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.

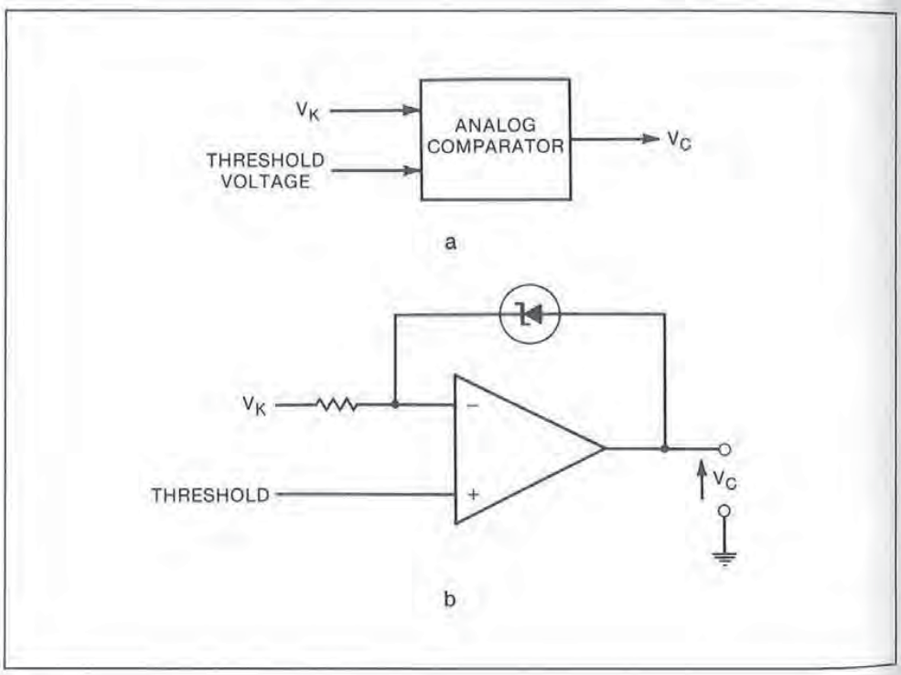
Spark Advance Correction Scheme

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.

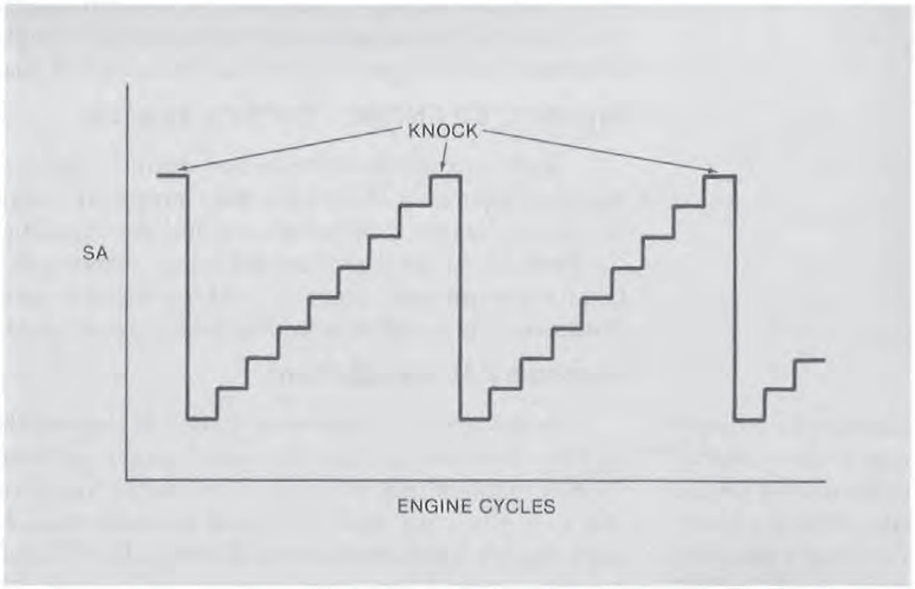
The fast correction ensures that minimum time is spent under heavy knocking conditions. Further, this scheme compensates for hysteresis (i.e., for

Figure 7.14 Knock Level Detector Circuit



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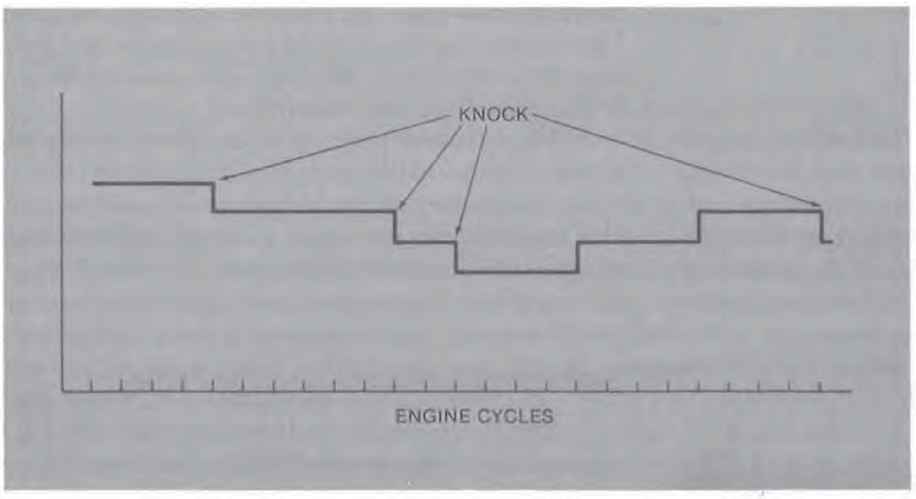
Figure 7.15
Fast Correction
Spark Advance



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



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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.

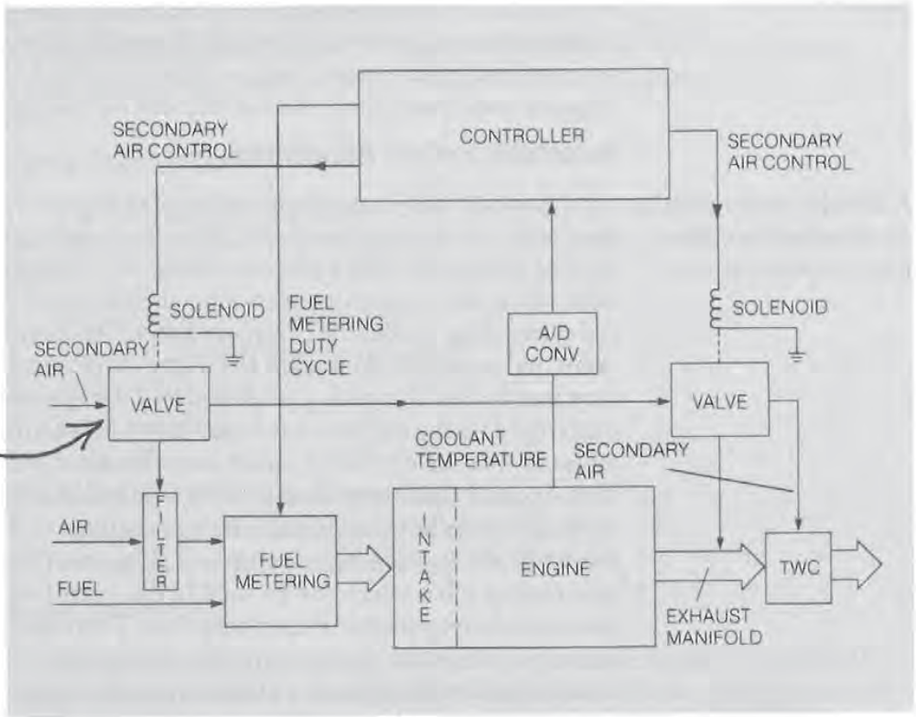
The computer program for the control mode selection logic can be modified to include the conditions for controlling secondary air. The computer controls secondary air by using two solenoid valves similar to the EGR valve. One valve switches air flow to the air cleaner or to the exhaust system. The other 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

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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

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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.

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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.

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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

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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

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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

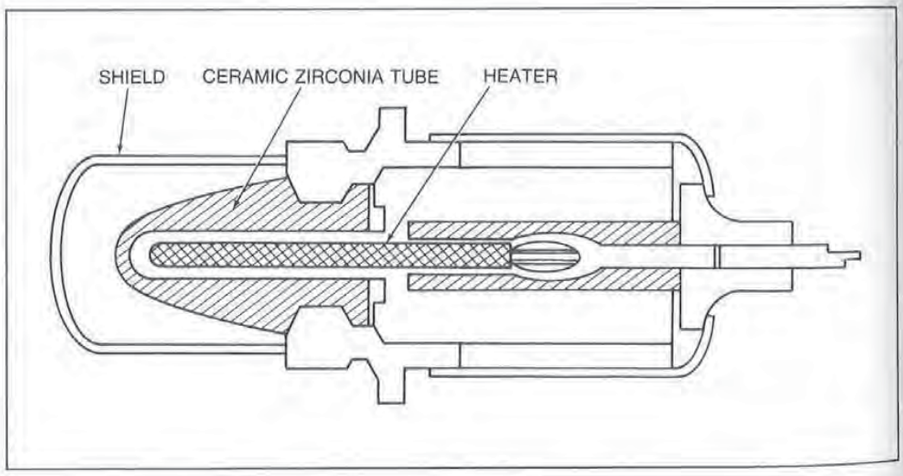


Figure 7.18
Heated Exhaust Gas Oxygen Sensor

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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.

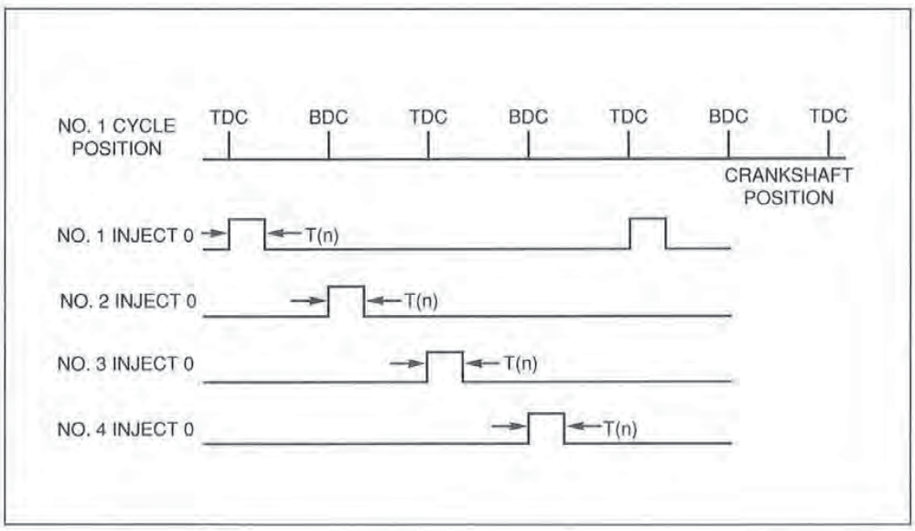


Figure 7.19
Injector Timing for 4-Cylinder Engine

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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

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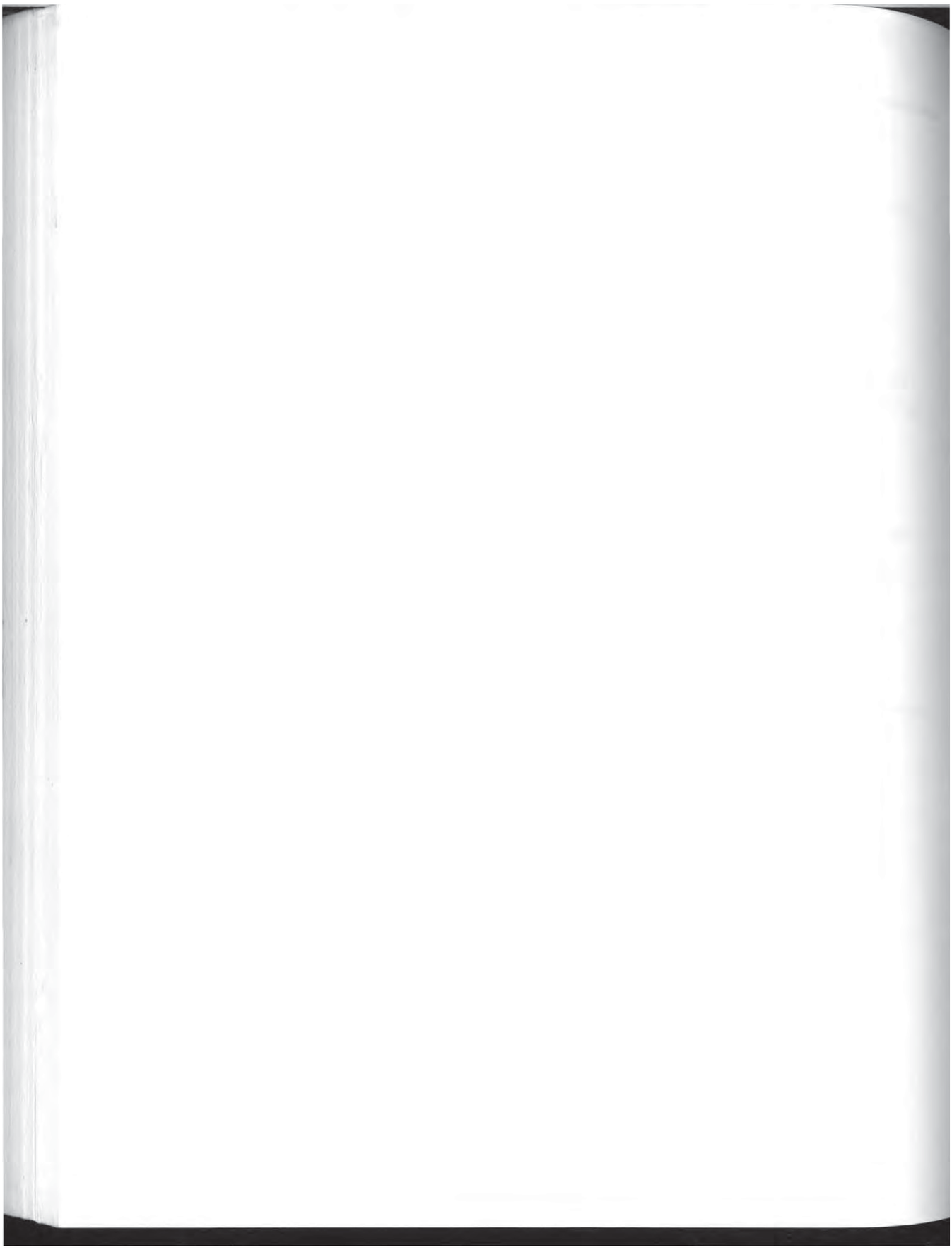
11. The secondary air management system is used
- **a.** to control EGR
- **b.** to avoid knock
- **c.** with low-octane fuels
- **d.** to improve performance of the catalytic converter

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

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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

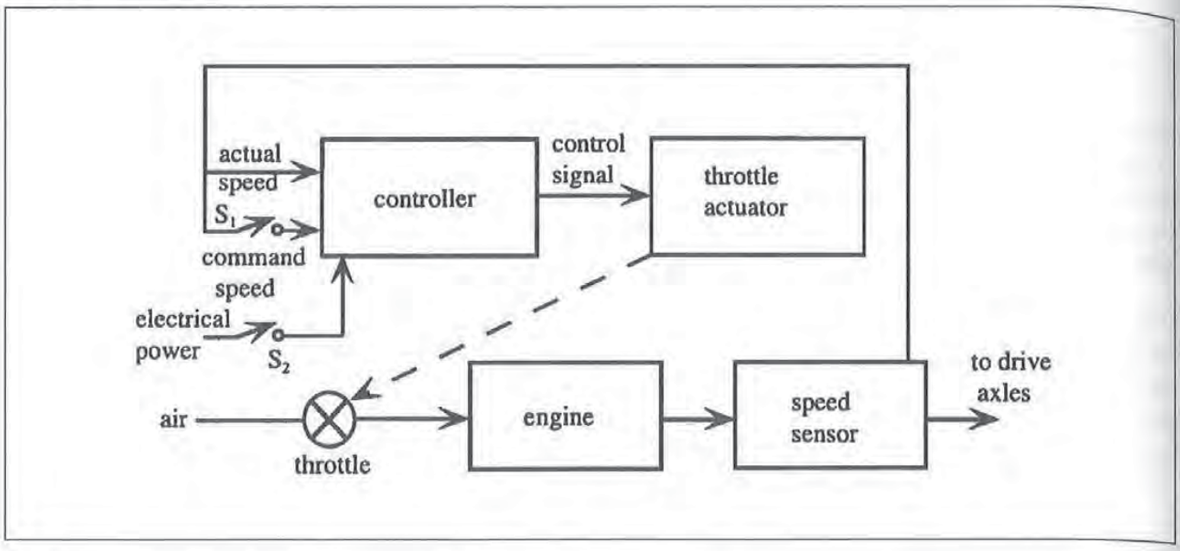
Automotive cruise control is an excellent example of the type of electronic feedback control system that was discussed in general terms in Chapter 2. Recall that the components of a control system include the plant, or system being controlled, and a sensor for measuring the plant variable being regulated. 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.

