of a motor drive electronics disable feature (*Figure 2*) comprising: a PCM having drive electronics for controlling a motor coupled to an electronic throttle plate (*Figure 3*), said PCM having control logic to disable said drive electronics and return said electronic throttle plate to a default position (*Figure 4*),

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

determine a default throttle position sensor (TPS) output voltage corresponding to said default position, command a full closing motor voltage, compare a full closing TPS output voltage to said default TPS output voltage (*Figure 5*), and engage failure mode management when said full closing TPS output voltage and said default TPS output voltage are significantly different from each other (*Figure 6*).



Volkswagen SSP 823603

As shown above, there is a Throttle Valve Control Module (J338), which in conjunction with the Throttle Drive Angle Sensor (G187) and Throttle Drive Angle Sensor 2 (G188), constitutes an electronic throttle control apparatus.

Figure 1

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

2015 Volkswagen Touareg (7P5) V6-3.6L (CGRA)

Vehicle » A L L Diagnostic Trouble Codes (DTC) » Testing and Inspection » P Code Charts » P0638 » Engine Control Module, 2016 MY

ENGINE CONTROL MODULE, 2016 MY

Engine Control Module, 2016 MY

DTC / Description	Monitor Strategy Description	Malfunction Criteria and Threshold Value	Secondary Parameters with Enable Conditions	Monitoring Time Length	MIL Illumination	Component Diagnostic Procedure
P0634 Control Module Internal Temperature "A" Too High	Engine Coolant Pump Over-Temperature Power Stage	Power stage temperature > 170° C	Ignition on	0.5 s Continuous	2 DCY	If a sensor/component DTC is also set, diagnose that code BEFORE replacing the ECM. Replace the Engine Control Module (J623) . Refer to appropriate repair manual.
	Supplementary Coolant Pump Over-Temperature Power Stage	Power stage temperature > 150° C				
	Fuel Pump Control (FPC) Over-Temperature Power Stage		Engine speed > 80 RPM			
P0638 Throttle Actuator Control Range/Performance Bank 1	Throttle Actuator Rationality Check Close Movement	Time to close to reference point > 0.6 s And Deviation to reference point > 2.88%	Engine speed 0 RPM Vehicle speed 0 km/h ECT > -20° C IAT > -20° C Case 1: Ignition on Case 2: Engine shut-off-time > 5.0 s Number of checks 3.0 [-]	5.0 s Multiple	2 DCY	Check the Throttle Valve Control Module (GX3) . Refer to ⇒ [Throttle Valve Control Module (GX3): Checking]
	Throttle Actuator Signal Range Check @ Mechanical Stop Low	TPS 1 signal voltage < 0.40; > 0.80 V Or TPS 2 signal voltage < 4.20; > 4.60 V	Engine speed 0 RPM Vehicle speed 0 km/h Case 1: Ignition on ECT -20 - 115° C IAT -20 - 143° C Case 2:	0.3 s Multiple		

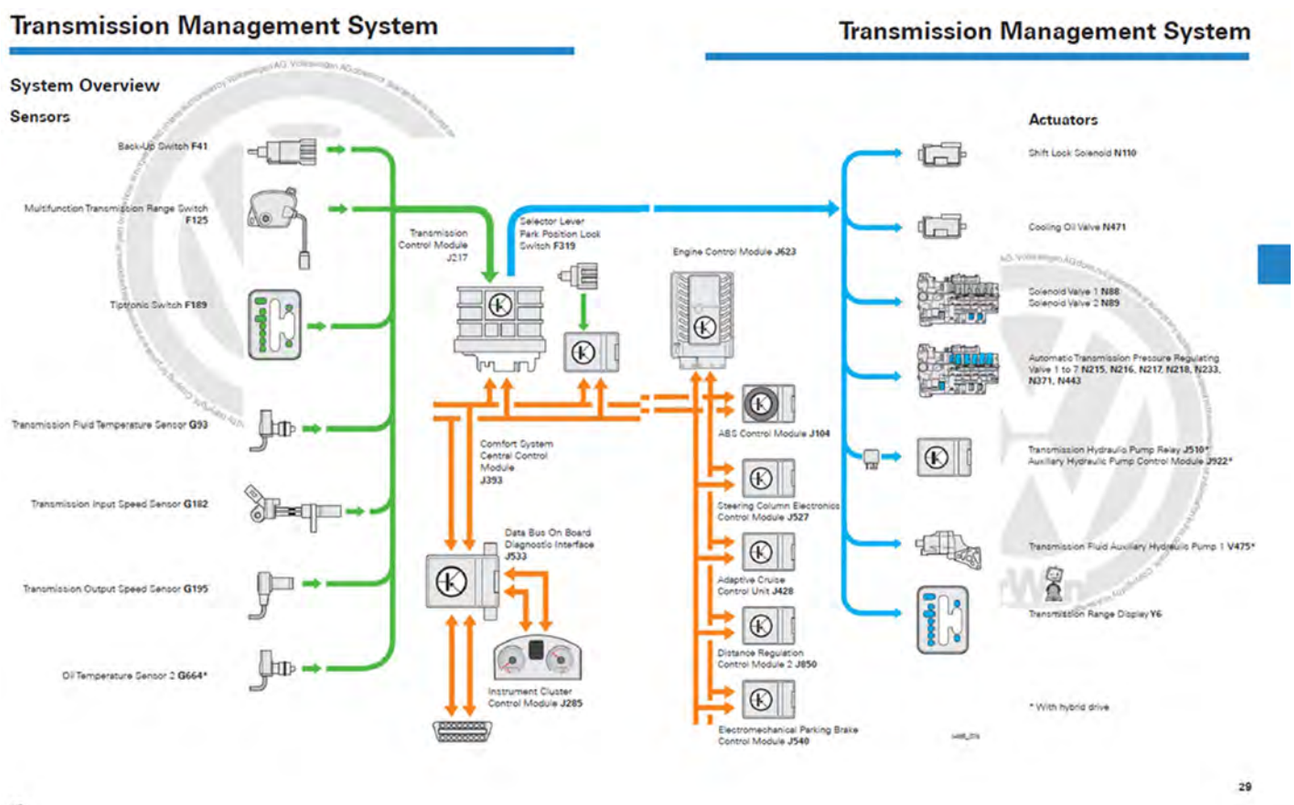
testing integrity of a motor drive electronics disable feature

As shown above, there is an Electronic Throttle Control (ETC)[J388] system which tests integrity of a motor drive electronics disable feature.

The PCM/ECM uses the Throttle Drive Angle Sensor (G187) and Throttle Drive Angle Sensor 2 (G188) to monitor the actual throttle blade position and when the actual position is out of range with the target position, the ECM (J623) will set the DTC P0638. Bank 1 refers to the side of the engine with cylinder number one, however most vehicles use one throttle body for all cylinders. This code is similar to code P0639. Most throttle bodies of this type are not serviceable and need to be replaced. The throttle body is spring actuated to hold it at an open position in the event of a motor failure; in some cases, with a complete failure, the throttle will be unresponsive, and the vehicle will only be capable of driving at a slow speed.

https://www.obd-codes.com/p0638

Figure 2

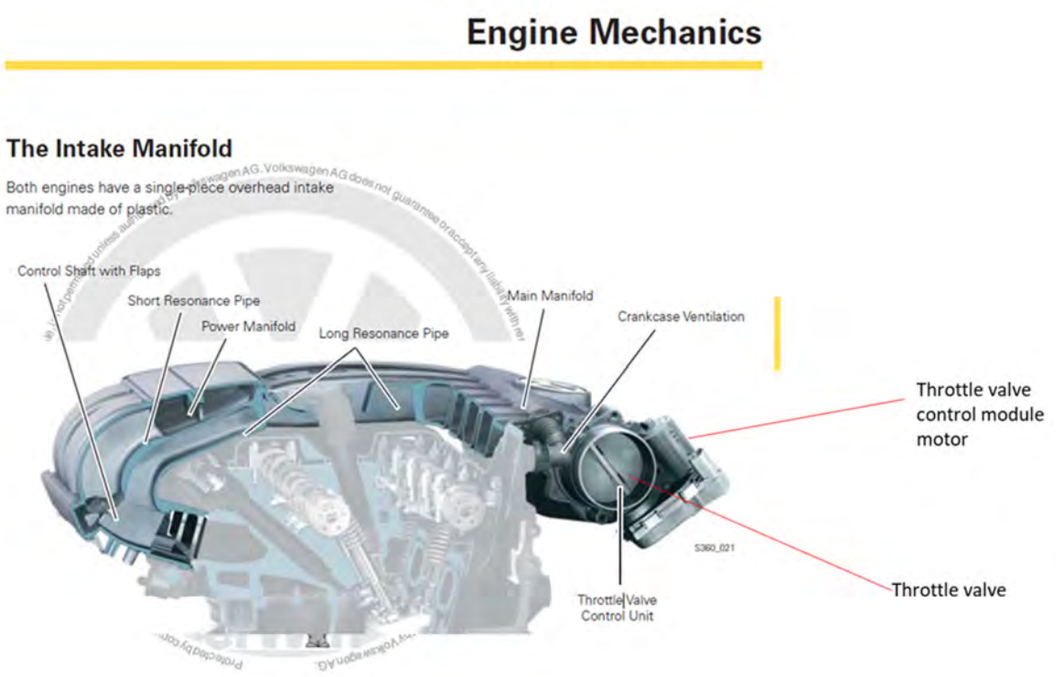


Volkswagen SSP 823603

The PCM (powertrain control module) comprises the ECM (J623) and the Transmission Control Module TCM (J217) (shown above).

The PCM, shown above, has drive electronics for controlling a throttle valve control module motor coupled to an electronic throttle plate/throttle valve (shown below).

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565



Volkswagen SSP 823603

Figure 3

2015 Volkswagen Touareg (7P5) V6-3.6L (CGRA)

Vehicle » A L L Diagnostic Trouble Codes (DTC) » Testing and Inspection » P Code Charts » P2106 » Engine Control Module, 2016 MY

ENGINE CONTROL MODULE, 2016 MY

Engine Control Module, 2016 MY

DTC / Description	Monitor Strategy Description	Malfunction Criteria and Threshold Value	Secondary Parameters with Enable Conditions	Monitoring Time Length	MIL Illumination	Component Diagnostic Procedure
P2106 Throttle Actuator Control System - Forced Limited Power	Throttle Actuator Short To Battery Plus / Short To Ground	Internal check failed		0.5 s Continuous	2 DCY	Check the Throttle Valve Control Module (GX3) . Refer to ⇒ | Throttle Valve Control Module (GX3), Checking |
	Throttle Actuator Open Circuit		Duty cycle > 80.0% Or Deviation throttle value angles vs. throttle value set point > 4.0 - 50.0%			
	Throttle Actuator Temperature / Current Monitoring					
	Throttle Actuator Functional Check					
P2122 Throttle/Pedal Position Sensor/Switch "D" Circuit Low	Accelerator Pedal Position (APP) Sensor 1 Out Of Range Low	Signal voltage < 0.65 V		0.5 s Continuous	2 DCY	Check the Accelerator Pedal Module (GX2) . Refer to ⇒ | Accelerator Pedal Module (GX2), Checking |
P2123 Throttle/Pedal Position Sensor/Switch "D" Circuit High	Accelerator Pedal Position (APP) Sensor 1 Out Of Range High	Signal voltage > 4.89 V		0.5 s Continuous	2 DCY	Check the Accelerator Pedal Module (GX2) . Refer to ⇒ | Accelerator Pedal Module (GX2), Checking |

DTC P2106 is exemplary of the DTCs that are more specific that will typically accompany DTC P0652.

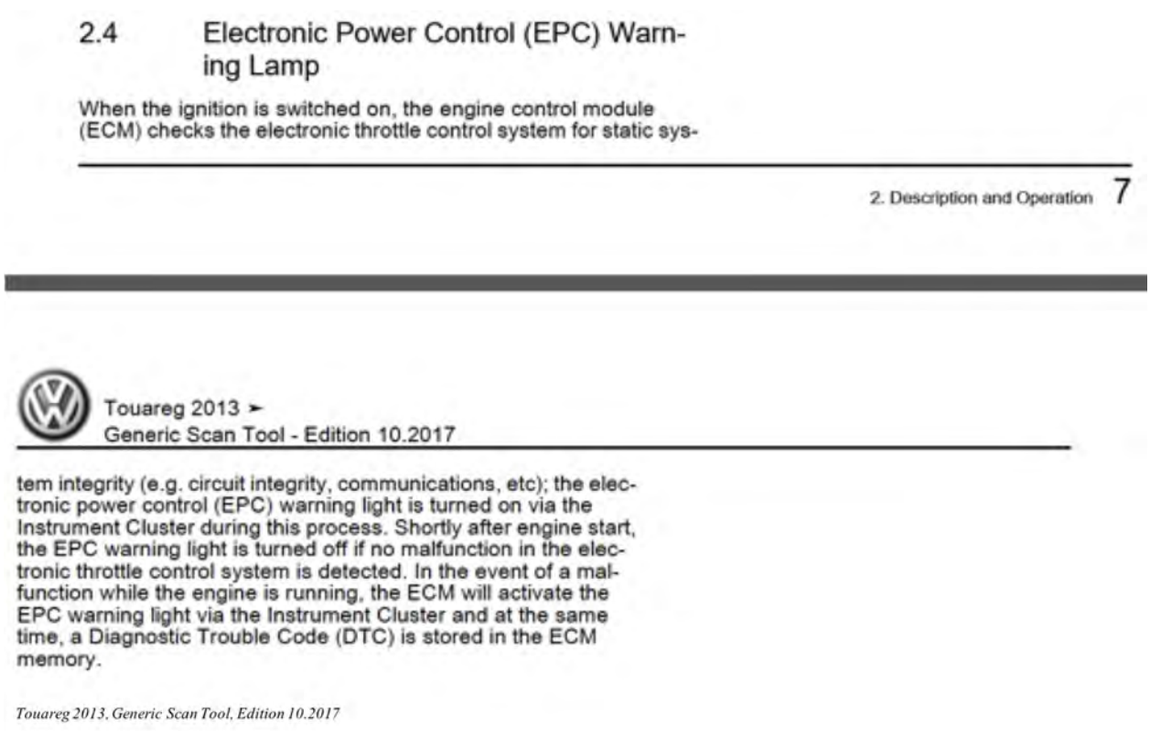
https://www.obd-codes.com

For example, as shown above, control logic in the ECM issues a command which controls the throttle actuator control system - limiting power where there is a sensor or circuit error or failure of the throttle valve functionality check affecting the Throttle Valve Control Module (J388) (shown above) (disable drive electronics).