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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:

$$e = V_d - V_a$$

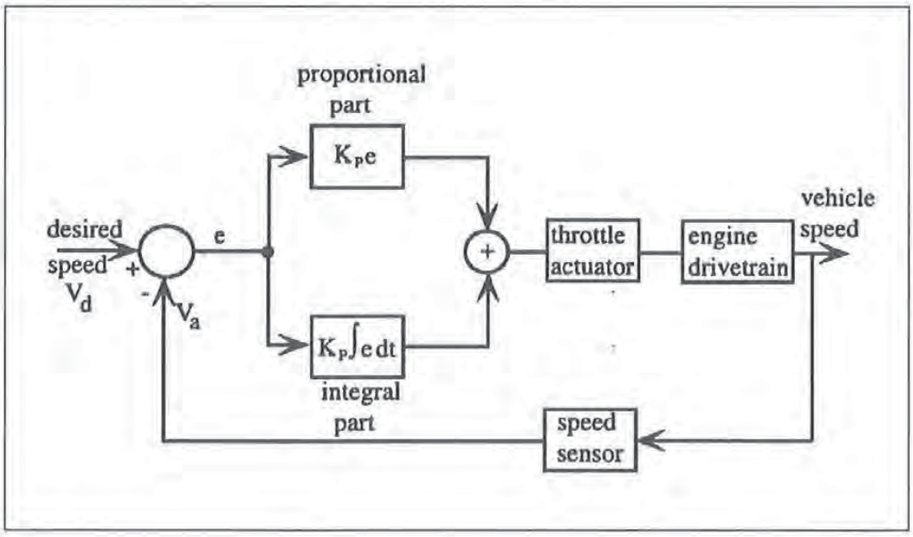
The controller then electronically generates the actuator signal by combining a term proportional to the error ($K_P e$) and a term proportional to the integral of the error (that is, $K_I \int e\,dt$). The actuator signal u is a combination of these two terms:

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

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

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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.

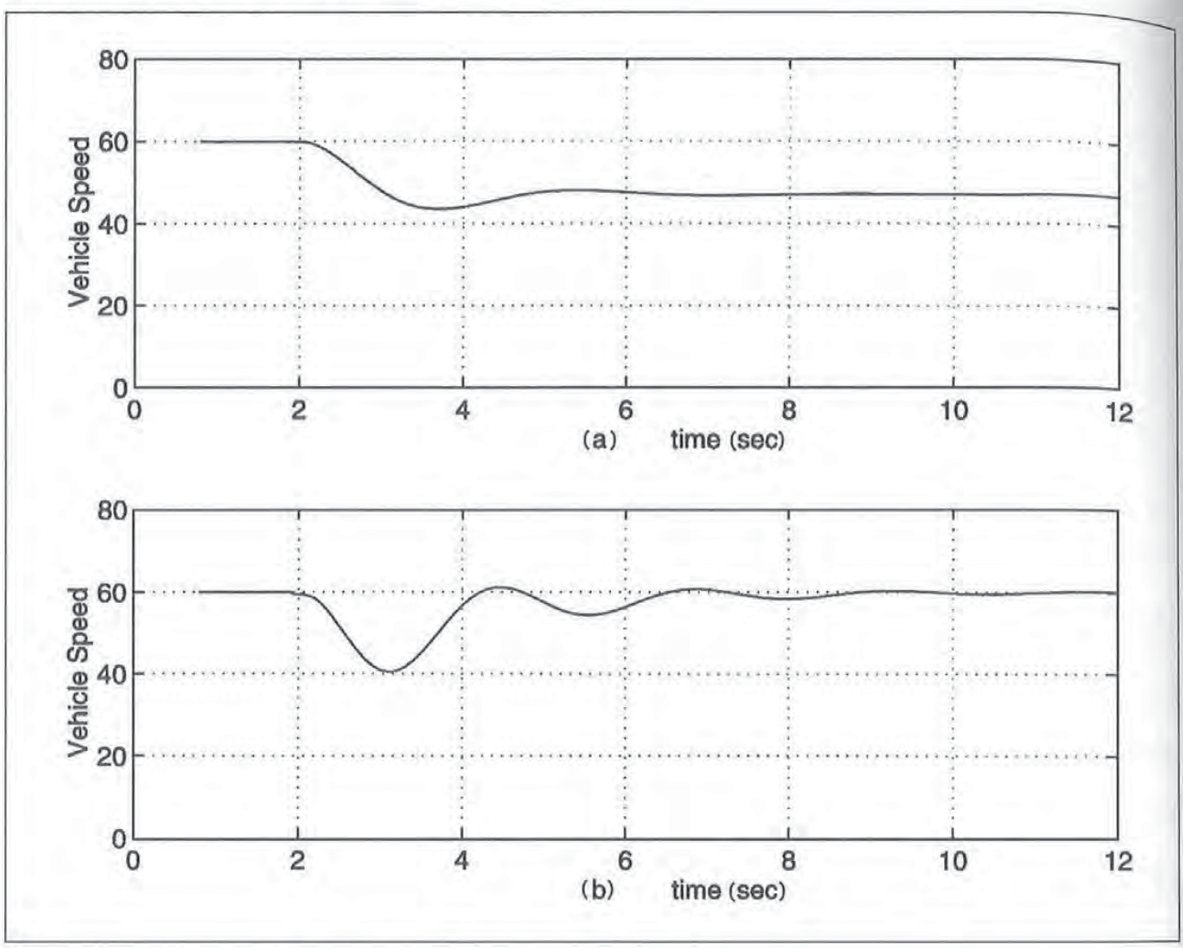
If the car were then to enter a long hill with a steady positive slope (i.e., a hill going up) while the throttle is set at the cruise position for level road, the engine will produce less power than required to maintain that speed on the hill. The hill represents a disturbance to the cruise control 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

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Figure 8.3
Cruise Control Speed Performance

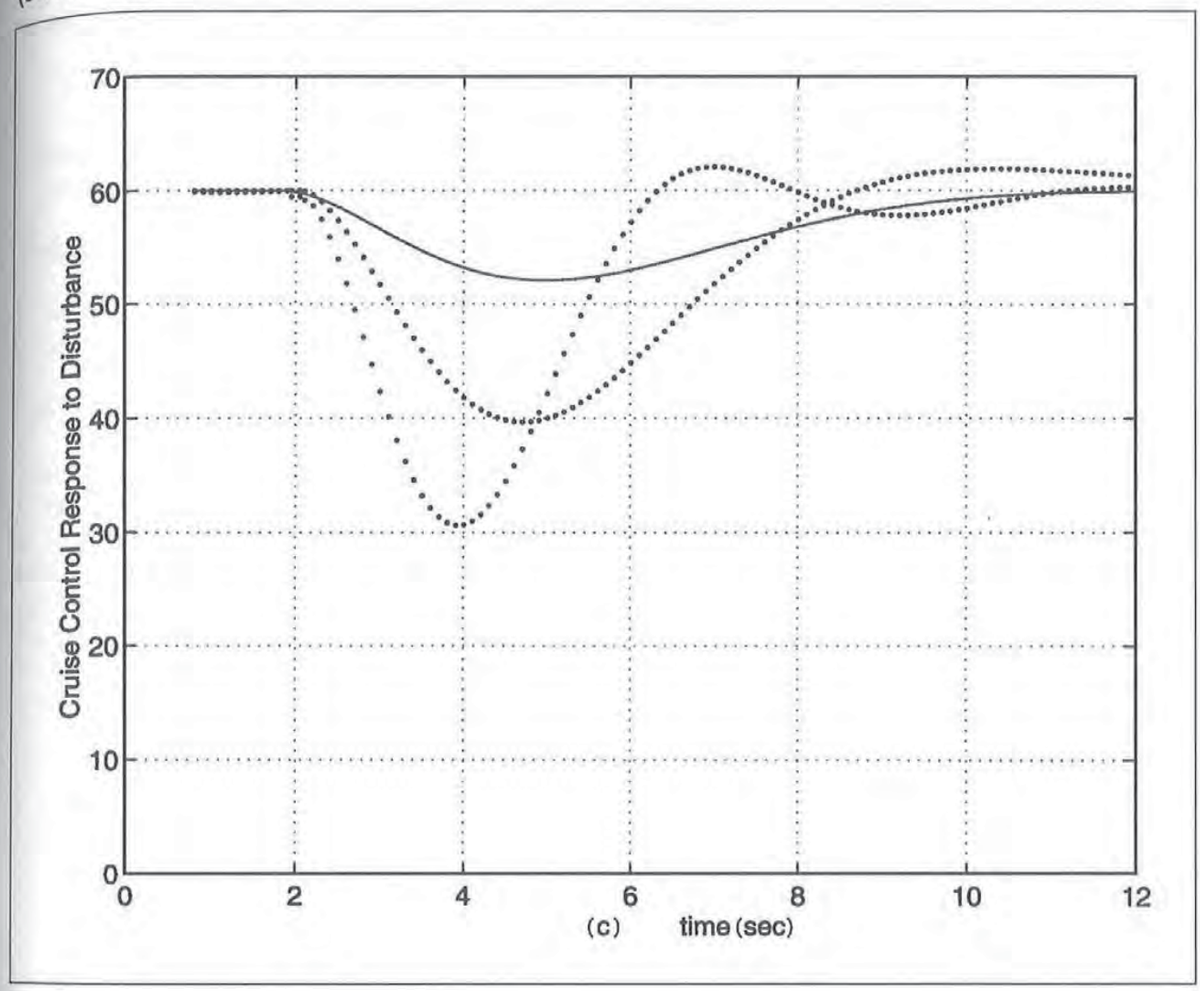


increase. In this case the actuator output will increase until the error is reduced to zero. The response of the cruise control with PI control is shown in Figure 8.3b.

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*.

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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

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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.

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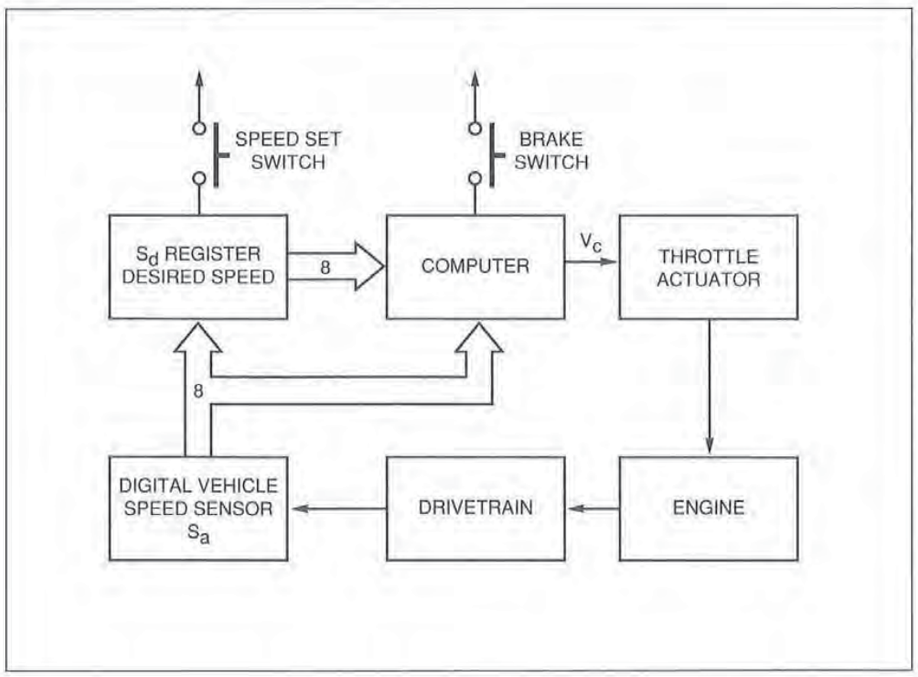


Figure 8.4 Digital Cruise Control System

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.

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Figure 8.5a Digital Speed Sensor

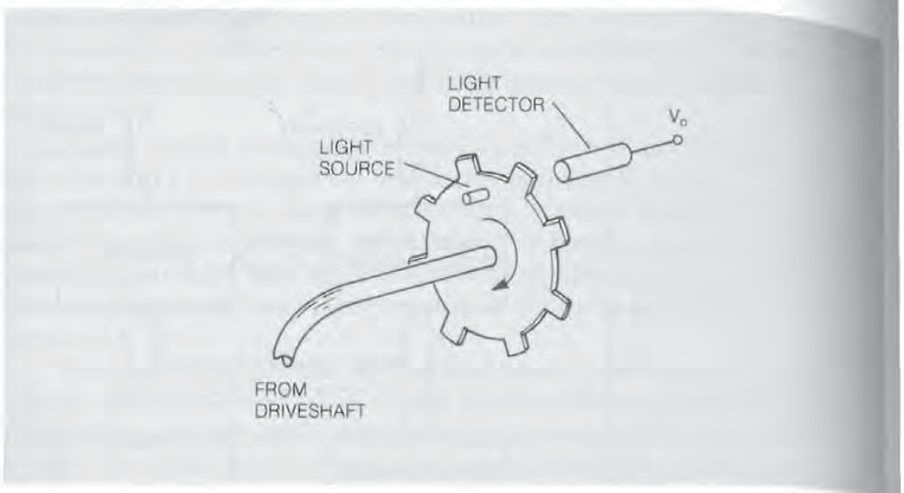
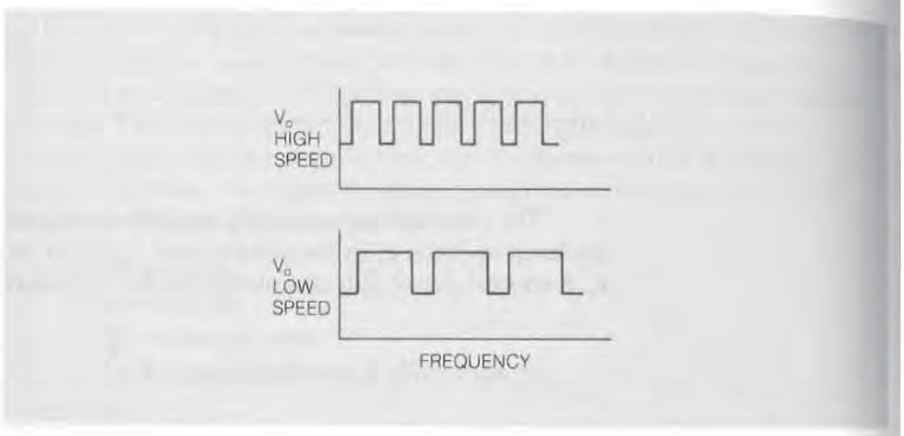


Figure 8.5b Digital Speed Signal



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

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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

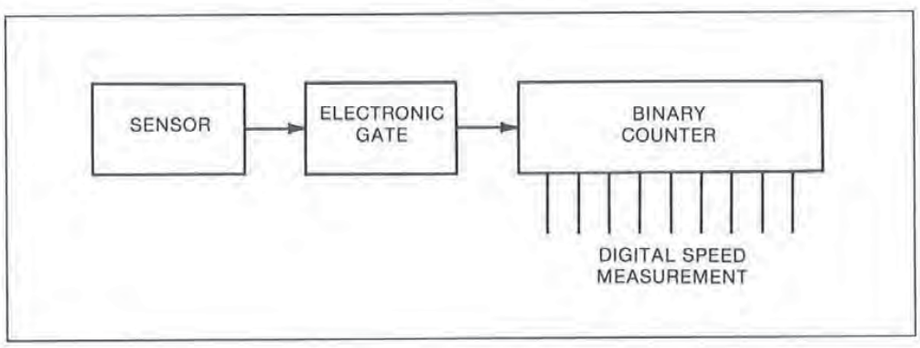


Figure 8.6 Digital Speed Measurement System

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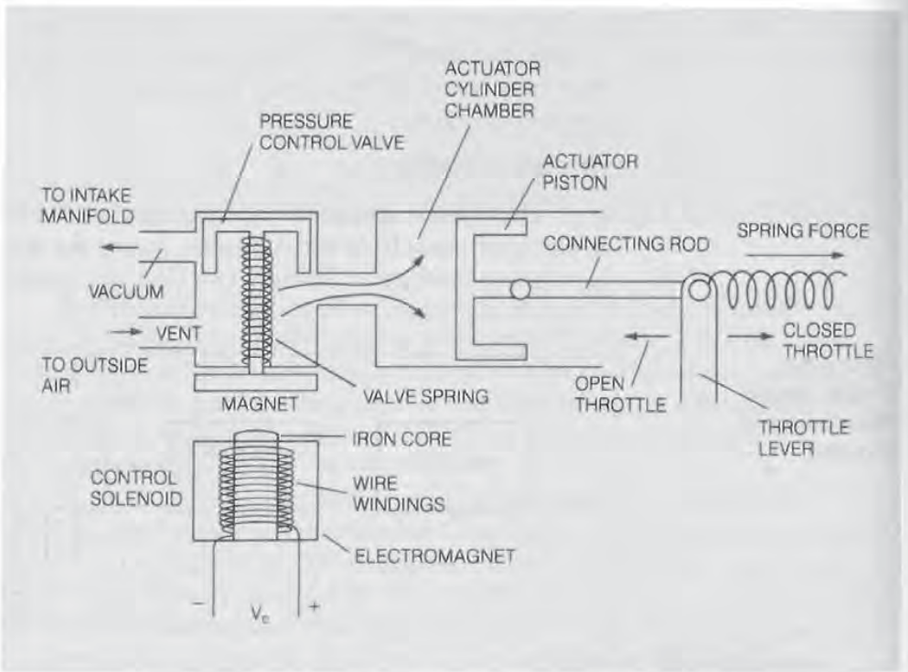
operate either from manifold vacuum or with a stepper motor. The stepper motor implementation operates similarly to the idle speed control actuator described in Chapter 7. The throttle opening is either increased or decreased by the stepper motor in response to the sequences of pulses sent to the two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



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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.

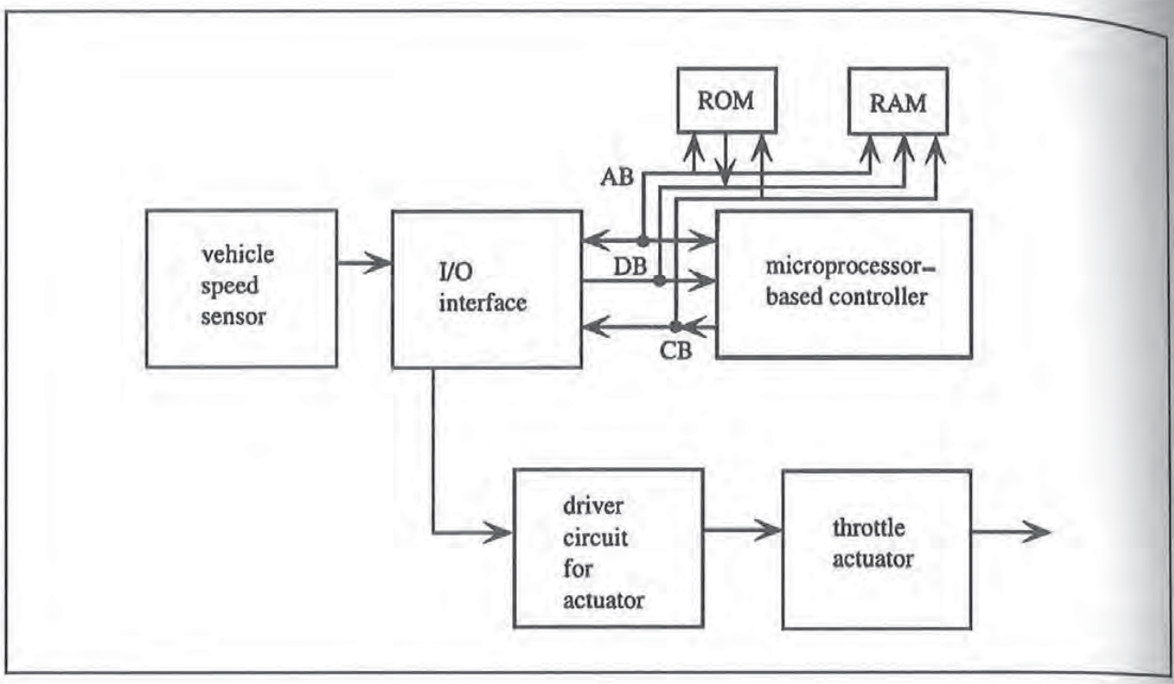
Cruise control can be implemented electronically in various ways, including with a microcontroller with special-purpose digital electronics or with analog electronics. It can also be implemented (in proportional control strategy alone) with an electromechanical speed governor.

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

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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.

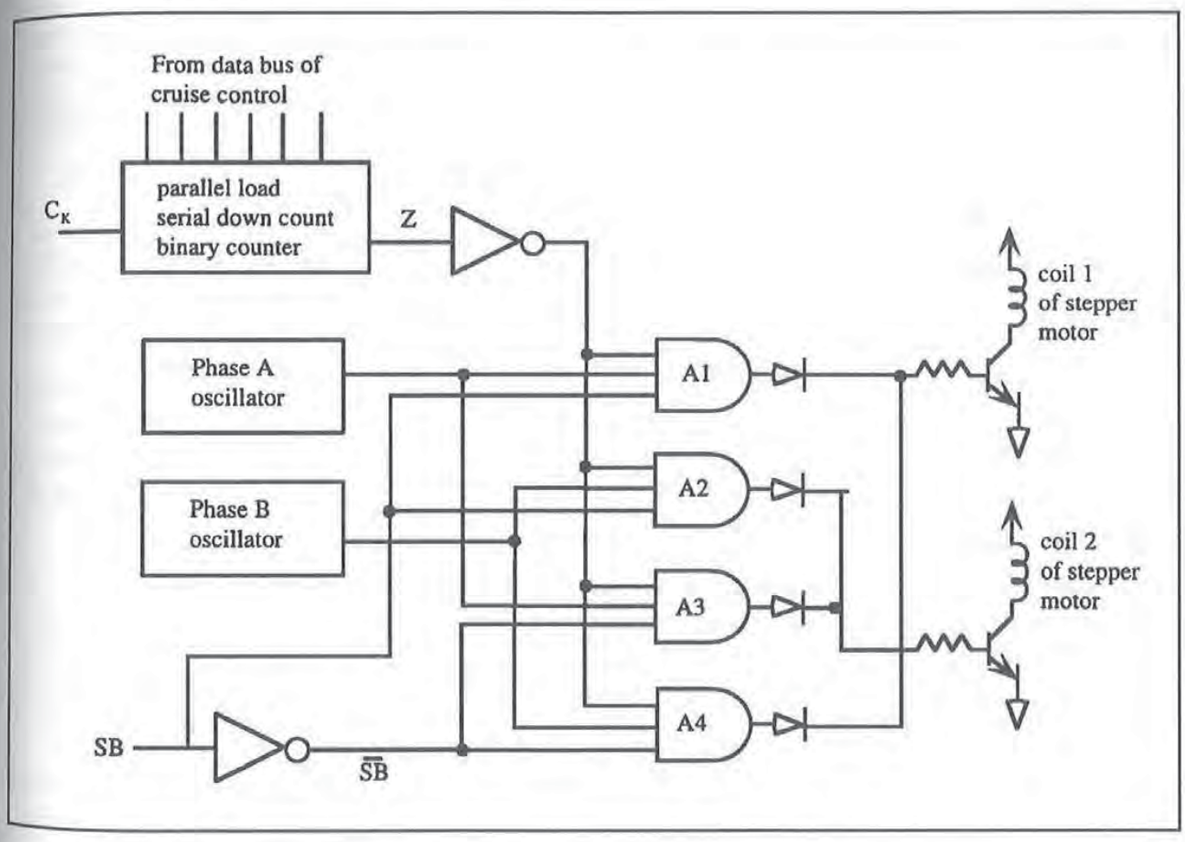
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Stepper Motor-Based Actuator

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



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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

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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

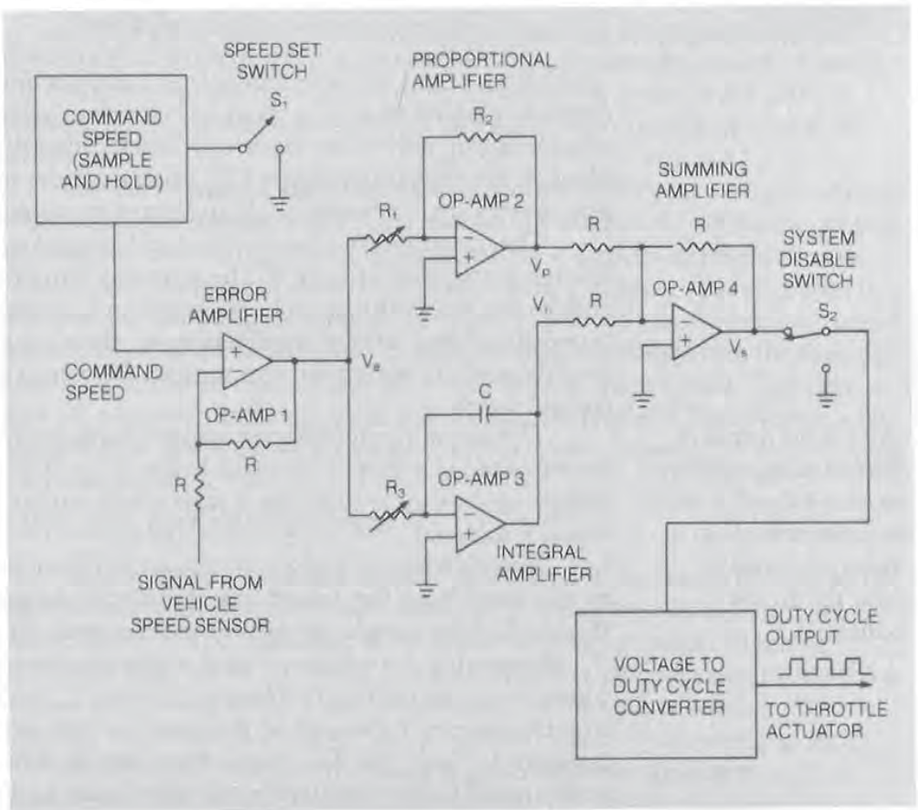


Figure 8.10 Cruise Control Electronics (Analog)

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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.

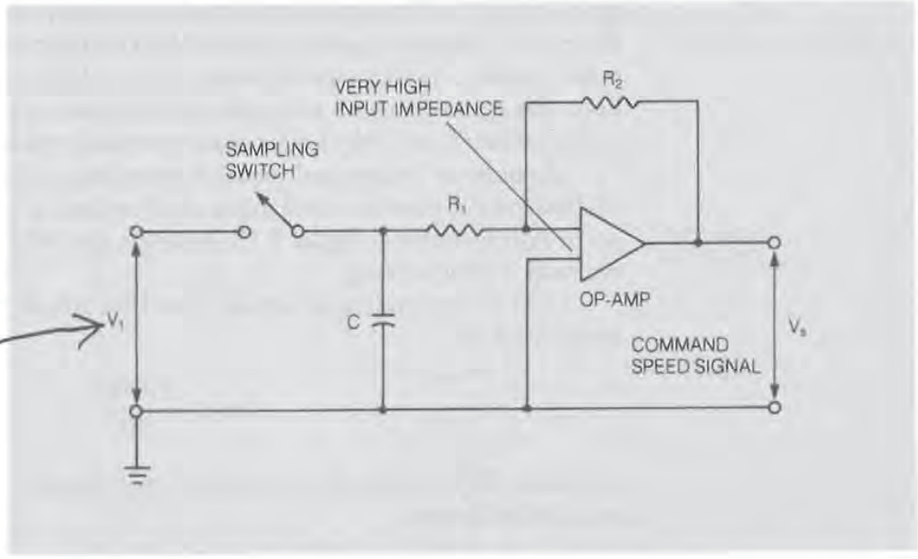
Because the output of the summing amplifier is an analog signal, it must be converted into a duty-cycle signal to pulse the throttle actuator.

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.

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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

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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

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

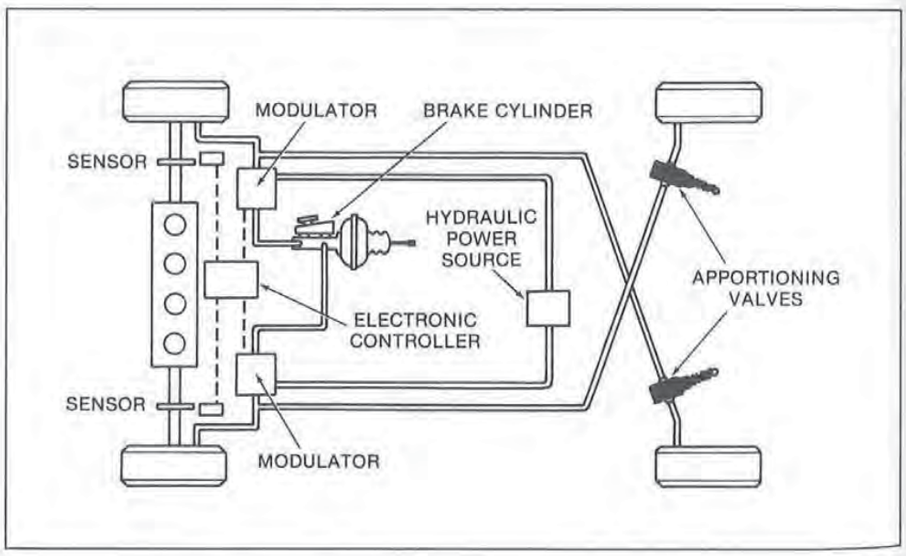
and where RPM is the wheel revolutions per minute. When the wheel is rolling (no applied brakes),

$$U = Rw$$

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.