When there is an error detected during continuous monitoring (P2106, above), or when the ECM performs specific checks (P0638, below), a Throttle Actuator Rationality Check for Close

Movement (Default Position) or a Throttle Actuator Signal Range Check at the low mechanical stop, the ECM Turns on the Electronic Power Control (EPC) warning lamp and the ECM returns the electronic throttle plate to a default position.

Further, the ECM relinquishes control of the Throttle Valve Control Module (J388) which remains in a default position.



2.4 Electronic Power Control (EPC) Warning Lamp

When the ignition is switched on, the engine control module (ECM) checks the electronic throttle control system for static system integrity (e.g. circuit integrity, communications, etc); the electronic power control (EPC) warning light is turned on via the Instrument Cluster during this process. Shortly after engine start, the EPC warning light is turned off if no malfunction in the electronic throttle control system is detected. In the event of a malfunction while the engine is running, the ECM will activate the EPC warning light via the Instrument Cluster and at the same time, a Diagnostic Trouble Code (DTC) is stored in the ECM memory.

2. Description and Operation 7

Touareg 2013 ➢
Generic Scan Tool - Edition 10.2017

Touareg 2013, Generic Scan Tool, Edition 10.2017

Figure 4

For example, as demonstrated by DTC P0638 included below. The ECM makes a determination of the amount of time required to reach a reference point (default position of the electronic throttle plate) and the deviation from the reference point. On information and belief, the control logic in the ECM disables the drive electronics for controlling the throttle motor by not supplying power to the throttle motor, whereby the electronic throttle plate is returned to a default position. DTC P0638 also demonstrates that the ECM commands full motor closing voltage (signal range check at mechanical stop) and compares that to TPS 1 output voltage (< 0.40; > 0.80 V) or TPS 2 output voltage (< 4.20; > 4.60 V). Any significant difference from these voltage ranges are considered out of range, resulting in at least DTC P0638. The algorithms executed by the ECM for DTC P0638 and DTC P2106 differ, as such errors during a continuous monitor (see P2106 above); however, DTC P0638 algorithms are typically performed during initialization or shut down.

2015 Volkswagen Touareg (7P5) V6-3.6L (CGRA)

Vehicle » A L L Diagnostic Trouble Codes (DTC) » Testing and Inspection » P Code Charts » P0638 » Engine Control Module, 2016 MY

ENGINE CONTROL MODULE, 2016 MY

Engine Control Module, 2016 MY

DTC / Description	Monitor Strategy Description	Malfunction Criteria and Threshold Value	Secondary Parameters with Enable Conditions	Monitoring Time Length	MIL Illumination	Component Diagnostic Procedure
P0634 Control Module Internal Temperature "A" Too High	Engine Coolant Pump Over-Temperature Power Stage	Power stage temperature > 170° C	Ignition on	0.5 s Continuous	2 DCY	If a sensor/component DTC is also set, diagnose that code BEFORE replacing the ECM. Replace the Engine Control Module (J623) . Refer to appropriate repair manual.
	Supplementary Coolant Pump Over-Temperature Power Stage	Power stage temperature > 150° C				
	Fuel Pump Control (FPC) Over-Temperature Power Stage		Engine speed > 80 RPM			
P0638 Throttle Actuator Control Range/Performance Bank 1	Throttle Actuator Rationality Check Close Movement	Time to close to reference point > 0.6 s And Deviation to reference point > 2.88%	Engine speed 0 RPM Vehicle speed 0 km/h ECT > -20° C IAT > -20° C Case 1: Ignition on Case 2: Engine shut-off-time > 5.0 s Number of checks 3.0 [-]	5.0 s Multiple	2 DCY	Check the Throttle Valve Control Module (GX3) . Refer to ⇒ [Throttle Valve Control Module (GX3), Checking]
	Throttle Actuator Signal Range Check @ Mechanical Stop Low	TPS 1 signal voltage < 0.40; > 0.80 V Or TPS 2 signal voltage < 4.20; > 4.60 V	Engine speed 0 RPM Vehicle speed 0 km/h Case 1: Ignition on ECT -20 - 115° C IAT -20 - 143° C Case 2:	0.3 s Multiple		

https://www.obd-codes.com

For example, as shown above, there are two checks for P0638; one is determined from the amount of time to reach a reference point (default position) and the deviation from the reference point. The second is a command for full motor closing voltage (signal range check at mechanical stop) is compared to TPS 1 output voltage (< 0.40; > 0.80 V) or TPS 2 output voltage (< 4.20; > 4.60 V) and any deviation from these voltage ranges are considered out of range and will set the DTC. These checks differ from errors detected during a continuous monitor (see above) and are typically performed during initialization or shut down.

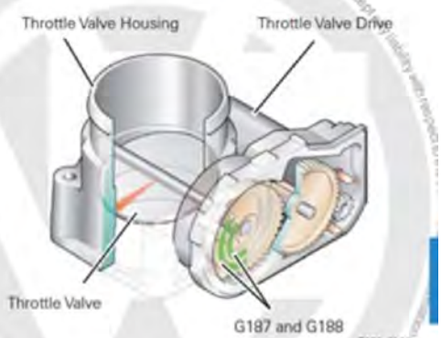
Figure 5

The Throttle Drive Angle Sensor 1 G187 and Throttle Drive Angle Sensor 2 G188 in the Throttle Valve Control Unit

These sensors determine the current position of the throttle valve and send this information to the ECM.

Signal Utilization

The ECM recognizes the position of the throttle valve from the angle sensors signals. The signals from the two sensors are redundant, meaning that both sensors provide the same signal.



Effects of a Signal Failure

Example 1

The ECM receives an implausible signal or no signal at all from an angle sensor:

- An entry is made in the DTC memory and the error light for electric throttle operation is switched on
- Systems which affect torque, (e.g. cruise control system or engine drag torque control), are switched off
- The load signal is used to monitor the remaining angle sensor
- The accelerator pedal responds normally

Example 2

The ECM receives an implausible signal or no signal from both angle sensors:

- An entry is made for both sensors in the DTC memory and the error light for electric throttle operation is switched on
- The throttle valve drive is switched off
- The engine runs only at an increased idle speed of 1,500 RPM and no longer reacts to the accelerator pedal

Volkswagen SSP 823603

2015 Volkswagen Touareg (7P5) V6-3.6L (CGRA)

Vehicle » A L L Diagnostic Trouble Codes (DTC) » Testing and Inspection » P Code Charts » P2106 » Engine Control Module, 2016 MY

ENGINE CONTROL MODULE, 2016 MY

Engine Control Module, 2016 MY

DTC / Description	Monitor Strategy Description	Malfunction Criteria and Threshold Value	Secondary Parameters with Enable Conditions	Monitoring Time Length	MIL Illumination	Component Diagnostic Procedure
P2106 Throttle Actuator Control System - Forced Limited Power	Throttle Actuator Short To Battery Plus / Short To Ground	Internal check failed		0.5 s Continuous	2 DCY	Check the Throttle Valve Control Module (GX3) . Refer to ⇒ [Throttle Valve Control Module (GX3), Checking]
	Throttle Actuator Open Circuit		Duty cycle > 80.0% Or Deviation throttle value angles vs. throttle value set point > 4.0 - 50.0%			
	Throttle Actuator Temperature / Current Monitoring					
	Throttle Actuator Functional Check					
P2122 Throttle/Pedal Position Sensor/Switch "D" Circuit Low	Accelerator Pedal Position (APP) Sensor 1 Out Of Range Low	Signal voltage < 0.65 V		0.5 s Continuous	2 DCY	Check the Accelerator Pedal Module (GX2) . Refer to ⇒ [Accelerator Pedal Module (GX2), Checking] .
P2123 Throttle/Pedal Position Sensor/Switch "D" Circuit High	Accelerator Pedal Position (APP) Sensor 1 Out Of Range High	Signal voltage > 4.89 V		0.5 s Continuous	2 DCY	Check the Accelerator Pedal Module (GX2) . Refer to ⇒ [Accelerator Pedal Module (GX2), Checking] .

For example, as shown above, engine failure mode management P2106 (throttle actuator control system-forced limited power) is engaged when a full closing TPS output voltage indicates a deviation of throttle angle values (as indicated by throttle output voltage [TPS1 output voltage signal) opposed to throttle value set point > 4% - 50%).

Figure 6

Based upon the totality of the foregoing evidence, and based further upon information and belief, the ’260 patent Accused Instrumentalities include “an apparatus for testing integrity of a motor drive electronics disable feature comprising: a PCM having drive electronics for controlling a motor coupled to an electronic throttle plate, said PCM having control logic to disable said drive

electronics and return said electronic throttle plate to a default position, determine a default throttle position sensor (TPS) output voltage corresponding to said default position, command a full closing motor voltage, compare a full closing TPS output voltage to said default TPS output voltage, and engage failure mode management when said full closing TPS output voltage and said default TPS output voltage are significantly different from each other."

COUNT II – INFRINGEMENT OF U.S. PATENT NO. 6,443,128

16. The allegations set forth in the foregoing paragraphs 1 through 15 are incorporated into this Second Claim for Relief.

17. On September 3, 2002, U.S. Patent No. 6,443,128 ("the '128 patent"), entitled "Method of Controlling an Internal Combustion Engine," was duly and legally issued by the United States Patent and Trademark Office. A true and correct copy of the '128 patent is attached as Exhibit 2.

18. Plaintiff is the assignee and owner of the right, title and interest in and to the '128 patent, including the right to assert all causes of action arising under said patents and the right to any remedies for infringement of them.

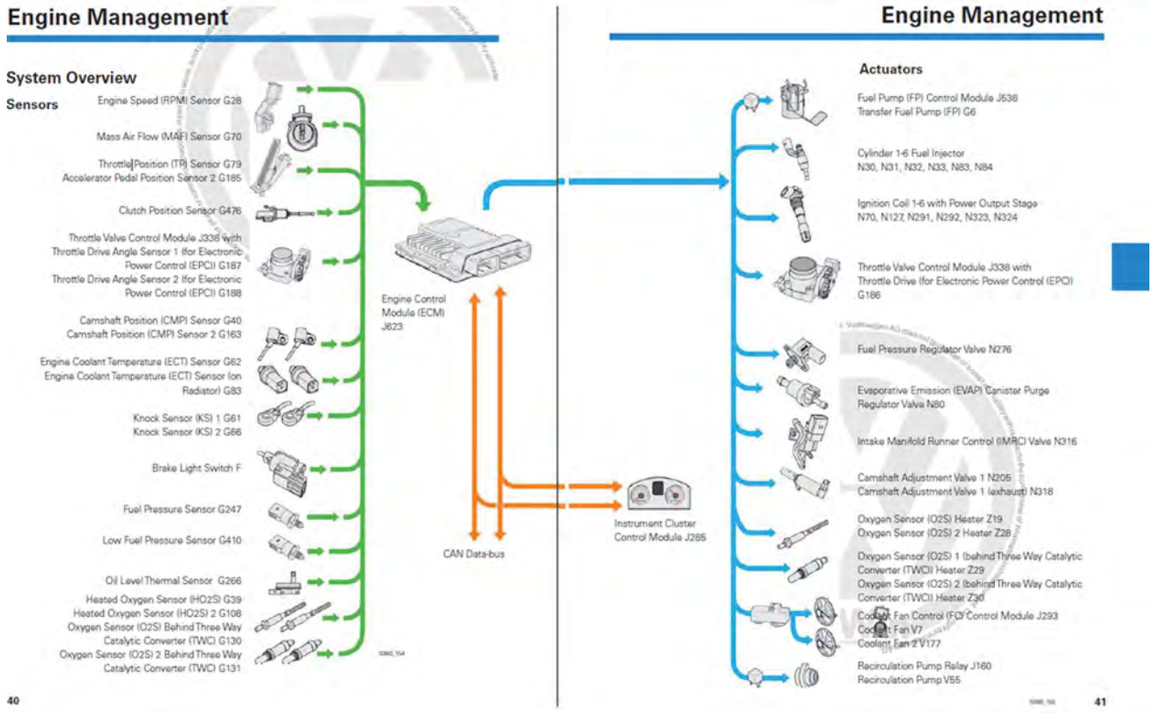
19. Upon information and belief, Defendants have directly infringed at least claim 1 of the '128 patent by making, using, selling, importing and/or providing and causing to be used the 2015-2018 3.6L Touareg (the "'128 patent Accused Instrumentalities").

20. In particular, claim 1 of the '128 patent recites a method of controlling an internal combustion engine, the engine having an engine controller and an electronically controlled throttle including a throttle control motor driven by a throttle control circuit, the method comprising: determining a throttle position command for the throttle control motor; applying the throttle position command to the throttle control motor with the throttle control circuit; detecting an open circuit condition in the throttle control circuit; detecting a closed circuit condition in the throttle control circuit; after detection of the closed circuit condition, clipping the throttle

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

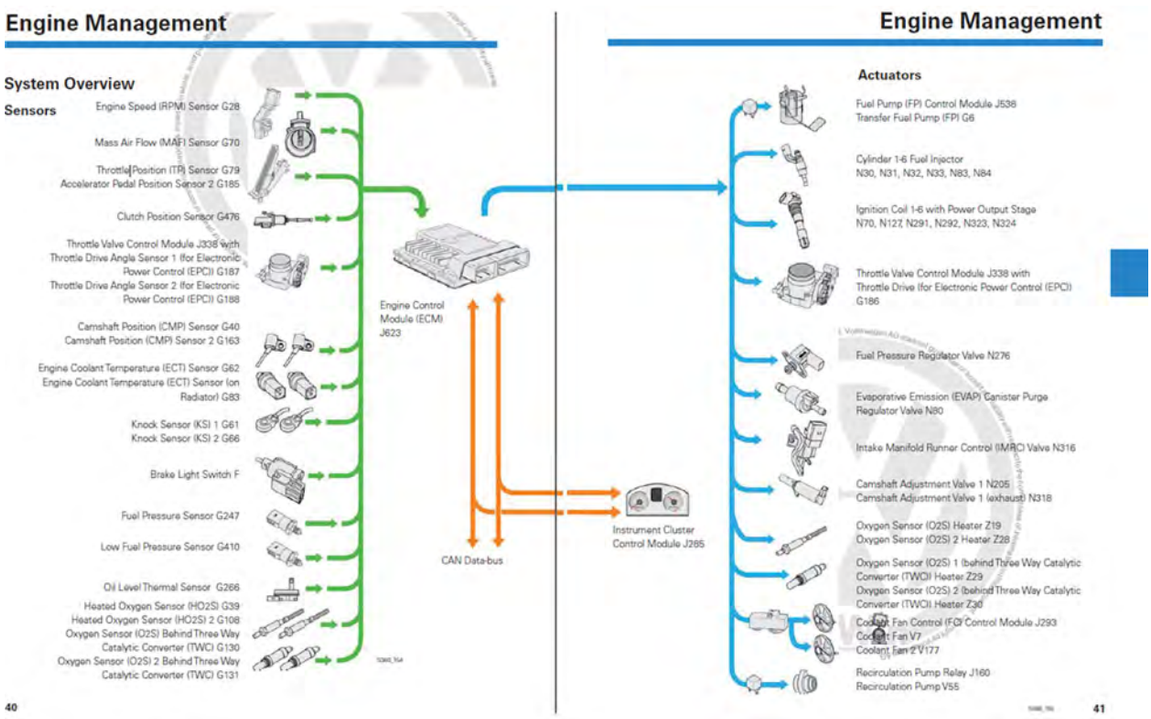
position command; and applying the clipped throttle position command to the throttle control motor with the throttle control circuit.

21. On information and belief, the '128 patent Accused Instrumentalities infringe at least claim 1 of the '128 patent. The '128 patent Accused Instrumentalities practice a method of controlling an internal combustion engine (*Figure 7*), the engine having an engine controller and an electronically controlled throttle including a throttle (*Figure 8*) control motor driven by a throttle control circuit (*Figure 8*), the method comprising: determining a throttle position command for the throttle control motor (*Figure 9*); applying the throttle position command to the throttle control motor with the throttle control circuit (*Figure 10*); detecting an open circuit condition in the throttle control circuit (*Figure 11*); detecting a closed circuit condition in the throttle control circuit (*Figure 11*); after detection of the closed circuit condition, clipping the throttle position command (*Figure 12*); and applying the clipped throttle position command to the throttle control motor with the throttle control circuit (*Figure 12*).



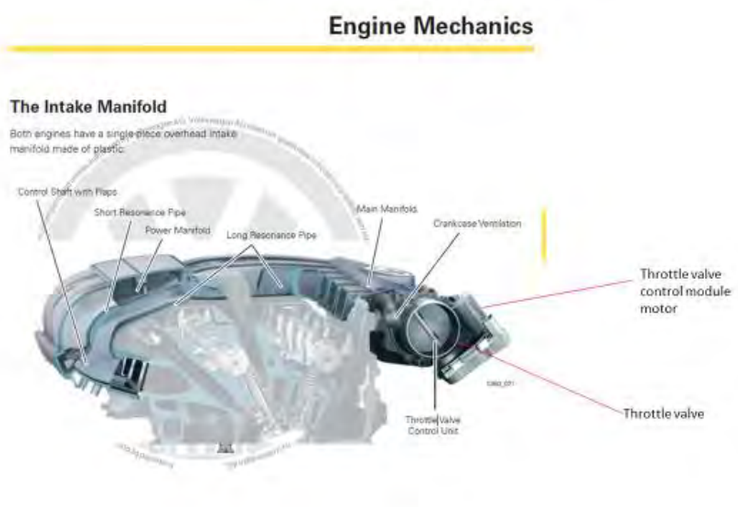
The Engine Control Module (J623) provides a method of controlling an internal combustion engine.

Figure 7

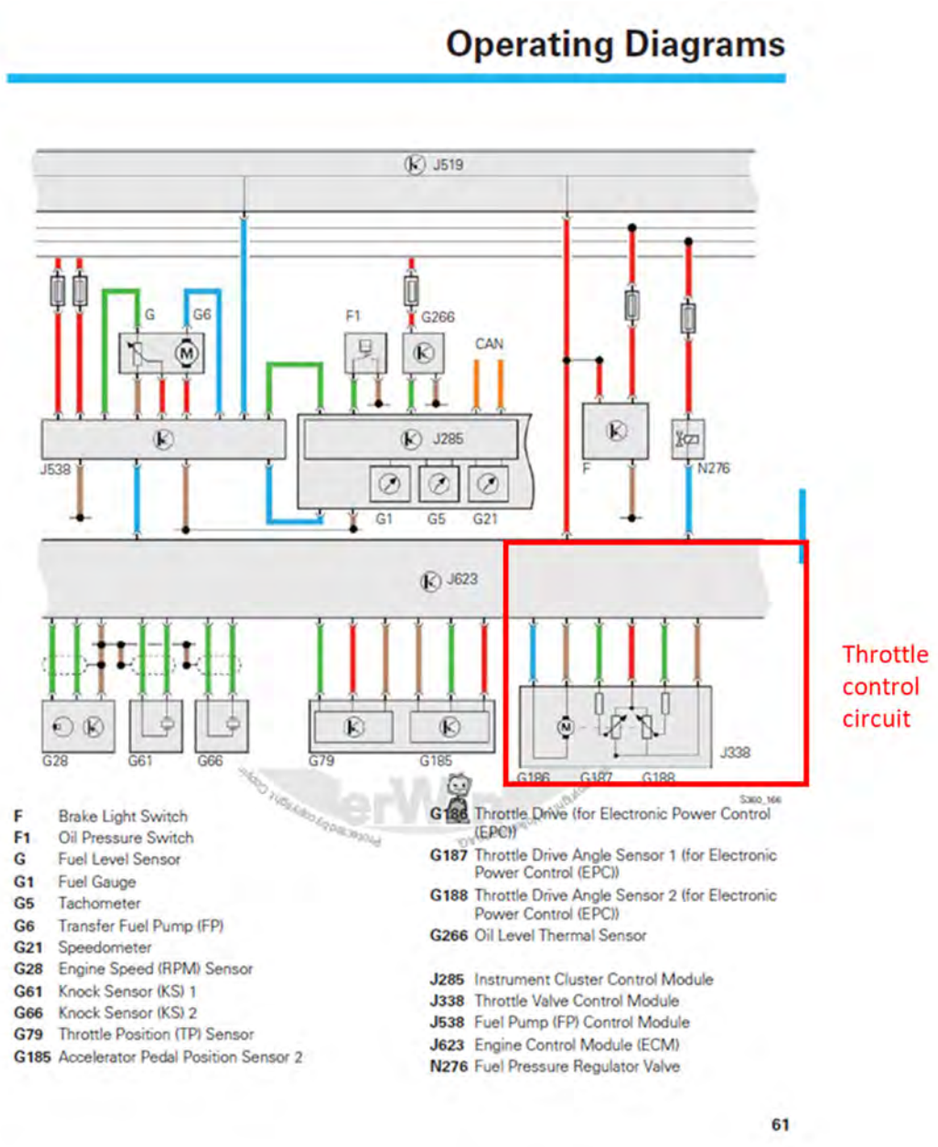


The ’128 patent Infringing Instrumentalities comprise an Engine controller, the ECM (J623) and an electronically controlled throttle (J338).

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

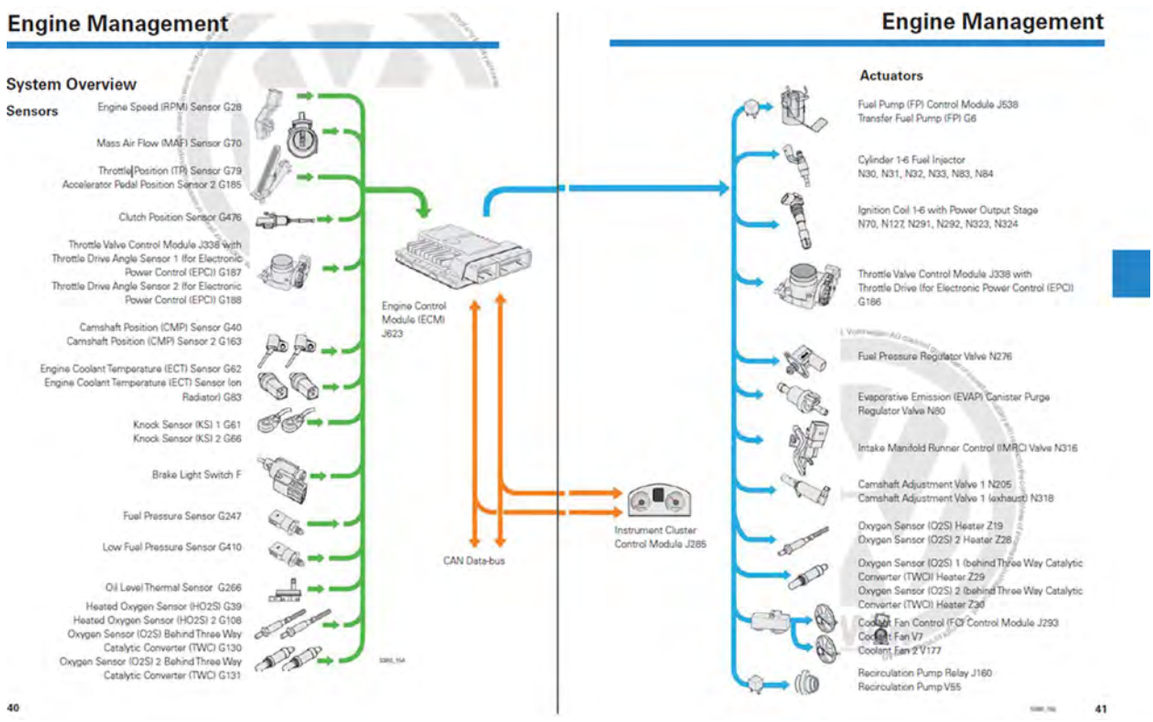


The method practiced by the ’128 patent Infringing Instrumentalities comprises an electronically controlled throttle (J338) including a throttle control motor driven by a throttle control circuit.