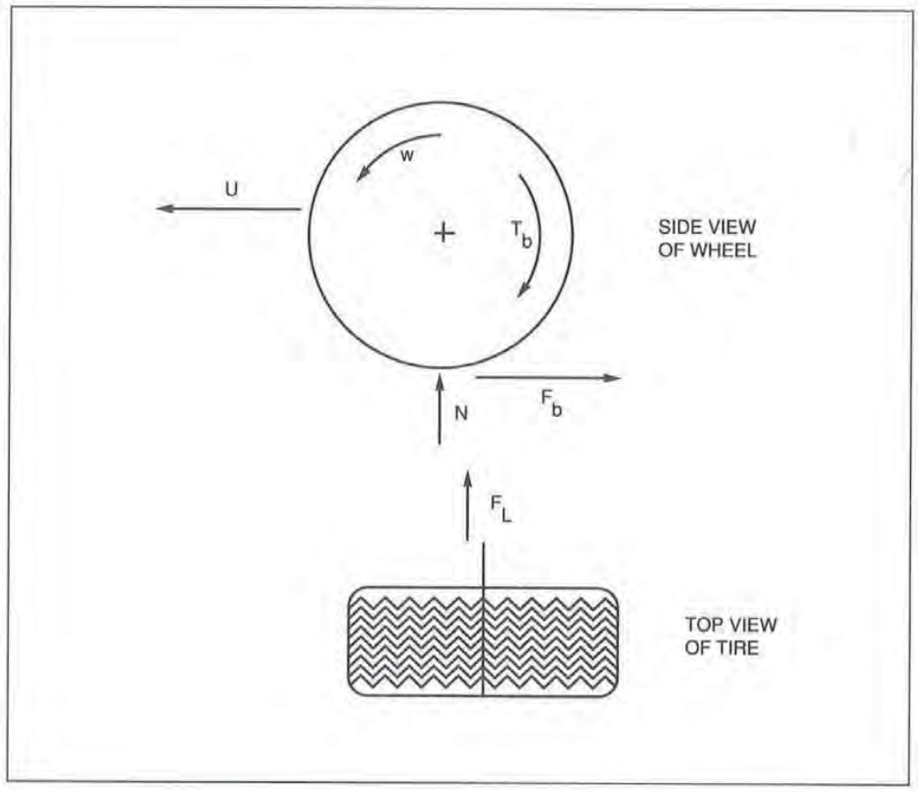
The wheel angular speed begins to decrease, causing a difference between the vehicle speed U and the tire speed over the road (i.e., wR). In effect, the tire

Figure 8.12 Antilock Braking System



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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

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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

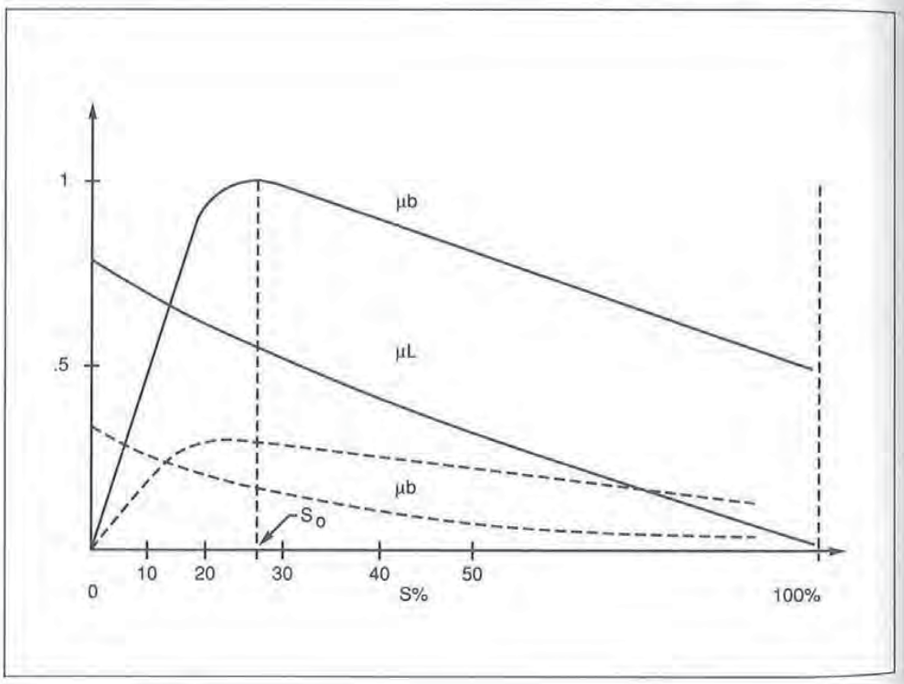


Figure 8.14 Braking Coefficients versus Tire Slip (Solid curves for dry road, dashed curves for wet or icy road):

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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

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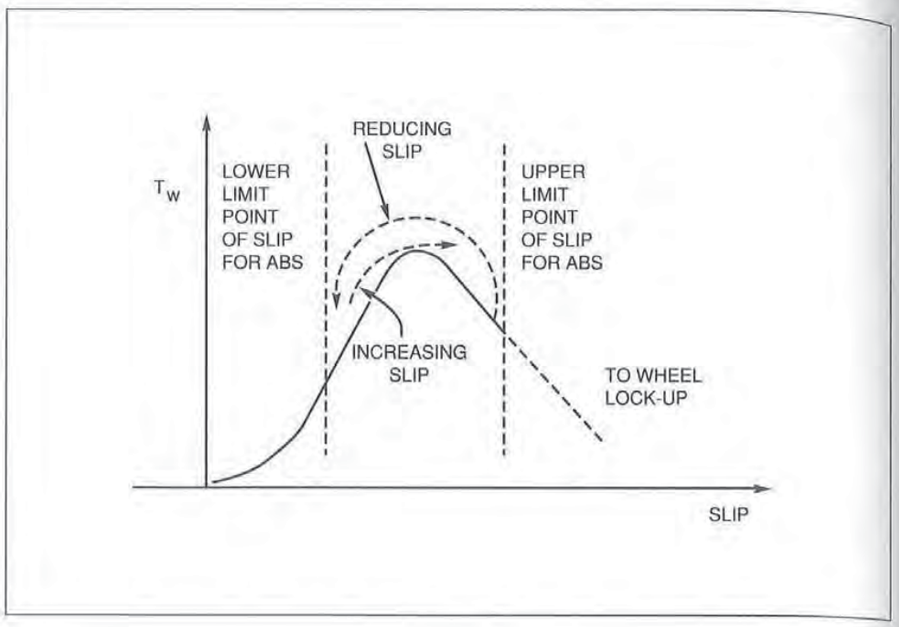


Figure 8.15
Wheel Torque versus Slip

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

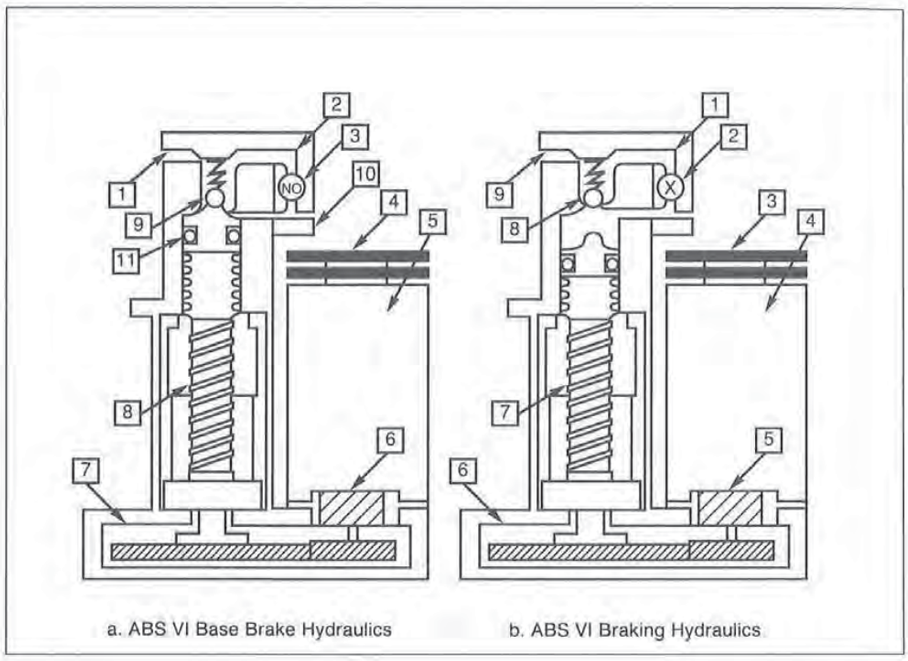
The numbers in Figure 8.16b refer to the following:

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.

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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,

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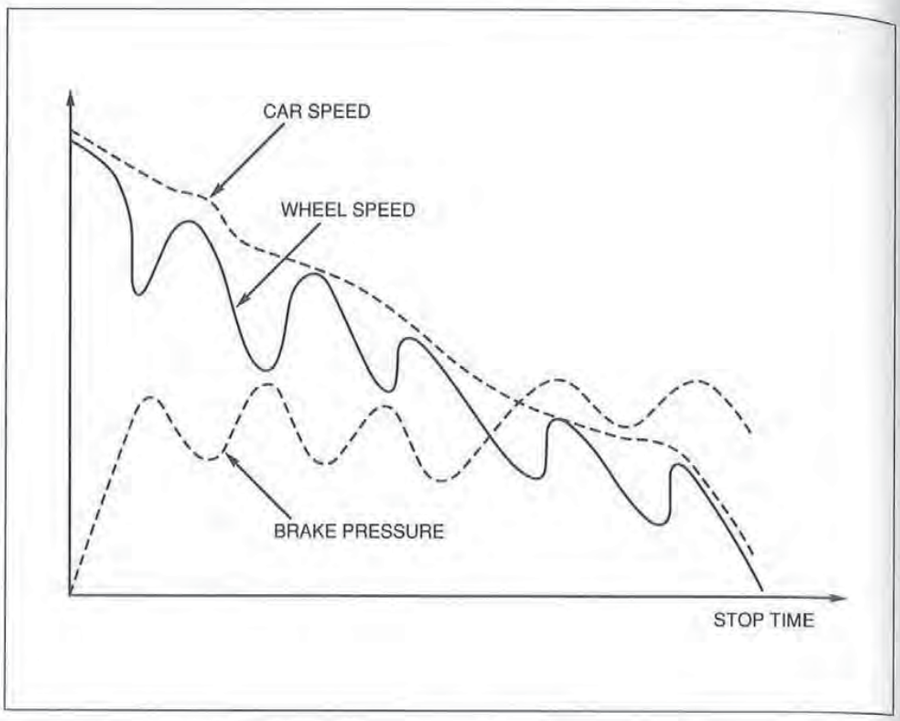


Figure 8.17
ABS Braking Action

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

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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

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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.

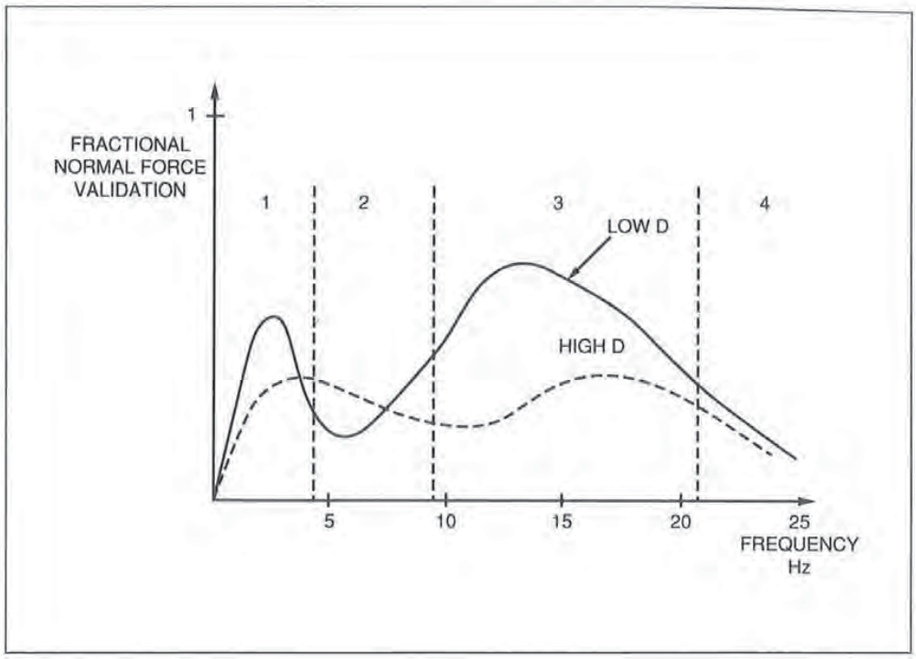
In Figure 8.18, the ordinate is the ratio of amplitude of force variation to the average normal load (i.e., due to weight). There are two relative peaks in this response. The lower peak is approximately 1 to 2 Hz and is generally associated with spring/sprung mass oscillation. The second peak, which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

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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.

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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 $0.6 < D/D_c < 0.8$.

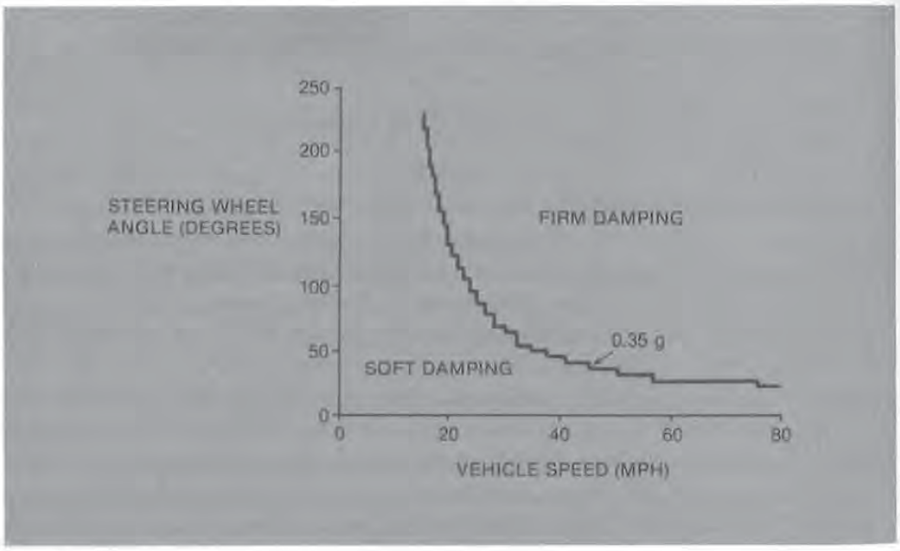


Figure 8.19 Switching Threshold versus Speed and Steering Inputs

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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).

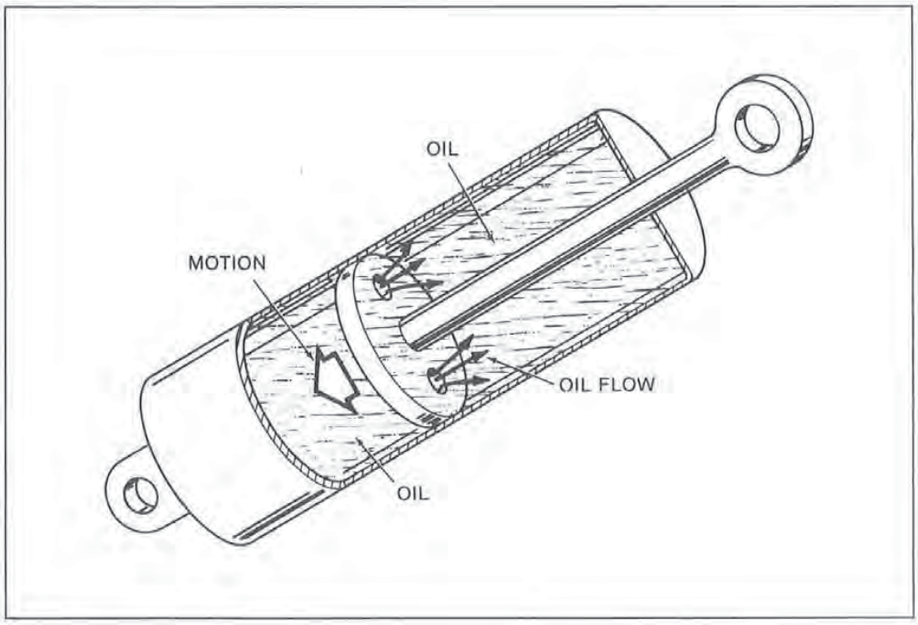
Figure 8.21 is an illustration of the force/relative velocity characteristics of a shock absorber having a solenoid-switched aperture.

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



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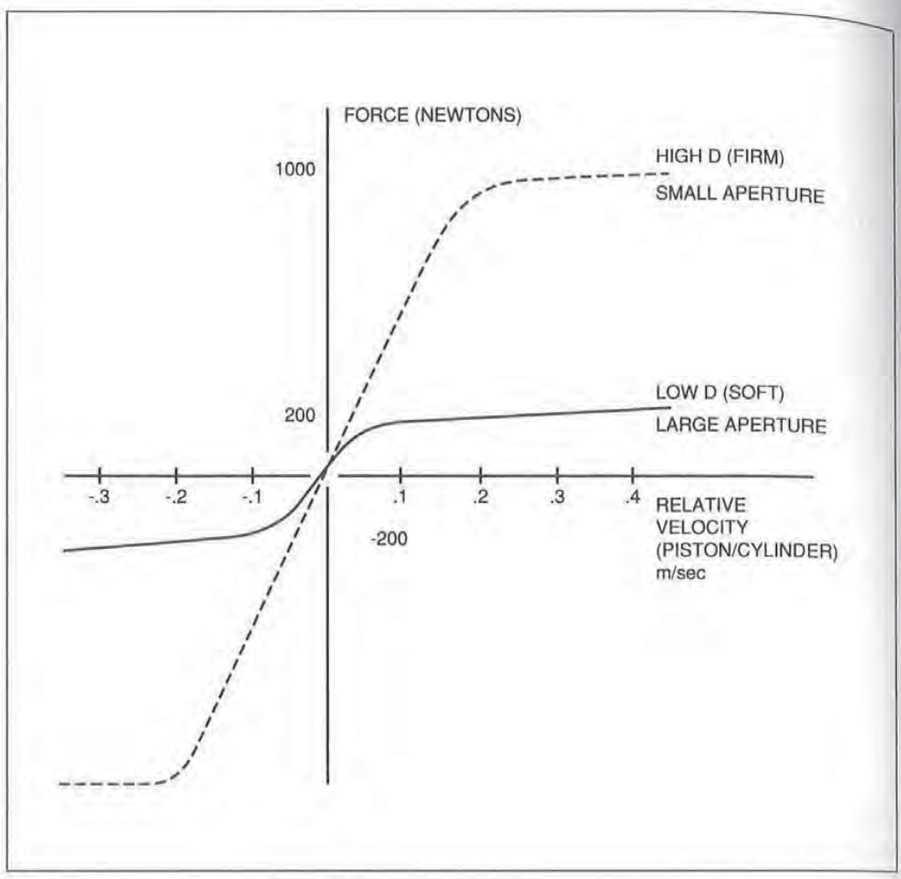


Figure 8.21 Force versus Relative Velocity of a Solenoid-Switched Aperture Shock Absorber

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

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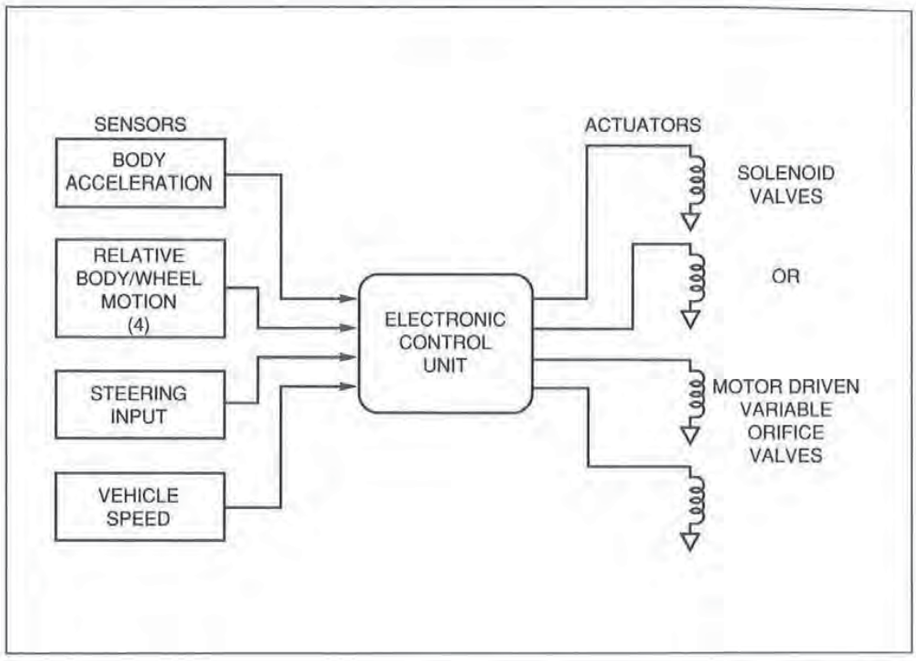


Figure 8.22 Semiactive Electronic Suspension System

(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).

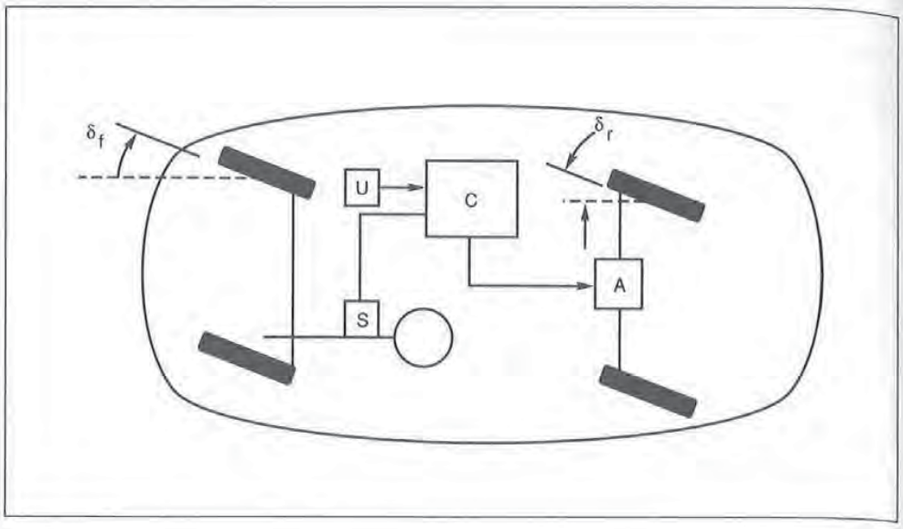
If in addition the vehicle is equipped with an accelerometer (usually located in the car body near the center of gravity) and with motor-driven variable-aperture shock absorbers, then an additional control strategy is possible. In this latter control strategy, the shock absorber apertures are adjusted 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

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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.

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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.

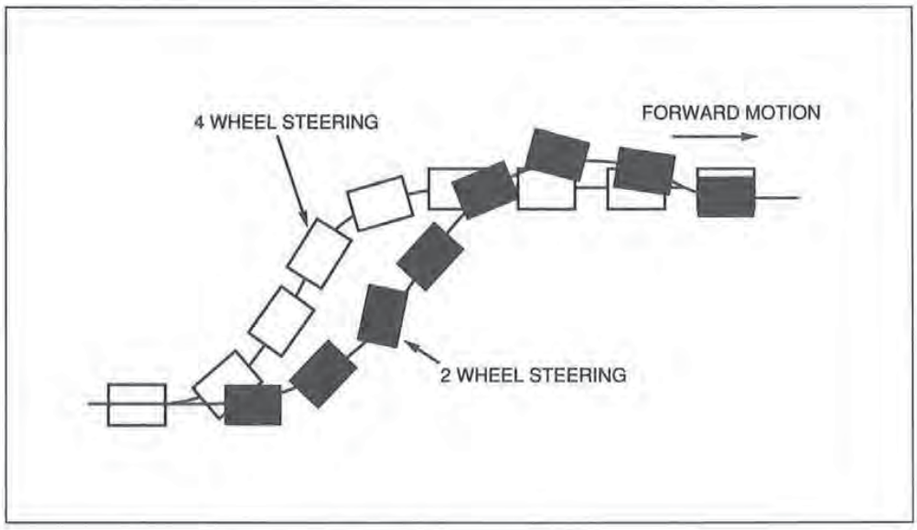


Figure 8.24 Lane Change Maneuver

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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

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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

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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

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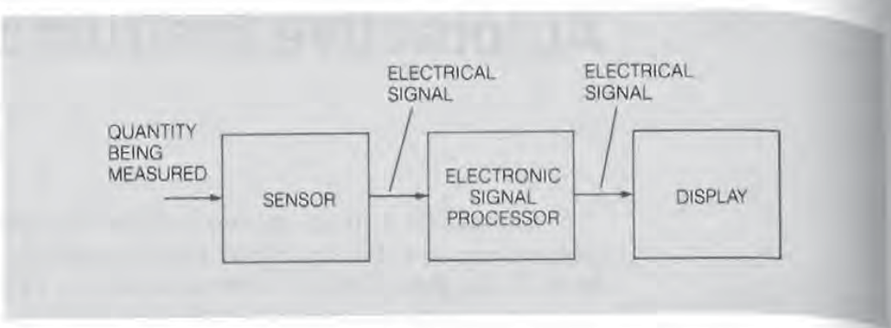


Figure 9.1 General Instrumentation Block Diagram

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.

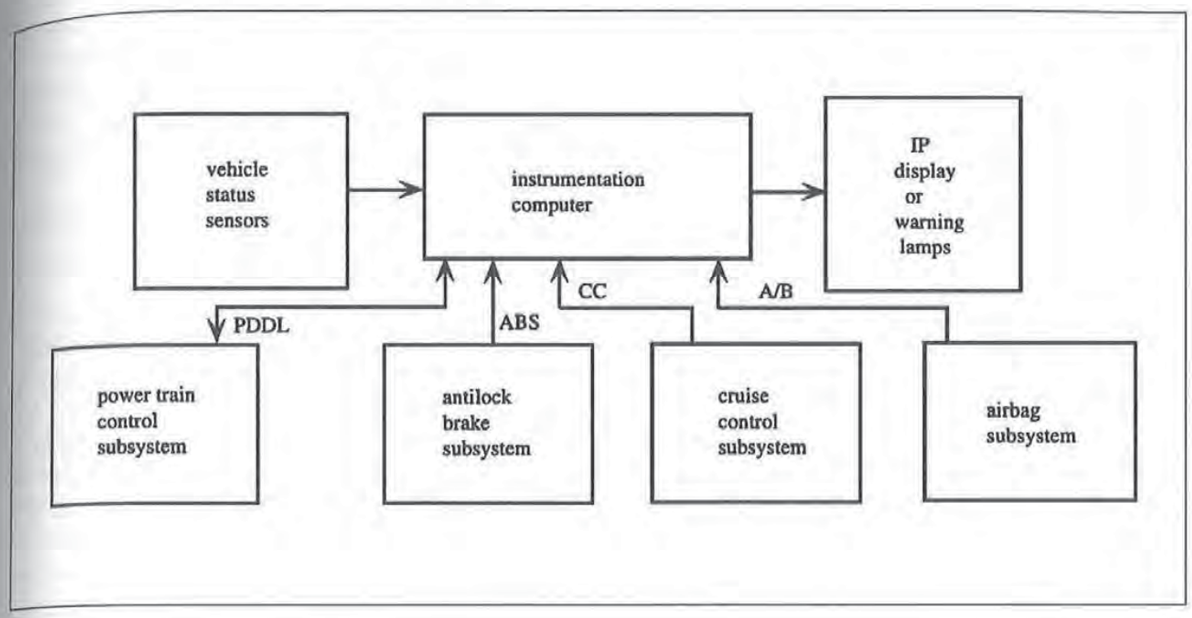
All measurements from the various sensors and switches are processed in a special-purpose digital computer. The processed signals are routed to the appropriate display or warning message. It is common practice in modern automotive instrumentation to integrate the display or warning in a single module 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

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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.

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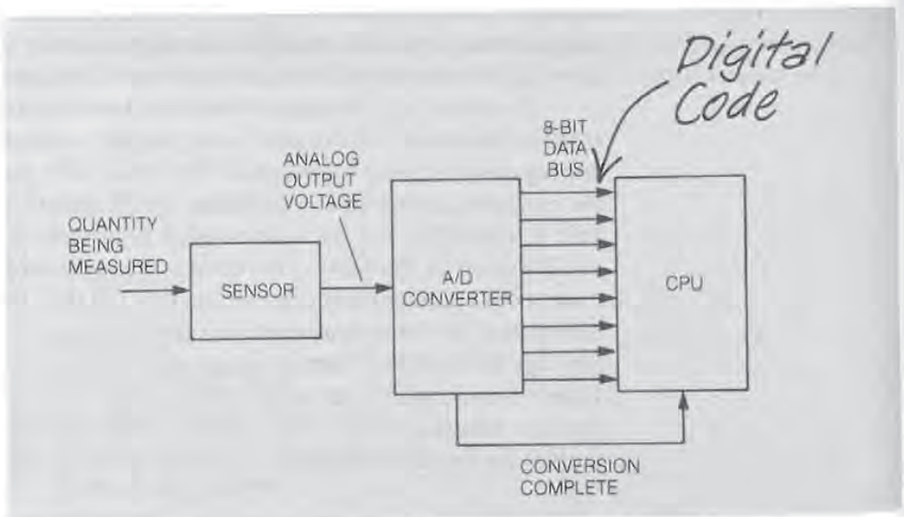
INPUT AND OUTPUT SIGNAL CONVERSION

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



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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.