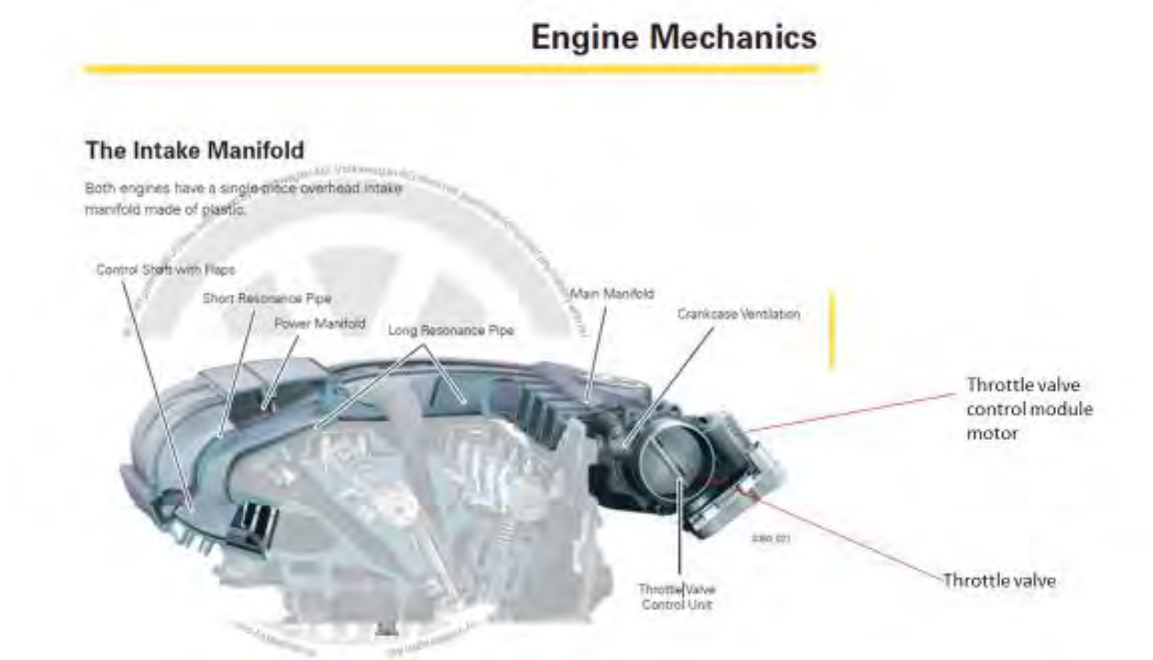
The electronically controlled throttle includes a throttle control motor (J338) driven by a throttle control circuit. *See above*.

Figure 8

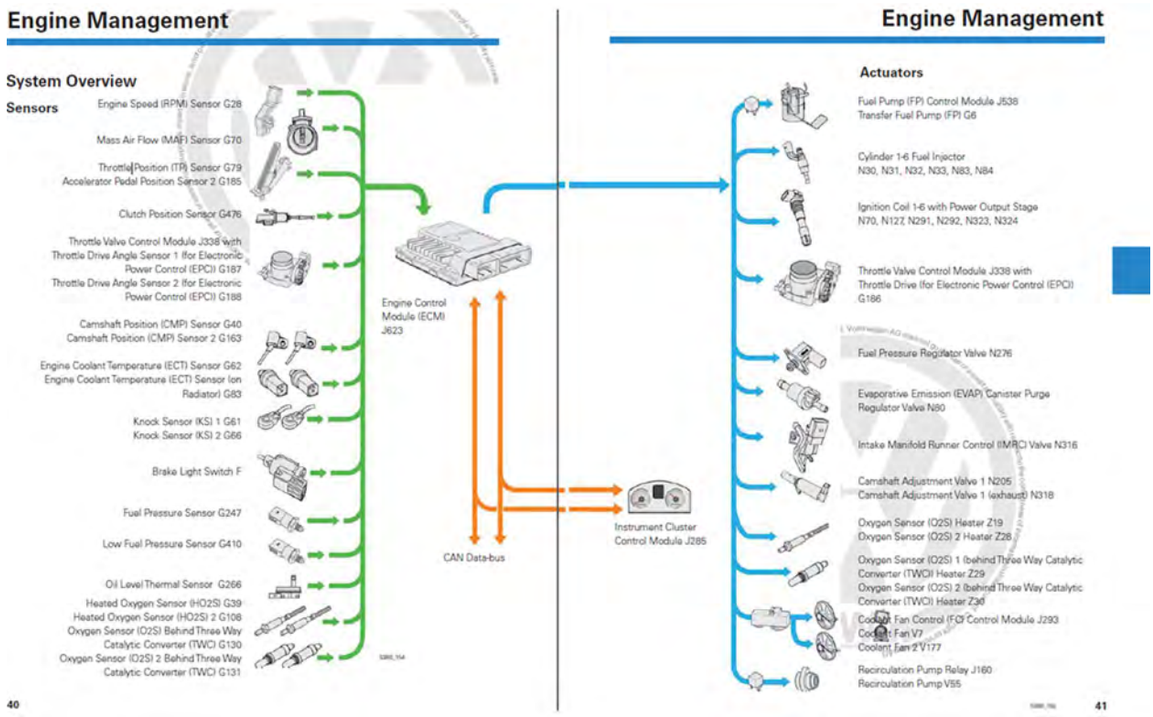


The throttle position command is sent to the Electronic Throttle Control module from the ECM (J623) by way of a motor operation signal. The throttle position command is derived from the accelerator pedal position sensor 2 (G185).

Figure 9



PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565



The throttle position command (from the Accelerator Pedal Position Sensor 2 G185) is applied to the throttle valve control module (J388) motor (shown below) with the throttle control circuit (shown above).

Figure 10

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

2015 Volkswagen Touareg (7P5) V6-3.6L (CGRA)

Vehicle » A L L Diagnostic Trouble Codes (DTC) » Testing and Inspection » P Code Charts » P2106 » Engine Control Module, 2016 MY

ENGINE CONTROL MODULE, 2016 MY

Engine Control Module, 2016 MY

DTC / Description	Monitor Strategy Description	Malfunction Criteria and Threshold Value	Secondary Parameters with Enable Conditions	Monitoring Time Length	MIL Illumination	Component Diagnostic Procedure
P2106 Throttle Actuator Control System - Forced Limited Power	Throttle Actuator Short To Battery Plus / Short To Ground	Internal check failed		0.5 s Continuous	2 DCY	Check the Throttle Valve Control Module (GX3) . Refer to ⇒ Throttle Valve Control Module (GX3), Checking
	Throttle Actuator Open Circuit		Duty cycle > 80.0% Or Deviation throttle value angles vs. throttle value set point > 4.0 - 50.0%			
	Throttle Actuator Temperature / Current Monitoring					
	Throttle Actuator Functional Check					

DTC P2106 Throttle Actuator Control System - Forced Limited Power – The monitor strategy looks for an open circuit condition in the throttle actuator, therefore, detecting open circuitry in the throttle control circuit.

Figure 11

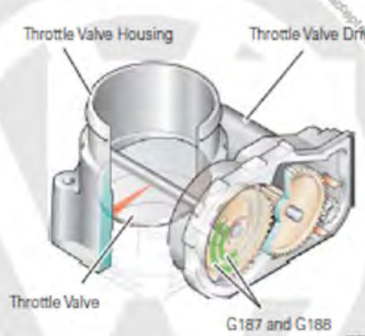
Engine Management

The Throttle Drive Angle Sensor 1 G187 and Throttle Drive Angle Sensor 2 G188 in the Throttle Valve Control Unit

These sensors determine the current position of the throttle valve and send this information to the ECM.

Signal Utilization

The ECM recognizes the position of the throttle valve from the angle sensors signals. The signals from the two sensors are redundant, meaning that both sensors provide the same signal.



Effects of a Signal Failure

Example 1

The ECM receives an implausible signal or no signal at all from an angle sensor:

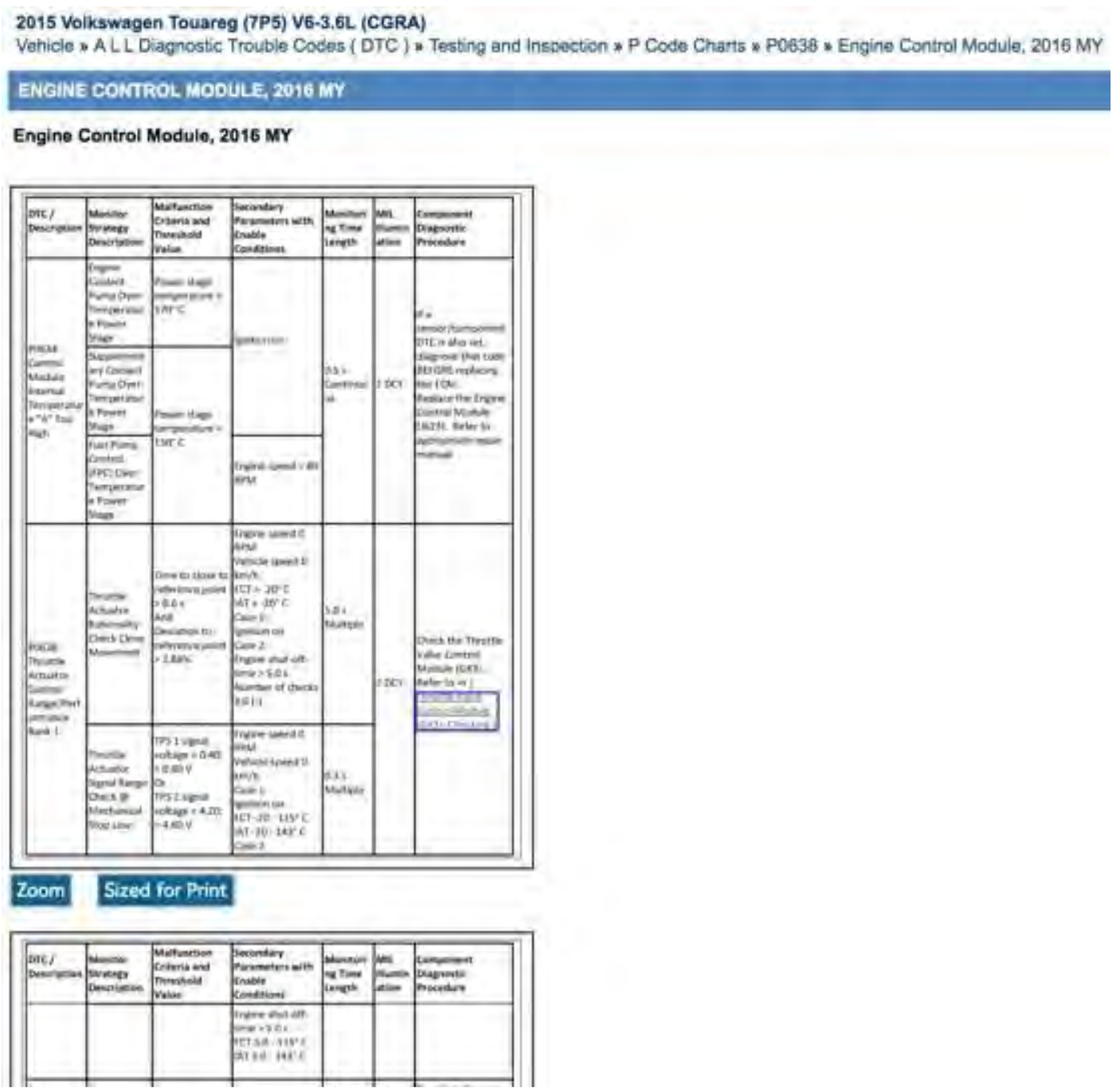
- An entry is made in the DTC memory and the error light for electric throttle operation is switched on
- Systems which affect torque, (e.g. cruise control system or engine drag torque control), are switched off
- The load signal is used to monitor the remaining angle sensor
- The accelerator pedal responds normally

Example 2

The ECM receives an implausible signal or no signal from both angle sensors:

- An entry is made for both sensors in the DTC memory and the error light for electric throttle operation is switched on
- The throttle valve drive is switched off
- The engine runs only at an increased idle speed of 1,500 RPM and no longer reacts to the accelerator pedal

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

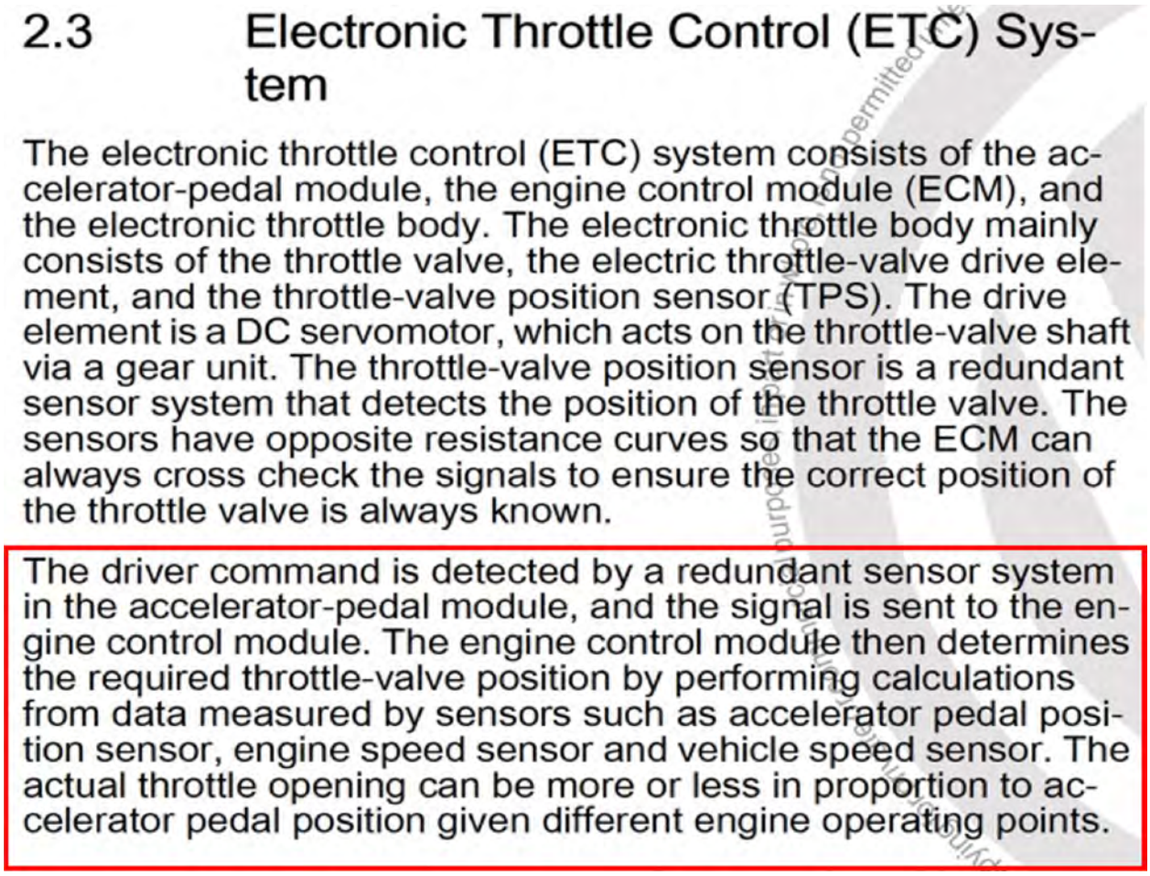


A circuit which removes the peak of a waveform is known as a clipper. A clipper is designed to prevent the output of a circuit from exceeding a predetermined voltage level. *https://www.allaboutcircuits.com/textbook/semiconductors/chpt-3/clipper-circuits/*