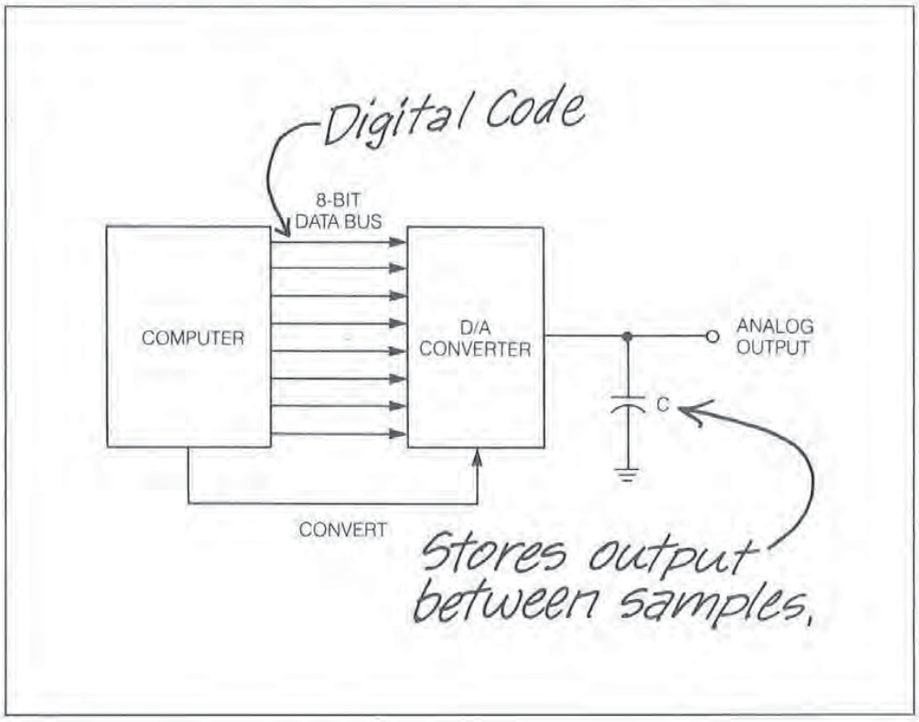


Figure 9.4 Digital-to-Analog Conversion

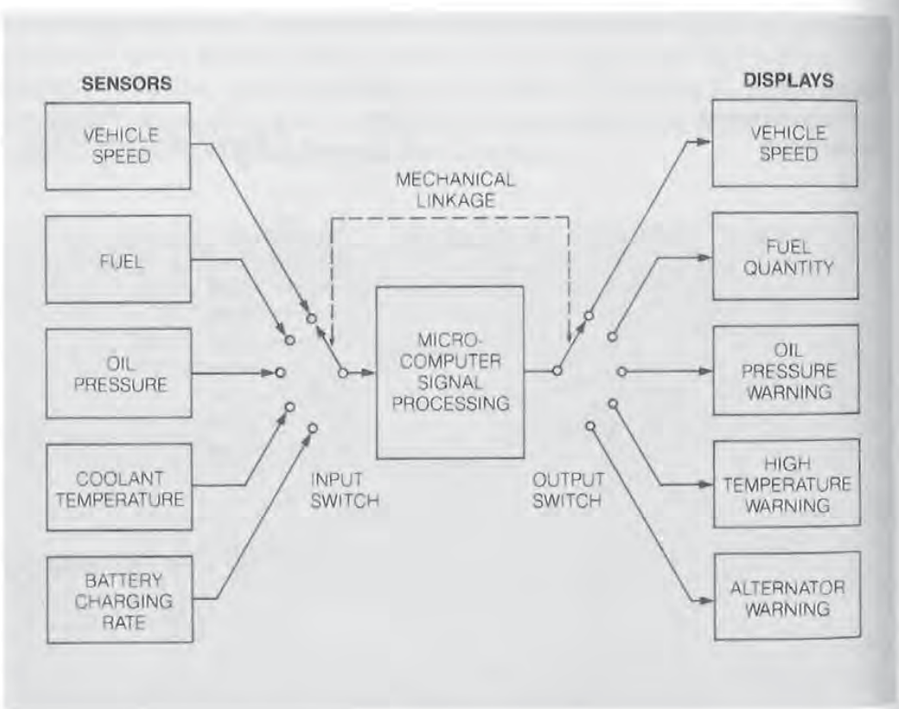
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In Figure 9.5 the various sensor outputs and display inputs are connected to a pair of multiposition rotary switches—one for the input and one for the output of the computer. The switches are functionally connected such that they rotate together. Whenever 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.

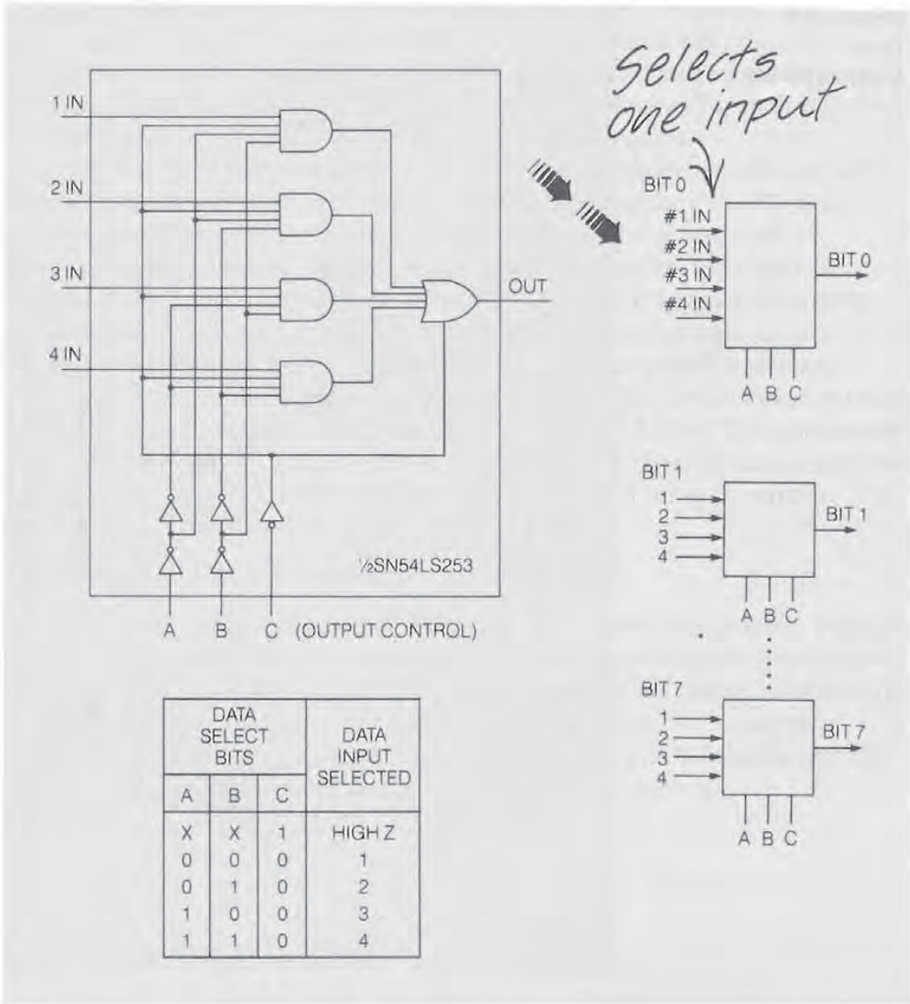
Typically, the computer controls the input and output switching operation. However, instead of a mechanical switch as shown in Figure 9.5, the actual switching is done by means of a solid-state electronic switching device called a *multiplexer* (MUX) that selects one of several inputs for each output. 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



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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.

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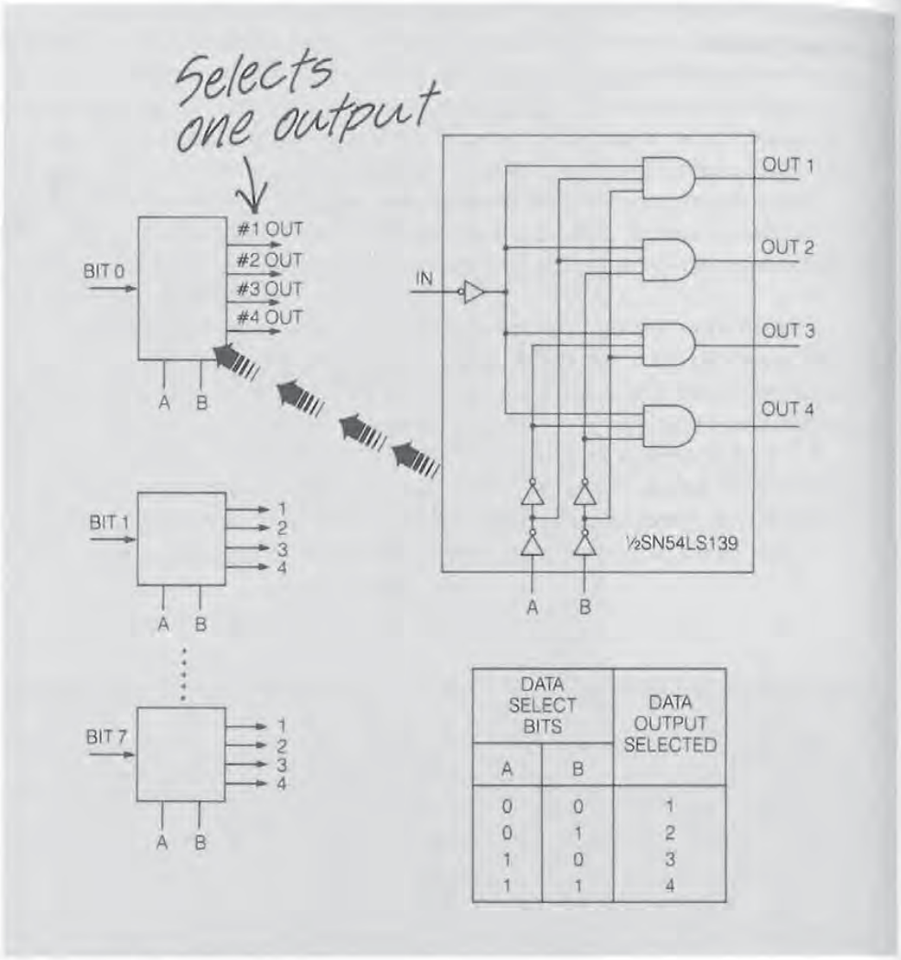


Figure 9.7
Data Demultiplexer

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,

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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).

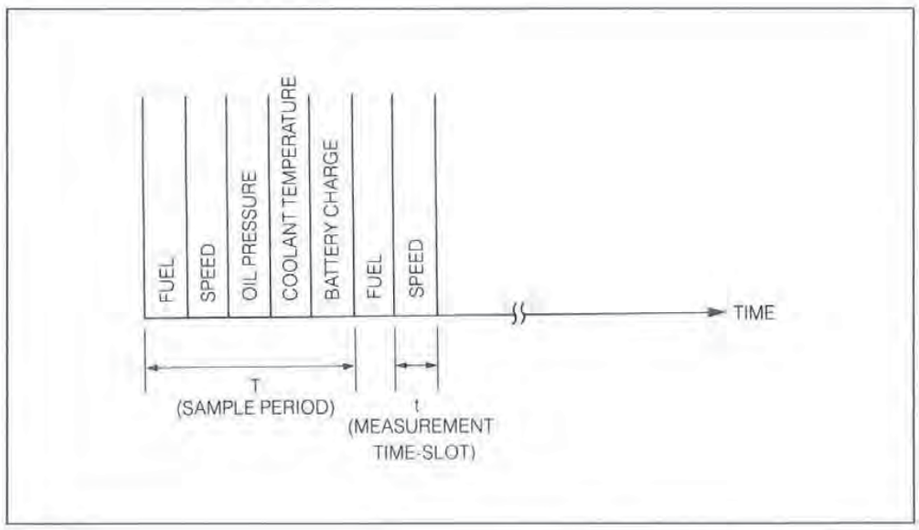


Figure 9.8 Sequential Sampling

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

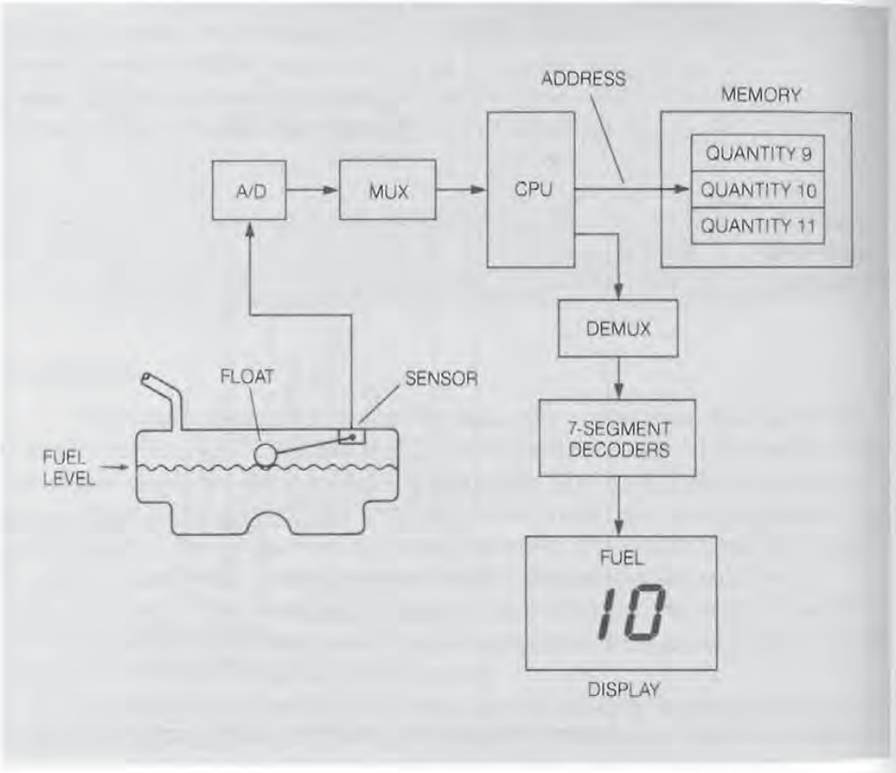
Another benefit of microcomputer-based electronic automotive instrumentation is its improved performance compared with conventional instrumentation. For example, the conventional fuel gauge system has errors that are associated with variations in the mechanical and geometrical characteristics of the 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



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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.

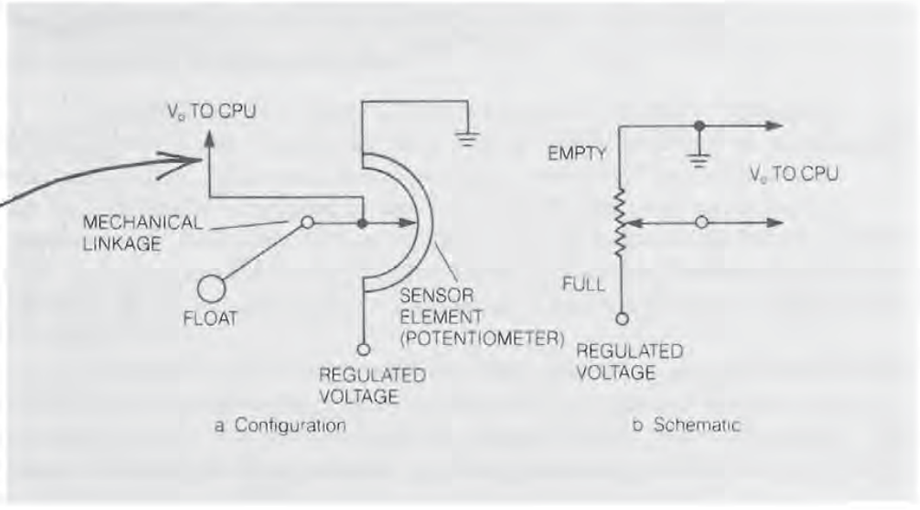
The computer reads the binary number from the A/D converter that corresponds to sensor voltage and uses it to address a particular memory location. Another binary number corresponding to the actual fuel quantity in gallons for that sensor voltage is stored in that memory location. The computer then uses 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.



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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.