Clipping prohibits a surge in engine power which results from an Accelerator Pedal Position Sensor 2 (G185) signaling to the Throttle Valve Control Module (J338) through the Electronic Control Module (ECM; J623)) that a sharp increase in power is needed. An open circuit condition in the throttle control circuit, may result in a driver applying more pressure to the accelerator pedal thereby causing the Accelerator Pedal Position Sensor 2 (G185) to send a

higher voltage signal to the ECM. On information in belief, the ECM creates a throttle position command based on the throttle position sensor. However, if there is a malfunction detected by the system, such as an open circuit condition in one drive cycle, which is later followed by a closed circuit condition, then the throttle position command will be clipped to a throttle position command. On information and belief, the clipped throttle position command is applied to the throttle control motor with the throttle control circuit.

The throttle position command is limited or clipped prior to application to the throttle control motor, resulting in smooth changing of the applied throttle position command.



2.3 Electronic Throttle Control (ETC) System

The electronic throttle control (ETC) system consists of the accelerator-pedal module, the engine control module (ECM), and the electronic throttle body. The electronic throttle body mainly consists of the throttle valve, the electric throttle-valve drive element, and the throttle-valve position sensor (TPS). The drive element is a DC servomotor, which acts on the throttle-valve shaft via a gear unit. The throttle-valve position sensor is a redundant sensor system that detects the position of the throttle valve. The sensors have opposite resistance curves so that the ECM can always cross check the signals to ensure the correct position of the throttle valve is always known.

The driver command is detected by a redundant sensor system in the accelerator-pedal module, and the signal is sent to the engine control module. The engine control module then determines the required throttle-valve position by performing calculations from data measured by sensors such as accelerator pedal position sensor, engine speed sensor and vehicle speed sensor. The actual throttle opening can be more or less in proportion to accelerator pedal position given different engine operating points.

The throttle position command is limited or clipped prior to application to the throttle control motor, resulting in smooth changing of the applied throttle position command. “The actual throttle opening can be more or less in proportion to accelerator pedal position given different engine operating points.”

P0121 Throttle/ Pedal Position Sensor/Switch "A" Circuit Range/ Performance	Throttle Position Sensor 1 Rationality Check	• TPS 1 – TPS 2 > 5.10 – 6.30% • And • Actual TPS 1 calculated value > actual TPS 2 calculated value • Or • TPS 1 calculated value > 9.0%	• Engine speed > 480 RPM	• 0.3 s • Multiple	• 2 DCY	– Check the Throttle Valve Control Module - GX3- . Refer to ⇒ "3.6.32 Throttle Valve Control Module GX3 , Checking", page 893 .

Figure 12

Based upon the totality of the foregoing evidence, and based further upon information and belief, the '128 patent Accused Instrumentalities practice a method for controlling an internal combustion engine, the engine having an engine controller and an electronically controlled throttle including a throttle control motor driven by a throttle control circuit, the method comprising: determining a throttle position command for the throttle control motor; applying the throttle position command to the throttle control motor with the throttle control circuit; detecting an open circuit condition in the throttle control circuit; detecting a closed circuit condition in the throttle control circuit; after detection of the closed circuit condition, clipping the throttle position command; and applying the clipped throttle position command to the throttle control motor with the throttle control circuit.

COUNT III – INFRINGEMENT OF U.S. PATENT NO. 6,581,565

22. The allegations set forth in the foregoing paragraphs 1 through 21 are incorporated into this Third Claim for Relief.

23. On June 24, 2003, U.S. Patent No. 6,581,565 ("the '565 patent"), entitled "Engine Torque Controller" was duly and legally issued by the United States Patent and Trademark Office. A true and correct copy of the '565 patent is attached as Exhibit 3.

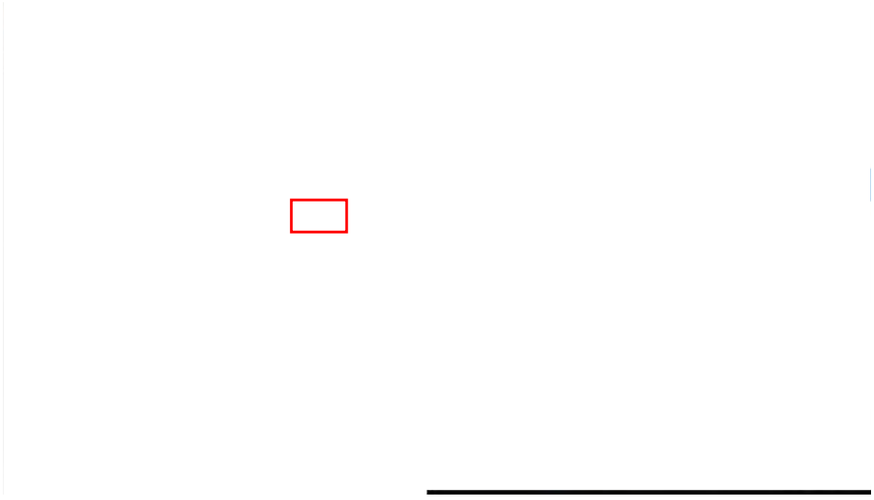
24. Plaintiff is the assignee and owner of the right, title and interest in and to the '565 patent, including the right to assert all causes of action arising under said patents and the right to any remedies for infringement of them.

25. Upon information and belief, Defendants have directly infringed at least claim 1 of the '565 patent by making, using, selling, importing and/or providing and causing to be used

the 2013-2018 Passat, 2012-2016 CC, 2012-2017 Touareg, 2018-2019 Atlas, and 2012-2016 Porsche Cayenne (the "'565 patent Accused Instrumentalities").

26. In particular, claim 1 of the '565 patent recites a device for controlling a torque output of an engine, the device comprising: a torque demand controller for generating a torque demand signal; and a torque producer which receives the torque demand signal, the torque producer includes: an estimator which receives as inputs a current spark angle signal, a current air/fuel ratio signal and an estimated air charge signal and outputs an estimated torque signal; a comparator which receives as inputs the estimated torque signal and a desired torque signal and outputs a difference signal; a high pass filter which receives as an input the difference signal and outputs a filtered difference signal in which low frequency components are absent; and a transient torque controller which receives as an input the filtered difference signal and outputs a fuel adjustment signal and a spark adjustment signal.

27. On information and belief, the '565 patent Accused Instrumentalities infringe at least claim 1 of the '565 patent. The '565 patent Accused Instrumentalities comprise a device for controlling (*Figure 13*) a torque output of an engine, the device comprising: a torque demand controller for generating a torque demand signal (*Figure 14*); and a torque producer which receives the torque demand signal (*Figures 15*), the torque producer includes: an estimator which receives as inputs a current spark angle signal (*Figure 16*), a current air/fuel ratio signal and an estimated air charge signal and outputs an estimated torque signal (*Figure 16*); a comparator which receives as inputs the estimated torque signal and a desired torque signal and outputs a difference signal (*Figure 17*); a high pass filter which receives as an input the difference signal and outputs a filtered difference signal in which low frequency components are absent (*Figure 18*); and a transient torque controller which receives as an input the filtered difference signal and outputs a fuel adjustment signal and a spark adjustment signal (*Figure 19*).



For example, as shown above, the Engine Control Module (ECM) J623 is a device for controlling the torque output of the engine.

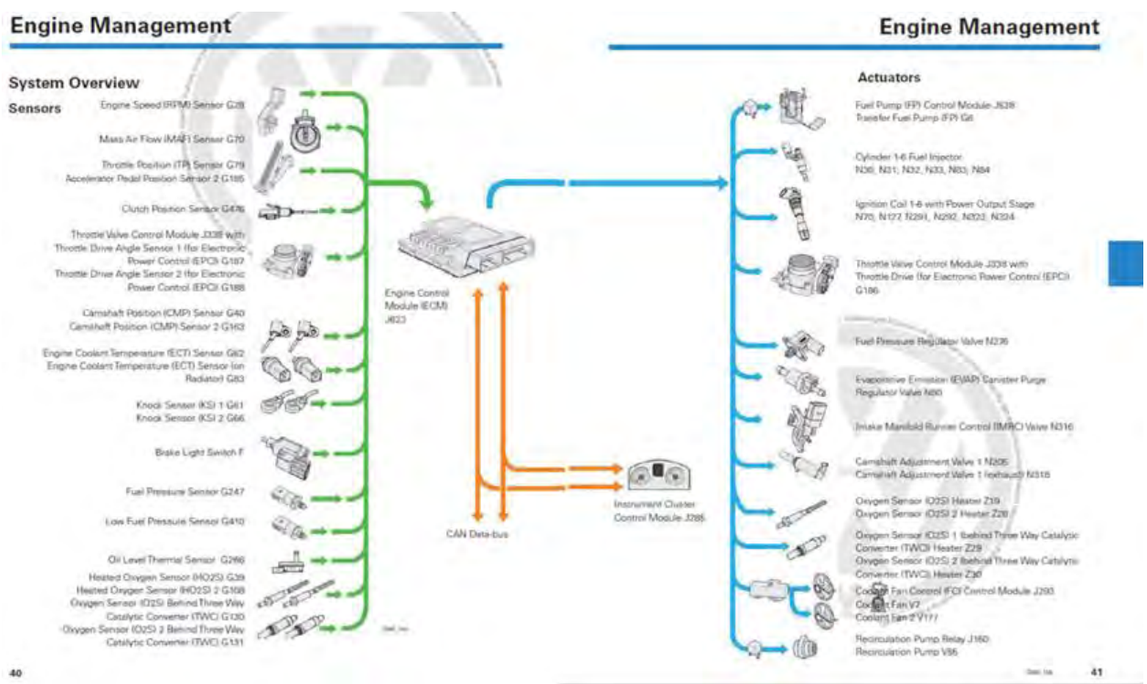
Figure 13

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

As shown above, the ’565 patent Accused Instrumentalities comprise a torque demand controller (ECM) that generates a torque demand signal based on at least an accelerator pedal position signal (Accelerator Pedal Position Sensor G185), an engine speed signal (Engine Speed Sensor G28) and engine coolant temperature signal (Engine Coolant Temperature (ECT) Sensor G62).

The ’565 patent Accused Instrumentalities comprise an engine coolant temperature signal (Engine Coolant Temperature (ECT) Sensor G62)).

Figure 14



The Engine Control Module ECM J623 is a torque producer device that controls the torque output of the engine and it receives the torque demand signal internally.