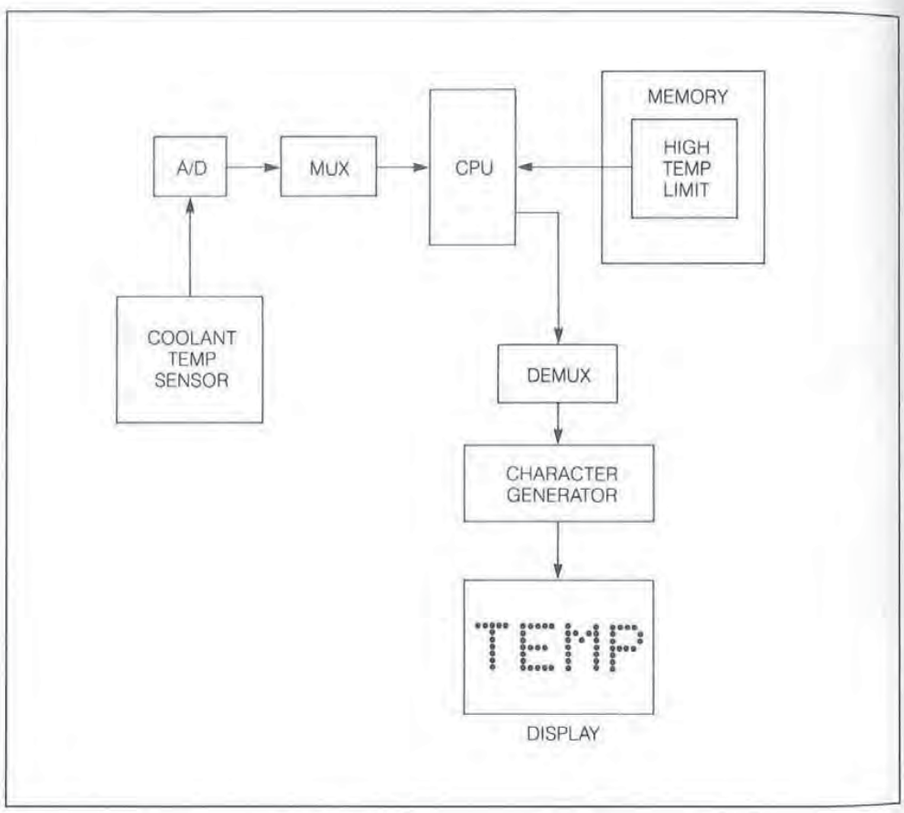


Figure 9.11 Coolant Temperature Measurement

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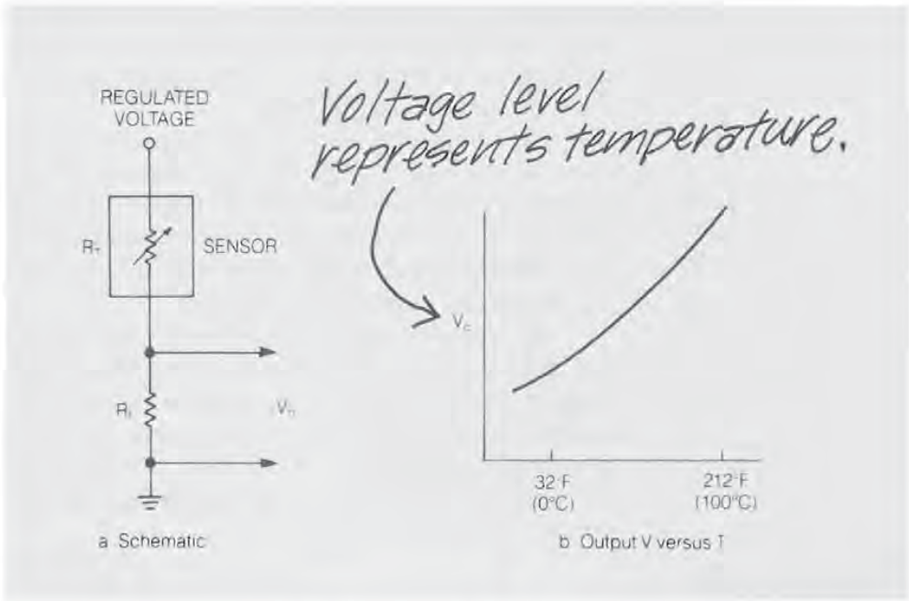


Figure 9.12 Coolant Temperature Sensor

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

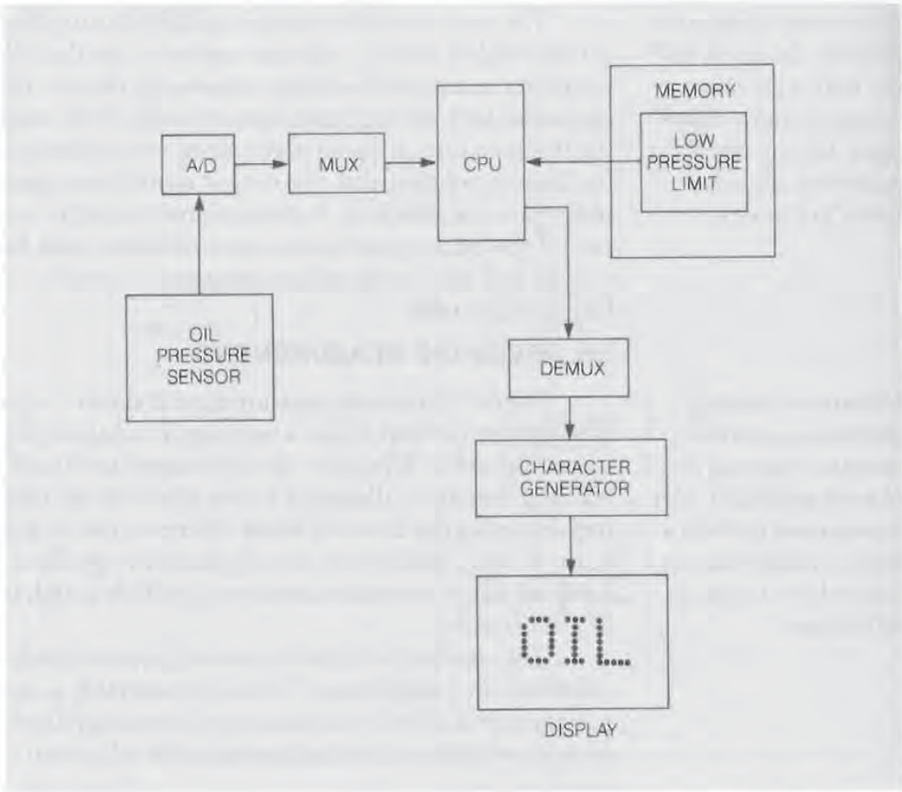
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the spring and to hold the switch open as long as the oil pressure exceeds the lower limit. Whenever the oil pressure falls below this limit the spring force is sufficient to close the switch. Switch closure is used to switch on the low oil pressure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

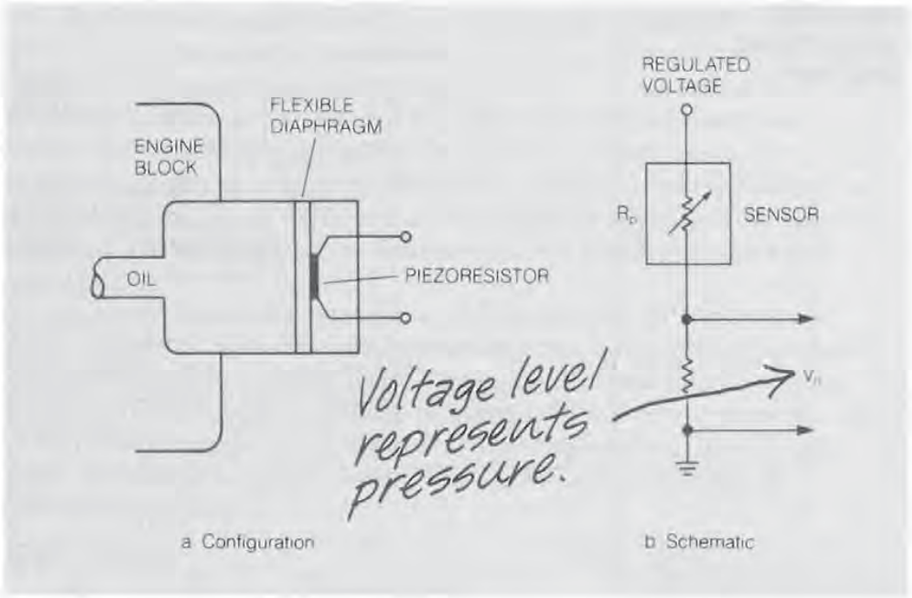
An oil pressure instrument that operates with a load- or speed-dependent threshold requires an oil pressure sensor rather than a switch. Such an oil pressure warning system is illustrated in Figure 9.13. This system uses a variable-resistance oil pressure sensor such as seen in Figure 9.14. A voltage 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



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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.

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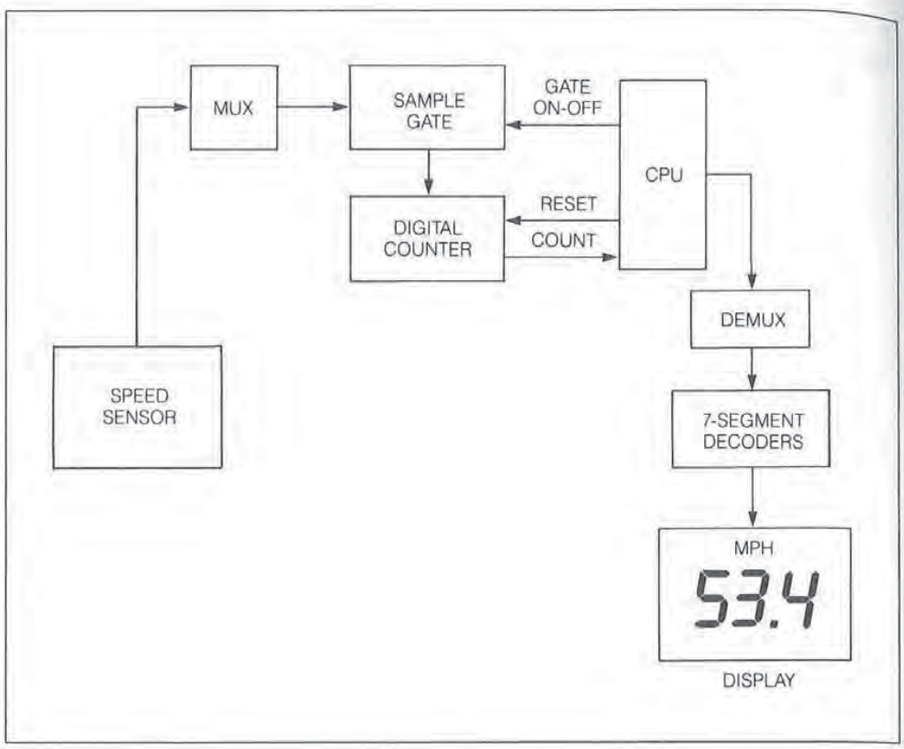


Figure 9.15 Vehicle Speed Measurement

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.

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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.

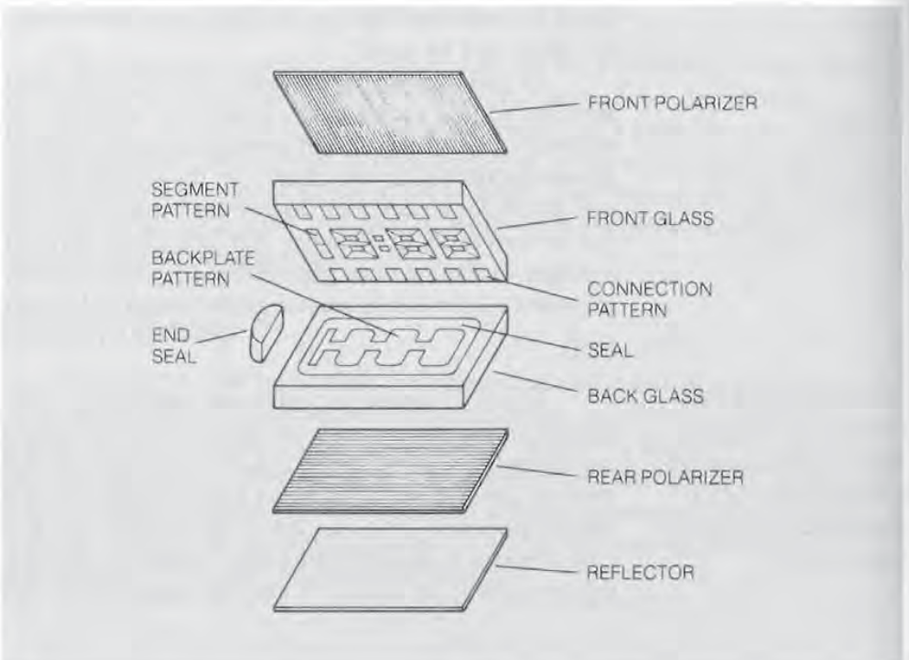
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Nonpolarized light can be polarized by passing the light through a polarizing material. To illustrate, think of a picket fence with narrow gaps between the pickets. If a rope is passed between two of the pickets and its end is whipped up and down, 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



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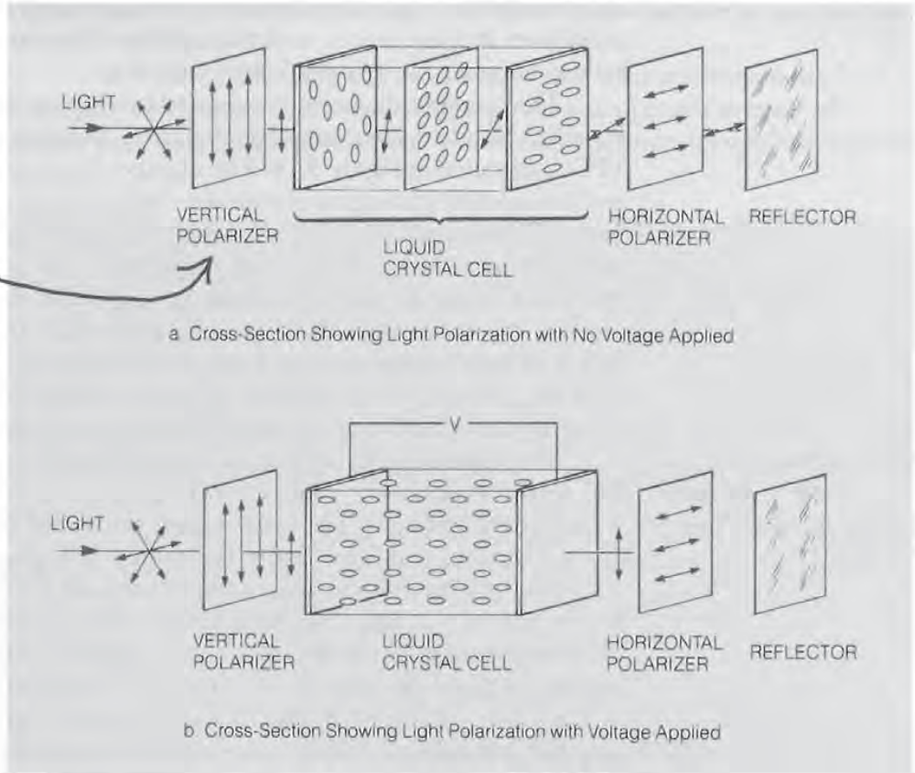
When current is not being applied to an LCD display, light entering the crystal is polarized by the front polarizer, rotated, passed through the rear polarizer, and then reflected off the reflector.
When a voltage is applied to a display segment, the crystal's molecules change and do not rotate the polarized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



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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