Figure 15

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

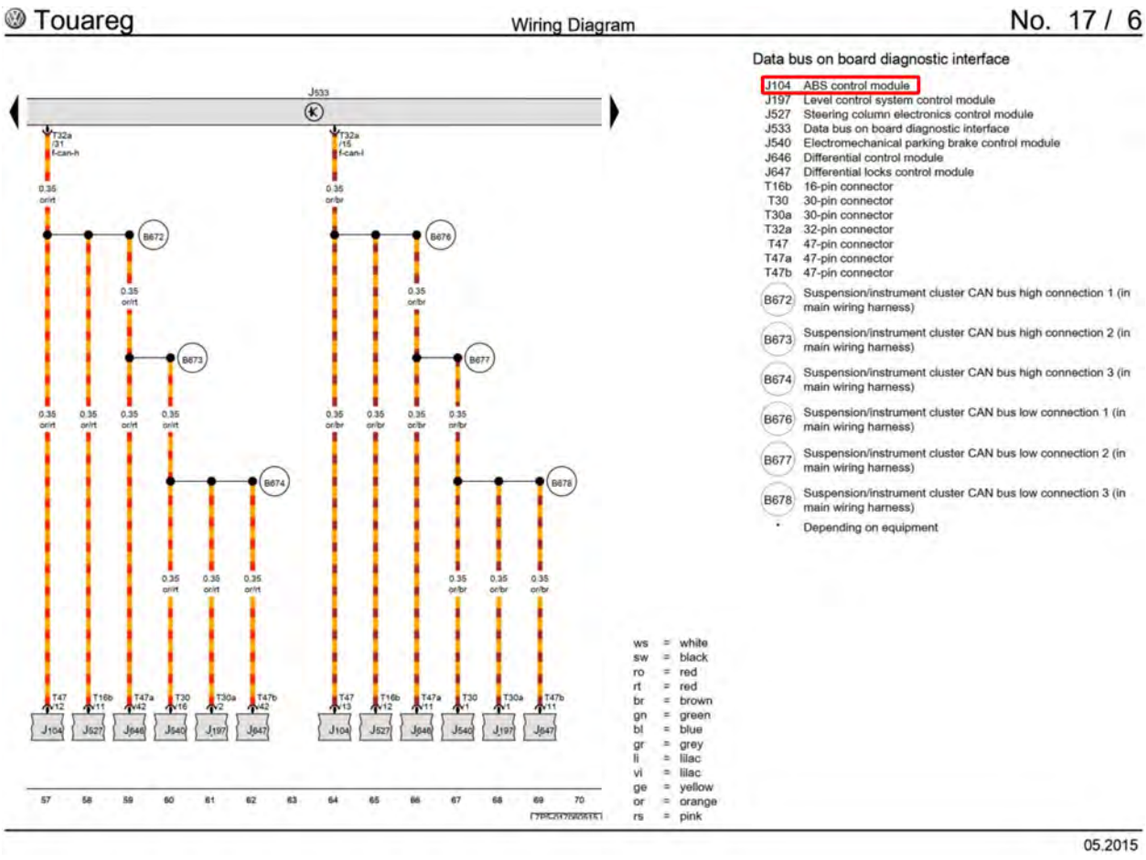


As shown above, the ’565 patent Accused Instrumentalities comprise an estimator (Engine Control Module ECM J623) which receives as inputs a current spark angle signal (Ignition coils 1-6), a current air/fuel ratio signal (Heated Oxygen Sensor (HO2S), G39 and Heated Oxygen Sensor (HO2S) 2, G108) and an estimated air charge signal (Mass Air Flow (MAF) signal G70) and outputs an estimated torque signal.

Estimated torque signal ECM J623 (torque demand controller) sends torque demand (reduction) signal within the ECM, wherein, based upon information a belief, there is a software-implemented estimator which makes calculations based at least partially upon sensor feedback signals from engine sensors (i.e. crankshaft position sensor (CKPS), mass airflow sensor (MAF), fuel injector duty cycle command) and calculates (estimates) an estimated torque signal prior to execution by the ECM.

Figure 16

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565



Upon information and belief, the comparator in the ECM receives two inputs: (1) the estimated torque signal calculated internally and (2) a desired torque signal calculated internally and includes input from the ABS control module J104 and the Transmission Control Module (TCM) J217.

Figure 17

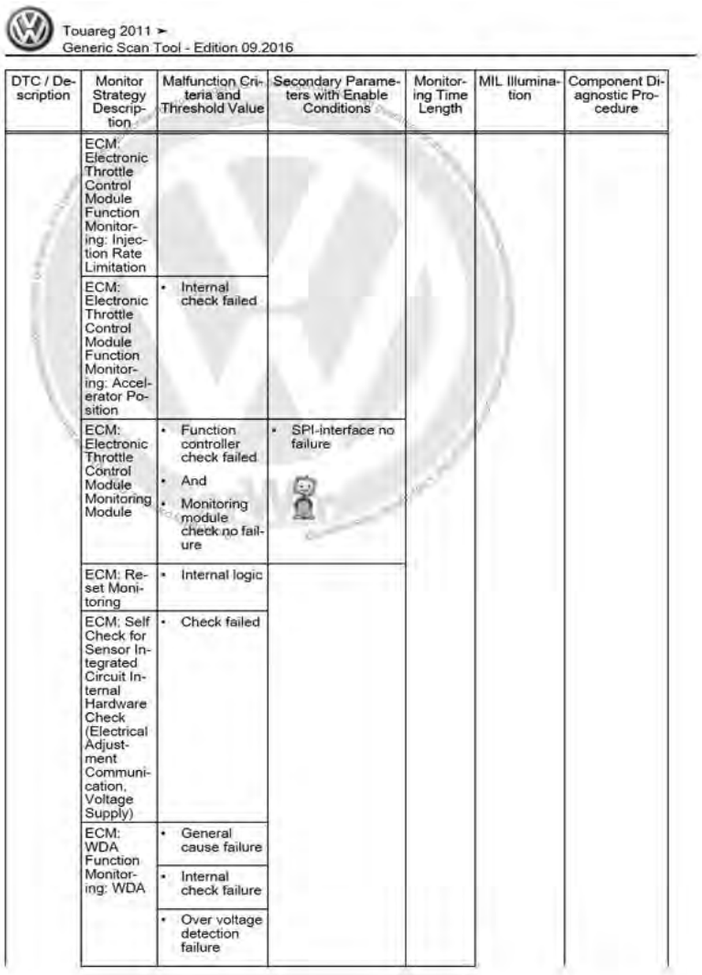
P0606 Control Module Processor	Barometric Pressure Sensor Plausibility Check	• Signal gradient > 14.0 kPa/s • Signal gradient < -14.0 kPa/s		• 2.0 s • Multiple	• 2 DCY	– Replace the Engine Control Module - J623- . Refer to appropriate repair manual.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

DTC / Description	Monitor Strategy Description	Malfunction Criteria and Threshold Value	Secondary Parameters with Enable Conditions	Monitoring Time Length	MIL Illumination	Component Diagnostic Procedure
	Barometric Pressure Sensor Short To Battery / Open Circuit	• Signal voltage > 4.88 V		• 1.0 s • Multiple		
	Barometric Pressure Sensor Short To Ground	• Signal voltage < 0.20 V				
	Barometric Pressure Sensor Out Of Range High	• Measured barometric pressure > 115.0 kPa		• 2.0 s • Continuous		
	Barometric Pressure Sensor Out Of Range Low	• Measured barometric pressure < 45.0 kPa				
	Mass Air Flow Sensor Functional Check	• MAF sensor signal > 0 µs	• MAF commanded off • After engine stop	• 0.4 s • Multiple		
	Ignition Control Communication Check	• Internal check failure • SPI communications check Identifier failure	• Engine speed > 80 RPM	• 0.5 s • Continuous		
	ECM: 5V Supply Voltage Internal Hardware Check	• Under-/ overvoltage detection		• 2.0 s • Continuous		
	ECM: EEPROM Functional Check	• Internal checksum failed	• Ignition on	• 0.5 s • Continuous		
	ECM: Electronic Throttle Control Module Function Monitoring: A/D Converter	• Test voltage / test pulse check failed				

DTC / Description	Monitor Strategy Description	Malfunction Criteria and Threshold Value	Secondary Parameters with Enable Conditions	Monitoring Time Length	MIL Illumination	Component Diagnostic Procedure
	ECM: Electronic Throttle Control Module Function Monitoring: Torque	• Comparison with allowed engine torque incorrect	• Internal engine speed > 1,240 RPM			
	ECM: Electronic Throttle Control Module Function Monitoring: Start/ Engine Running	• Engine restart/run not allowed				
	ECM: Electronic Throttle Control Module Function Monitoring: Start Control/ Start Automatic	• Engine start not allowed				
	ECM: Electronic Throttle Control Module Function Monitoring: Engine Speed Deviation	• Difference between calculated and internal engine speed > 320 RPM	• Internal engine speed > 520 RPM			
	ECM: Electronic Throttle Control Module Function Monitoring: Ignition Timing	• Internal check failed				
	ECM: Electronic Throttle Control Module Function Monitoring: Intern	• System reaction incorrect				

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565



Touareg 2011 ➢
Generic Scan Tool - Edition 09.2016

DTC / Description	Monitor Strategy Description	Malfunction Criteria and Threshold Value	Secondary Parameters with Enable Conditions	Monitoring Time Length	MIL Illumination	Component Diagnostic Procedure
	ECM: Electronic Throttle Control Module Function Monitoring: Injection Rate Limitation					
	ECM: Electronic Throttle Control Module Function Monitoring: Accelerator Position	• Internal check failed				
	ECM: Electronic Throttle Control Module Monitoring Module	• Function controller check failed • And • Monitoring module check no failure	• SPI-interface no failure			
	ECM: Reset Monitoring	• Internal logic				
	ECM: Self Check for Sensor Integrated Circuit Internal Hardware Check (Electrical Adjustment Communication, Voltage Supply)	• Check failed				
	ECM: WDA Function Monitoring: WDA	• General cause failure				
		• Internal check failure				
		• Over voltage detection failure				

330 Rep. Gr.ST - Generic Scan Tool

Touareg 2011 ➢
Generic Scan Tool - Edition 09.2016

DTC / Description	Monitor Strategy Description	Malfunction Criteria and Threshold Value	Secondary Parameters with Enable Conditions	Monitoring Time Length	MIL Illumination	Component Diagnostic Procedure
	CAN: Internal Fault CAN Controller RAM Check	• RAM error memory checksum error	• Initialization phase	• None [-] • Once / DCY		

Upon information and belief, DTC P0606 (pp. 327-331) above exemplifies the ’565 patent Accused Instrumentalities comprise an ECM comprising a comparator, which compares the difference between the current torque and allowed engine torque (desired torque signal) to generate an error signal (DTC P0606). Upon information and belief, the error signal is filtered by a high pass filter that filters and the resulting filtered error signal is used by the transient torque controller to generate signals to temporarily adjust the torque produced by the engine.

Figure 18

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

P0506 Idle Control System RPM - Lower Than Expected	Idle Air Control System RPM Lower Than Expected	• Engine speed Deviation > 100 RPM AND • RPM controller torque value >= calculated max value	• Engine speed – idle • Vehicle speed 0 MPH • Altitude < 2,700 m • ECT, > 20° C • IAT, @ manifold > -48° C • external torque request not demanded • EVAP purge valve closed FOR MANUAL TRANSMISSION: • engine load < 28.01 – 37.99%	• 5.0 s • Multiple	• 2 DCY	– Check the Throttle Valve Control Module - GX3- . Refer to ⇒ "3.6.32 Throttle Valve Control Module GX3 , Checking" page 893 .

Transient torque is known in the art as a temporary torque condition which exists only until the vehicle stabilizes and in cases where the torque is excessive enough for the vehicle to lose traction, it requires a torque reduction output signal from the ABS/ESC. Based upon information and belief, the transient torque controller (software within the ECM) receives as an input the filtered difference signal (described above) and outputs a fuel adjustment signal (to the ECM) and spark adjustment signal (used for engine control intervention).

Based upon information and belief, the ECM detects external torque demands as shown in the DTC P0506. which causes the throttle opening to be either increased or decreased, thereby further requiring the addition (adjustment) of fuel and an adjustment in spark timing.

Figure 19

Based upon the totality of the foregoing evidence, and based further upon information and belief, the '565 patent Accused Instrumentalities incorporate "a device for controlling a torque output of an engine, the device comprising: a torque demand controller for generating a torque demand signal; and a torque producer which receives the torque demand signal, the torque producer includes: an estimator which receives as inputs a current spark angle signal, a current air/fuel ratio signal and an estimated air charge signal and outputs an estimated torque signal; a comparator which receives as inputs the estimated torque signal and a desired torque signal and outputs a difference signal; a high pass filter which receives as an input the difference signal and outputs a filtered difference signal in which low frequency components are absent; and a transient torque controller which receives as an input the filtered difference signal and outputs a fuel adjustment signal and a spark adjustment signal."

COUNT IV – INFRINGEMENT OF U.S. PATENT NO. 6,379,281

28. The allegations set forth in the foregoing paragraphs 1 through 27 are incorporated into this Forth Claim for Relief.

29. On April 30, 2002, U.S. Patent No. 6,379,281 ("the '281 patent"), entitled "Engine Output Controller" was duly and legally issued by the United States Patent and Trademark Office. A true and correct copy of the '281 patent is attached as Exhibit 4.

30. Plaintiff is the assignee and owner of the right, title and interest in and to the '281 patent, including the right to assert all causes of action arising under said patents and the right to any remedies for infringement of them.

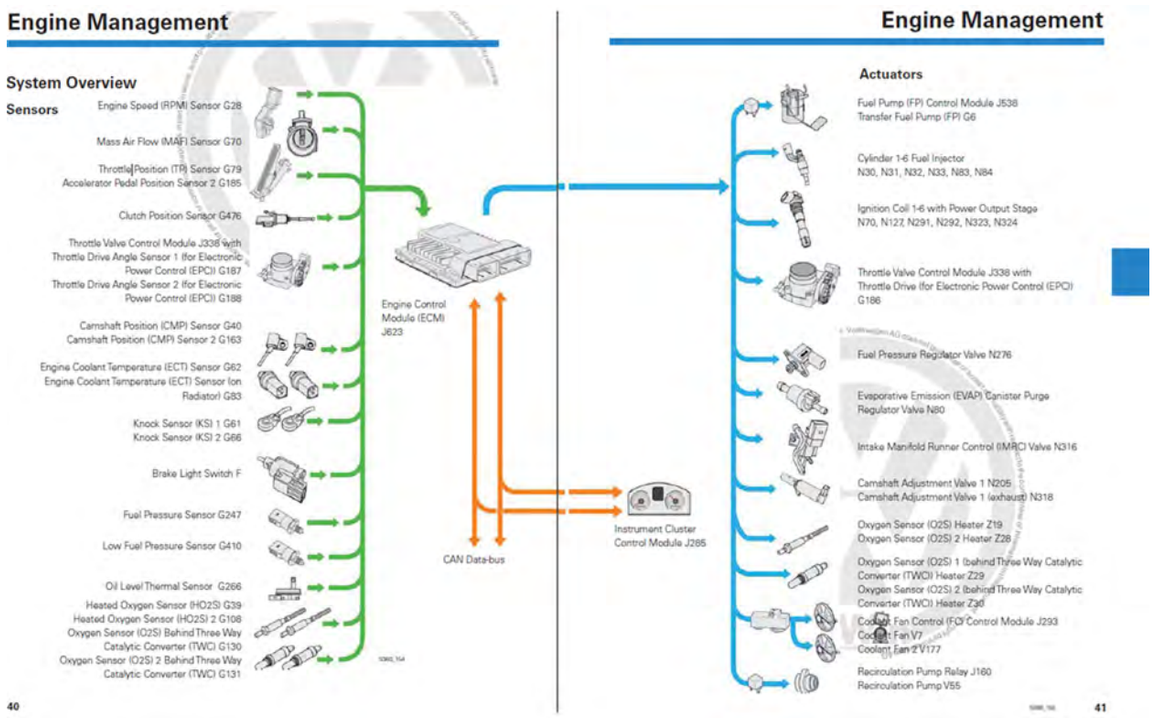
31. Upon information and belief, Defendants have directly infringed at least claims 1, 7 and 10 of the '281 patent by making, using, selling, importing and/or providing and causing to be used the 2010-2015 Touareg 2011-2017 (the "'281 patent Accused Instrumentalities").

32. In particular, claim 1 of the '281 patent recites an engine output control method for a vehicle having a drive by wire engine system responsive to a desired engine torque signal, the method comprising the steps of: generating a driver demanded acceleration value corresponding to an operator input; generating a gear value as a function of a vehicle speed value and said driver demanded acceleration value; deriving a driveline torque demand comprising an inertial model torque value of said vehicle driveline corresponding to said driver demanded acceleration and said gear value, and a dynamic transmission model torque value for said gear value; deriving a demanded engine torque value from said driveline torque demand and a torque converter model; and controlling said engine output as a function of said demanded engine torque value.

33. On information and belief, the '281 patent Accused Instrumentalities infringe at least claim 1 of the '281 patent. The '281 patent Accused Instrumentalities practice an engine

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

output control method for a vehicle having a drive by wire engine system (*Figure 20*) responsive to a desired engine torque signal (*Figure 20*), the method comprising the steps of: generating a driver demanded acceleration value corresponding to an operator input (*Figure 21*); generating a gear value as a function of a vehicle speed value and said driver demanded acceleration value (*Figure 22*); deriving a driveline torque demand comprising an inertial model torque value of said vehicle driveline corresponding to said driver demanded acceleration and said gear value, and a dynamic transmission model torque value for said gear value (*Figure 23*) deriving a demanded engine torque value from said driveline torque demand and a torque converter model (*Figure 24*); and controlling said engine output as a function of said demanded engine torque value (*Figure 25*).

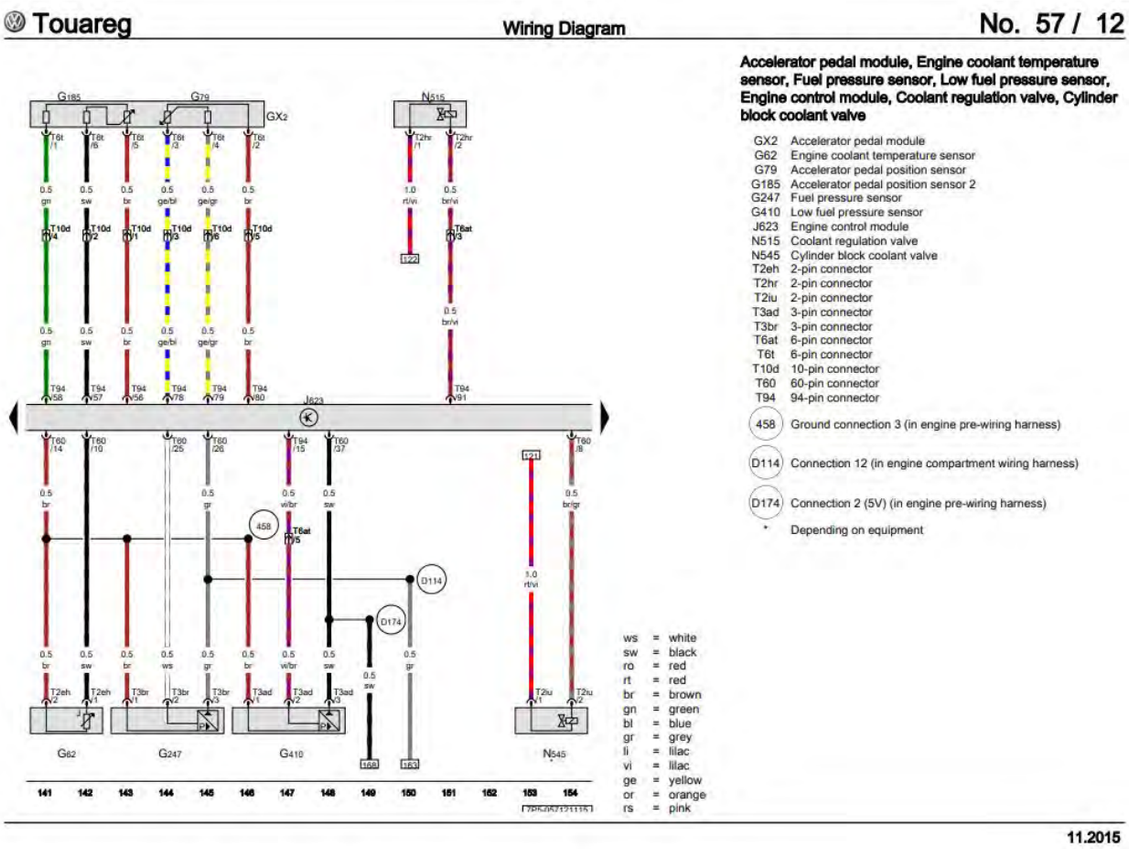


The ’281 patent Accused Instrumentalities comprise a CAN (Controller Area Network) which allows microcontrollers like the Engine Control Module (ECM), Transmission Control Module (TCM), and Antilock Brake System/Electronic Stability Control (ABS/ESC) to communicate with each other.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

For example, as shown above, the drive by wire system comprises an Engine Control Module (J623), Accelerator pedal module (GX2), Throttle Position (TP) Sensor (G79), Accelerator pedal position sensor 2 (G185), throttle valve control module (J338) containing the throttle drive angle sensor 1 (for electronic power control (EPC) (G187, throttle drive angle sensor 2 (for EPC) (G188), and is controlled by the ECM (J623) via the CAN bus.

Figure 20

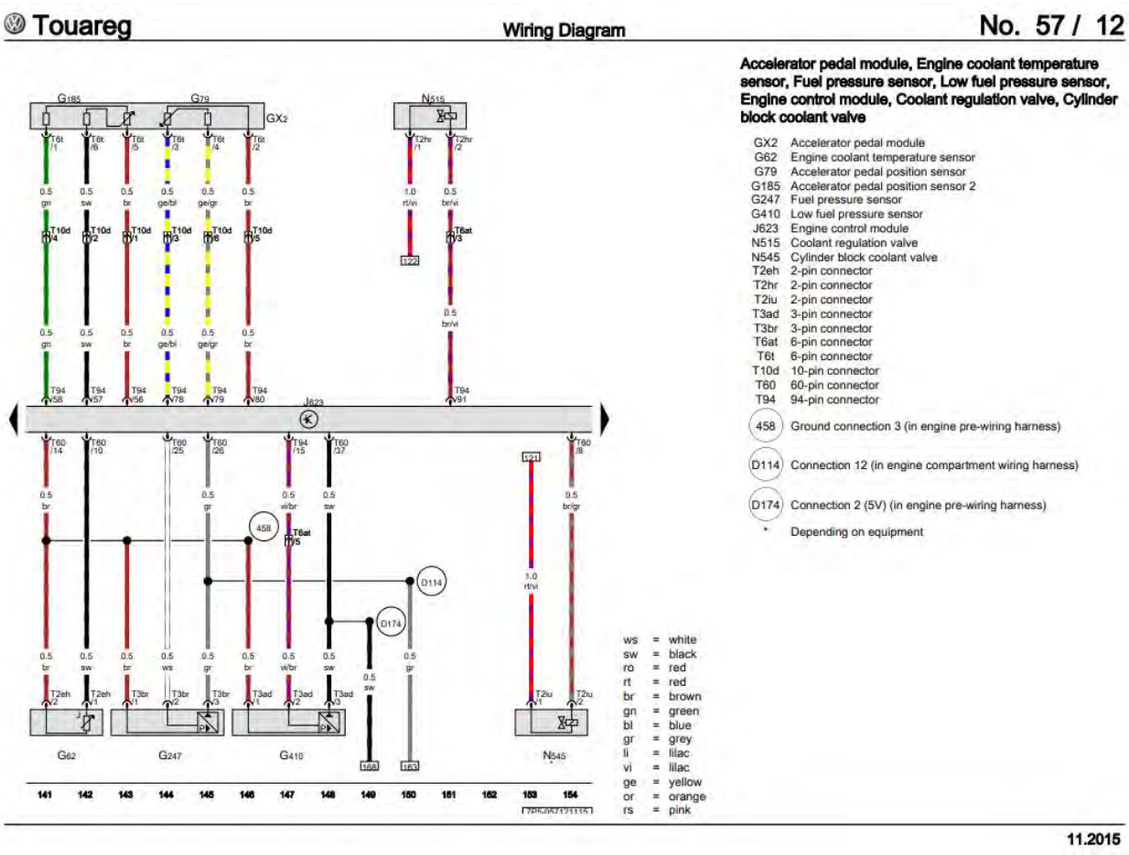


The ’281 patent Accused Instrumentalities comprise an Accelerator pedal module (GX2), Accelerator pedal position sensor 2 (G79), Accelerator pedal position sensor 2 (G185), throttle valve control module (J338) containing the throttle drive angle sensor 1, electronic power control (EPC; G187), throttle drive angle sensor 2 (G188), which send a voltage signal to the ECM and generates a driver demanded acceleration value corresponding to operator input. *See above*.

For example, the Accelerator pedal module (GX2), Throttle Position (TP) Sensor (G79), and Accelerator pedal position sensor 2 (G185) each send a respective voltage signal to the ECM, which generates a driver demanded acceleration value corresponding to operator input (the operator pressing the accelerator pedal)

Figure 21

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565



Automatic transmissions have used mechanical (hydraulic) shift logic for years based on vehicle speed and driver demanded acceleration value to determine a gear value. Modern automatic transmission control logic (software) is modeled based on this mechanical shift logic. In short, this function is certainly present in the ’281 patent Accused Instrumentalities.

As shown below, the gear values (transmission shift points) are determined by the Transmission Control Module (TCM; J217) based upon vehicle speed (vehicle speed value) provided by the ECM (J623) and the throttle percentage open value (derived from the APS and driver demanded acceleration value).

This is evidenced by DTC code P0730 – Incorrect Gear Ratio. For example, if the TCM detects that the transmission is trying to shift to a lower gear than intended DTC code P0730 is produced. The DTC code is based on monitoring actual gear position by checking the torque converter slip ratio calculated by the TCM as follows:

Torque converter slip ratio = A x C/B

A: Output shaft revolution signal from speed sensor (revolution sensor)
B: Engine speed signal from Engine Control Module (ECM)
C: Gear ratio determined as gear position which TCM supposes

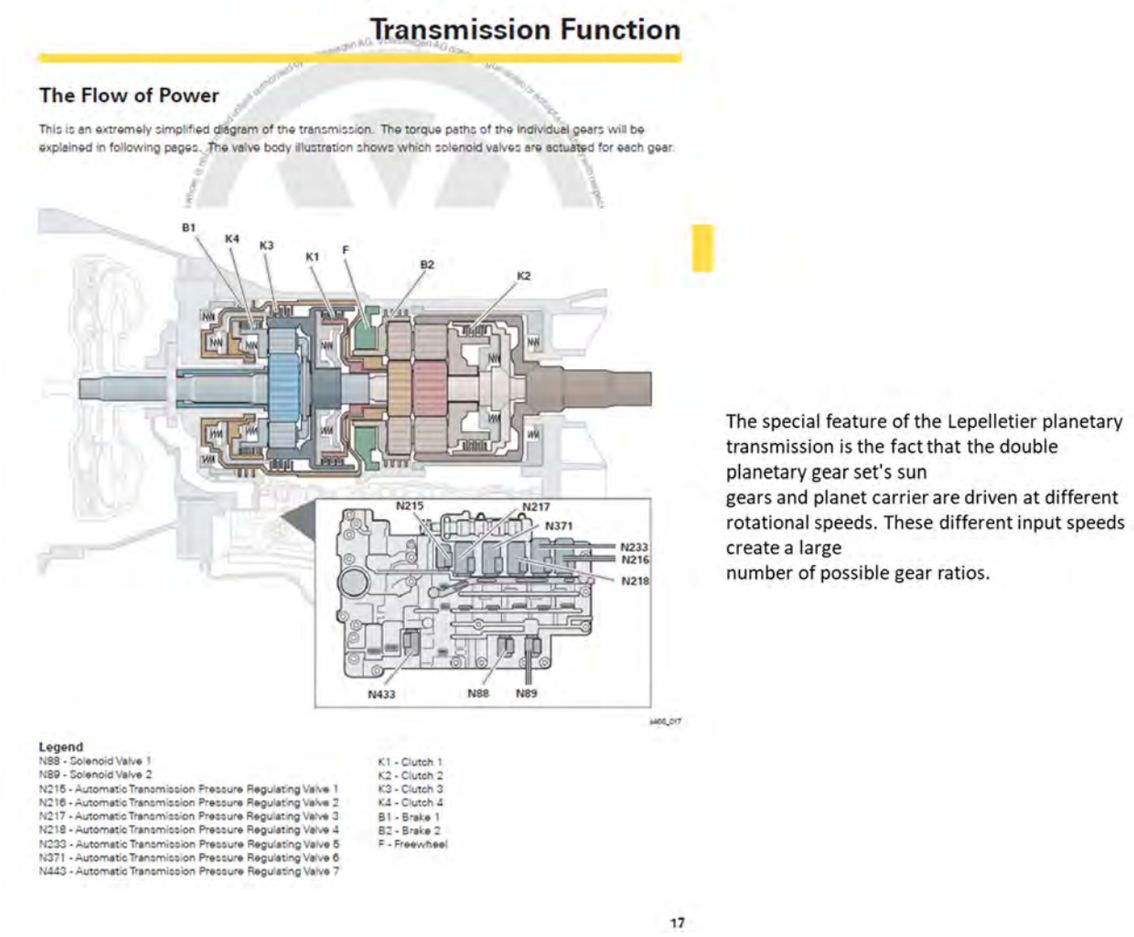
If the actual gear position is higher than the position supposed by the TCM, the slip ratio will be more than normal. In case the ratio exceeds the specified value, the TCM judges this diagnosis malfunction.

https://www.autocodes.com/p0730.html

The engine speed signal is based on the Accelerator pedal module (GX2), Throttle Position (TP) Sensor (G79), and Accelerator pedal position sensor 2 (G185) which each send a respective voltage signal to the ECM, which generates a driver demanded acceleration value corresponding to operator input.

There are two transmission speed sensors, also commonly referred to as a vehicle speed sensors (VSS) which send data (respective inputs) to the powertrain control module (PCM), which compares these two inputs and calculates which gear the transmission should engage for efficient driving. The actual gear ratio is then compared to the desired gear ratio. If the desired gear and the actual gear do not match, then the PCM will set a diagnostic trouble code (DTC) and illuminate the Check Engine Light.

Figure 22

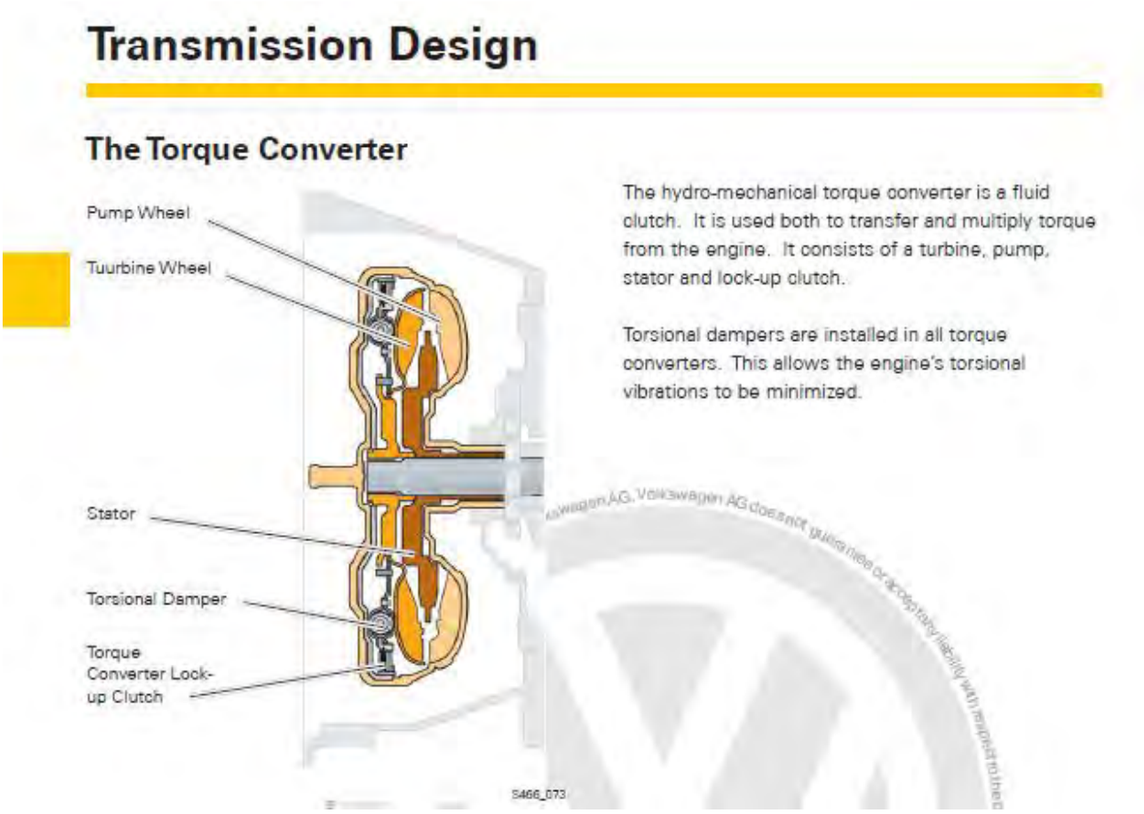


Additionally, adaptations are used to allow the system to learn during vehicle operation.

As shown by the exemplary images below, the Transmission Control Module (TCM; J217) (shown above) derives a driveline torque demand which, based upon information and belief for the reasons discussed below, is comprised of an inertial model torque value of the vehicle driveline corresponding with the driver demanded acceleration and gear values discussed above, and a dynamic transmission model torque value for the gear value..

Upon information and belief, the ECM/TCM calculates an inertial model torque value and a dynamic transmission model torque value.

Figure 23



The torque converter can be expressed as functions of the engine speed (demanded engine torque value) and the turbine speed from driveline torque demand and a torque converter model.

The input-output characteristics of the torque converter can be expressed as functions of the engine speed and the turbine speed. In this example, the direction of power flow is always assumed to be from the impeller to the turbine (see Equation 2).

Equation 2

$$T_i = \frac{N_e^2}{K^2}$$

$K = f_2\frac{N_{in}}{N_e}$ = K-factor (capacity)

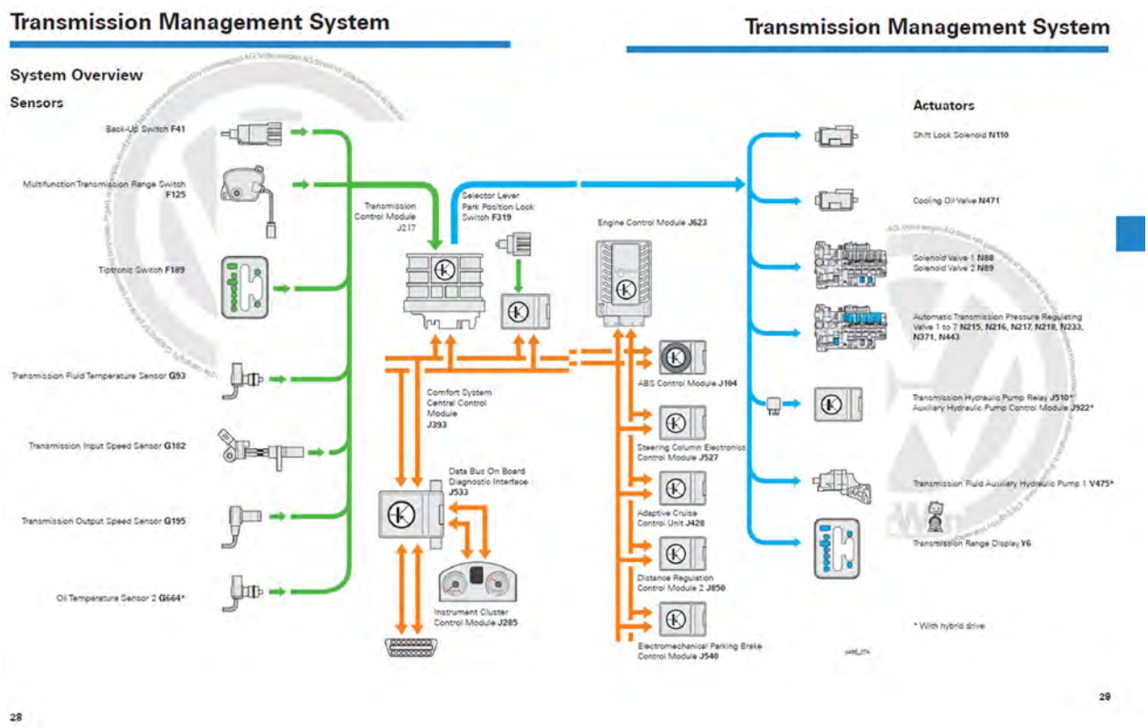
N_{in} = speed of turbine (torque converter output) = transmission input speed (RPM)

$R_{TQ} = f_3\frac{N_{in}}{N_e}$ = torque ratio

https://www.mathworks.com/help/simulink/examples/modeling-an-automatic-transmission-controller.html?s_tid=gn_loc_drop

Upon information and belief, the ECM/TCM calculates a demanded engine torque value and a driveline torque demand.

Figure 24



Service Training Self Study Program 850103 The 8-Speed Automatic Transmission 0C8 Design and Function

As demonstrated above, and further supported below, the ECM/TCM controls engine output as a function of demanded engine torque value.

Based upon the totality of the foregoing evidence, and based further upon information and belief, the ’281 patent Accused Instrumentalities practice an engine output control method for a vehicle having a drive by wire engine system responsive to a desired engine torque signal, the method comprising the steps of: generating a driver demanded acceleration value corresponding to an operator input; generating a gear value as a function of a vehicle speed value and said driver demanded acceleration value; deriving a driveline torque demand comprising an inertial model torque value of said vehicle driveline corresponding to said driver demanded acceleration and said gear value, and a dynamic transmission model torque value for said gear value; deriving a demanded engine torque value from said driveline torque demand and a torque converter model; and controlling said engine output as a function of said demanded engine torque value.

Figure 25

COUNT V – INFRINGEMENT OF U.S. PATENT NO. 6,763,804

34. The allegations set forth in the foregoing paragraphs 1 through 33 are incorporated into this Fifth Claim for Relief.

35. On July 20, 2004, U.S. Patent No. 6,763,804 ("the '804 patent"), entitled "Electronic Throttle Servo Overheat Protection System," was duly and legally issued by the United States Patent and Trademark Office. A true and correct copy of the '804 patent is attached as Exhibit 5.

36. Plaintiff is the assignee and owner of the right, title and interest in and to the '804 patent, including the right to assert all causes of action arising under said patents and the right to any remedies for infringement of them.

37. Upon information and belief, Defendants have directly infringed at least claims 1 and 11 of the '804 patent by making, using, selling, importing and/or providing and causing to be used the 2013-2018 Passat, 2012-2016 CC, 2012-2017 Touareg, 2018-2019 Atlas, and 2012-2016 Porsche Cayenne (the "'804 patent Accused Instrumentalities").

38. In particular, claim 1 of the '804 patent recites a method for controlling a positioning device of an internal combustion engine, the method comprising the steps of: providing an electric motor for actuating the positioning device; commanding the positioning device to change to a commanded position; detecting a control effort required to change to said commanded position; determining whether said control effort exceeds a threshold for a predetermined time period; and reducing said control effort when said control effort exceeds said threshold for said predetermined time period; wherein commanding the positioning device to change to said commanded position comprises at least one of commanding the positioning device to open to a hold open mode and commanding the positioning device to close to a hold close mode.

39. On information and belief, the '804 patent Accused Instrumentalities infringe at least claim 1 of the '804 patent. The '804 patent Accused Instrumentalities practice a method for controlling a positioning device of an internal combustion engine (*Figure 26*), the method

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565

comprising the steps of: providing an electric motor for actuating the positioning device (*Figure 27*); commanding the positioning device to change to a commanded position (*Figure 28*); detecting a control effort required to change to said commanded position (*Figure 29*); determining whether said control effort exceeds a threshold for a predetermined time period (*Figures 28-30*); and reducing said control effort when said control effort exceeds said threshold for said predetermined time period (*Figure 31*); wherein commanding the positioning device to change to said commanded position comprises at least one of commanding the positioning device to open to a hold open mode and commanding the positioning device to close to a hold close mode (*Figure 32*).



For example, as shown above the Engine Control Module (ECM) J623 controls a positioning device, the Throttle Valve Control Module J338 of an internal combustion engine (VW 3.2L & 3.6L).

Figure 26

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565