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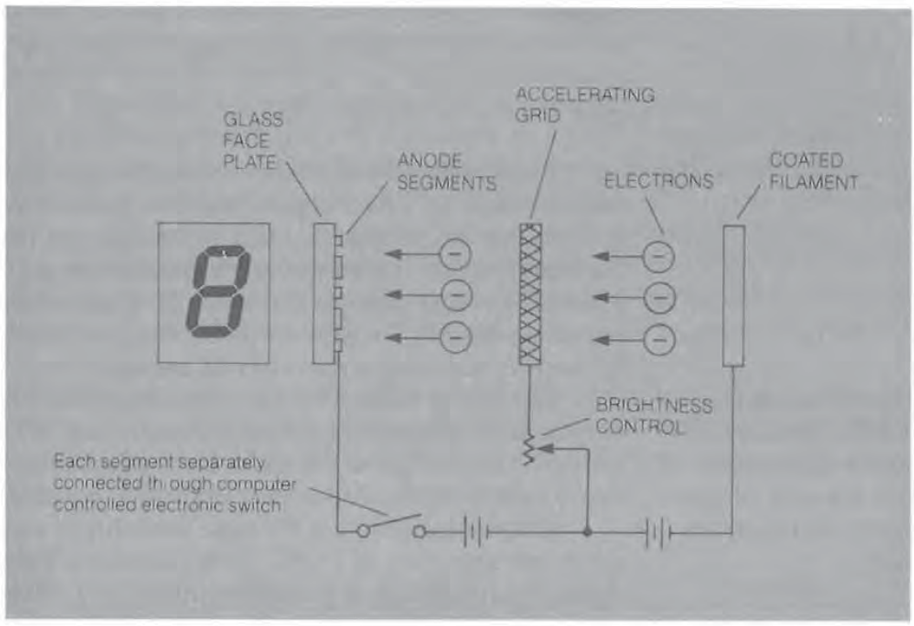


Figure 9.18 Simplified Vacuum-Fluorescent Display Configuration

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

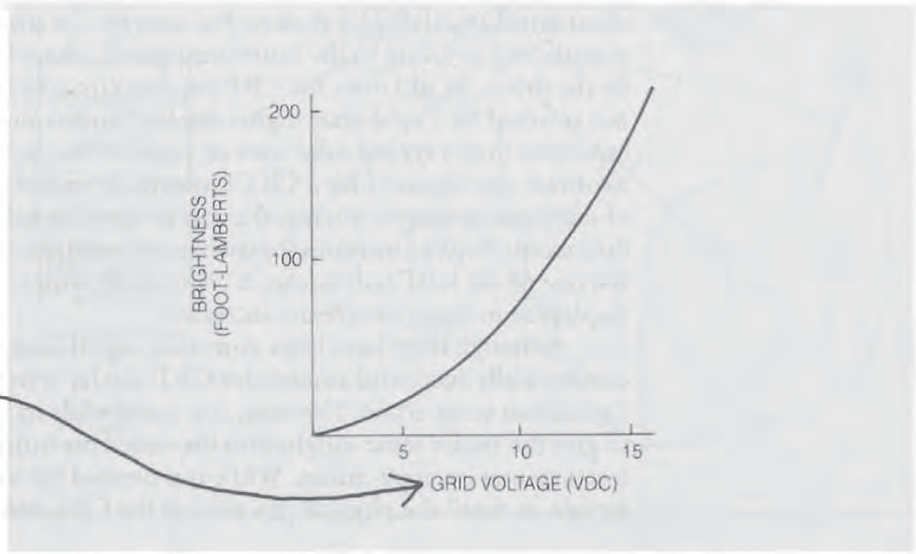


Figure 9.19 Brightness Control Range for Vacuum-Fluorescent Display

Increasing grid voltage increases brightness.

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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

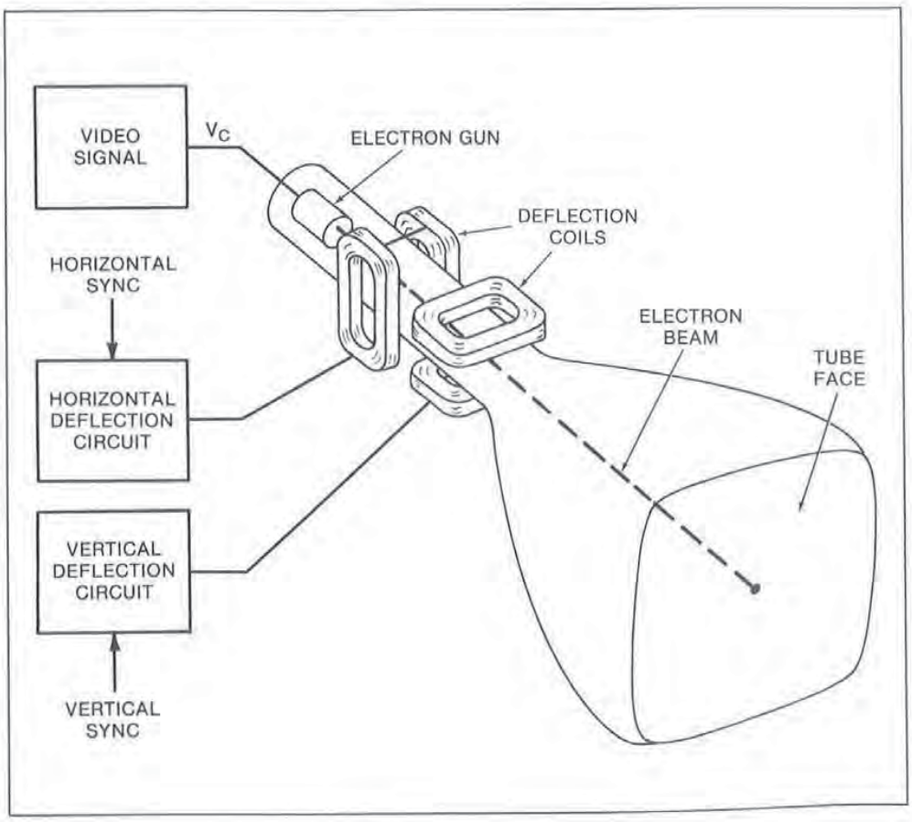
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circuits, a relatively simple overview of the functional operation of the CRT as a display device is straightforward and should serve to illustrate some potential automotive applications.

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



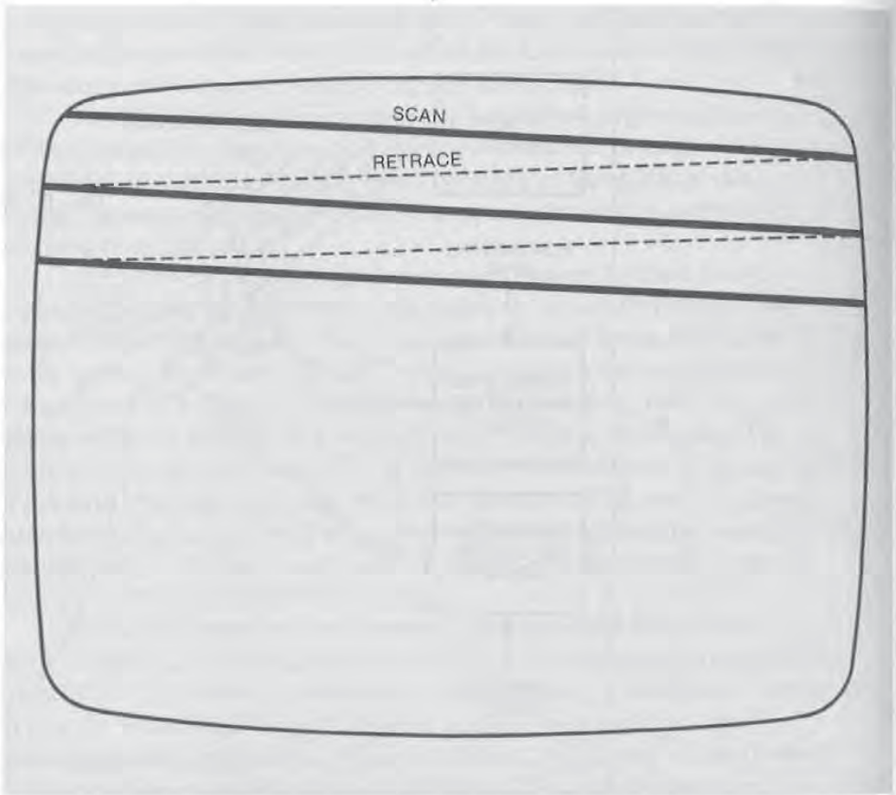
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In the majority of applications (including TV), the electron beam is scanned in a pattern known as a *raster* by means of specially located electromagnets (see Figure 9.20). The magnetic fields created by the scanning coils deflect the beam horizontally 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



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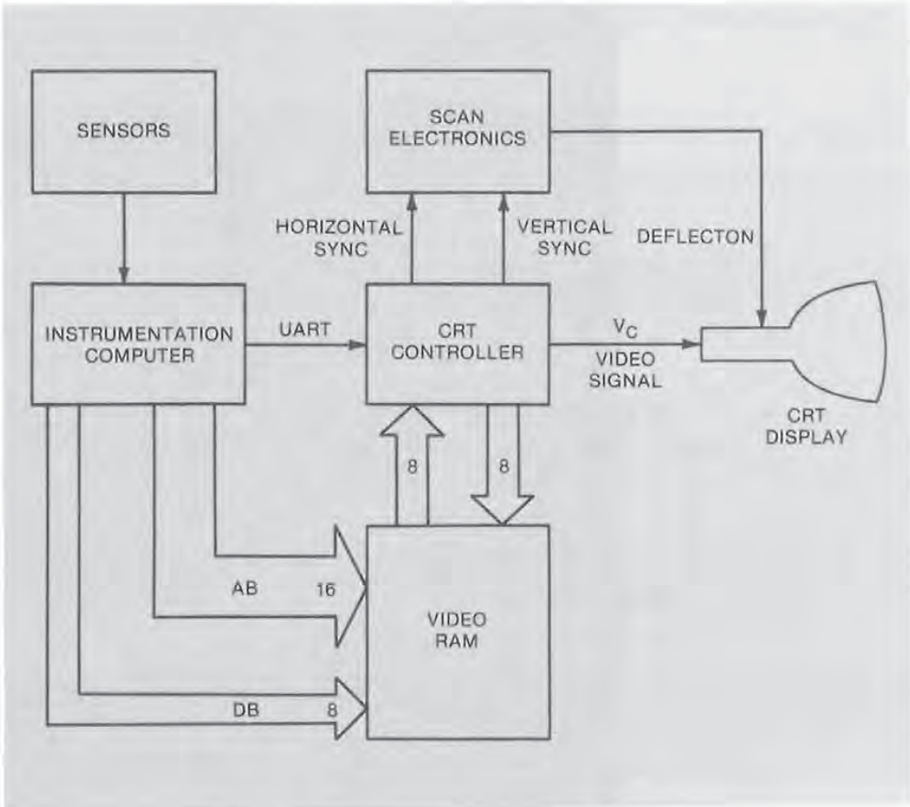
In automotive instrumentation applications, a CRT display is driven by a special electronics system called the CRT controller.

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



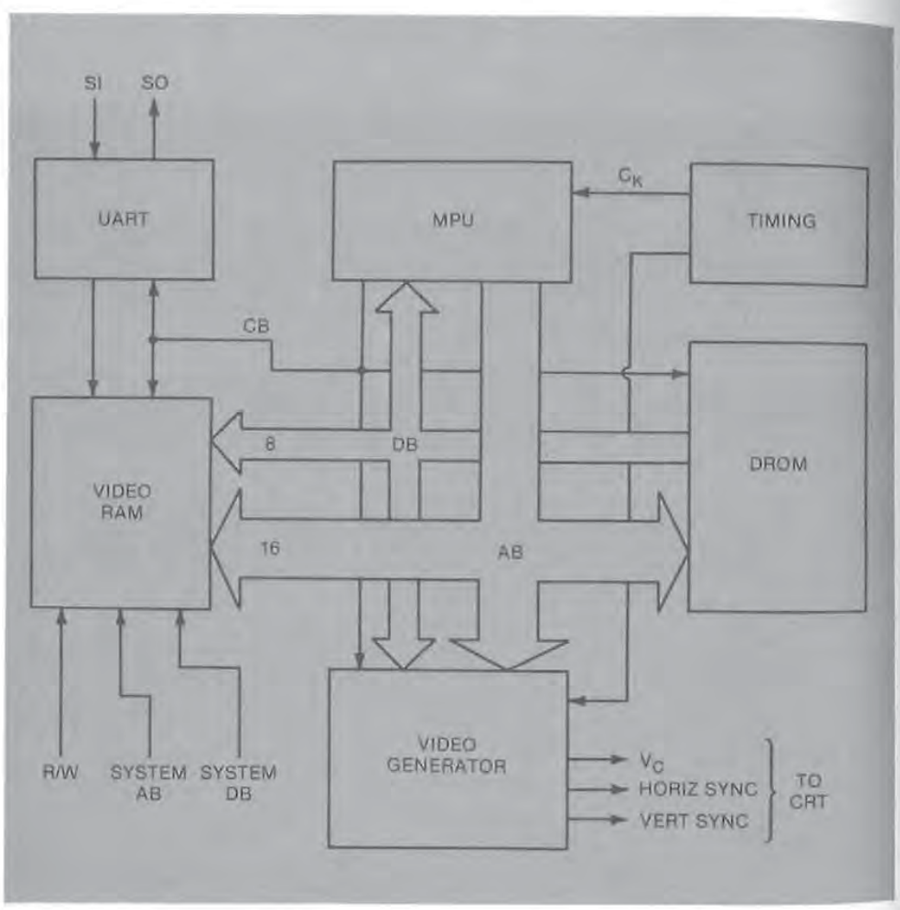
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converts it to the relevant video signal (V_c). At the same time, the CRT controller generates the horizontal and vertical sync necessary to operate the raster scan in synchronism with the video signal.

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



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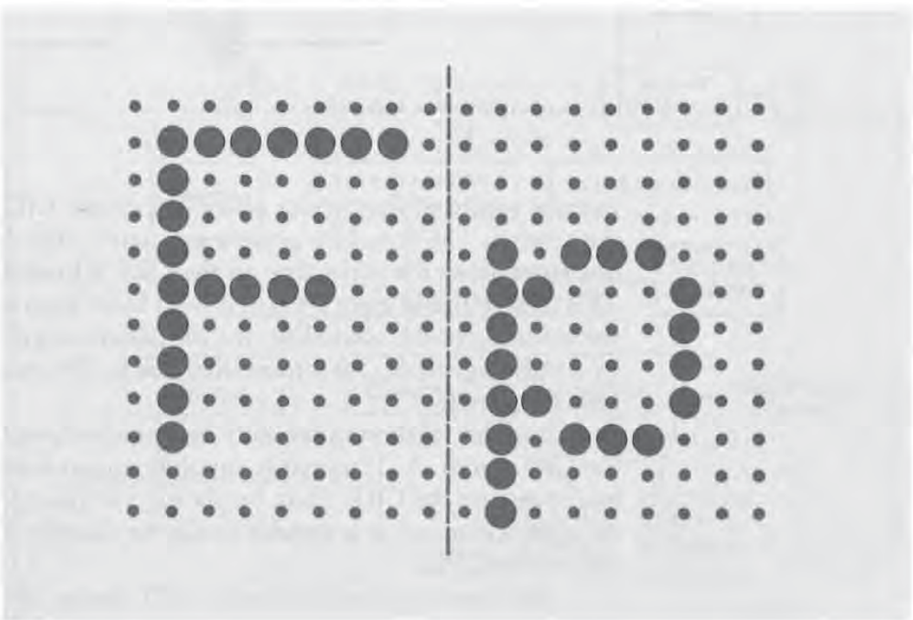
The operation of the CRT controller is under control of the instrumentation computer. This computer transfers data that is to be displayed to the video RAM, and signals the CRT controller via the UART link. During the display time, the MPU operates under control of programs stored in the DROM. These 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



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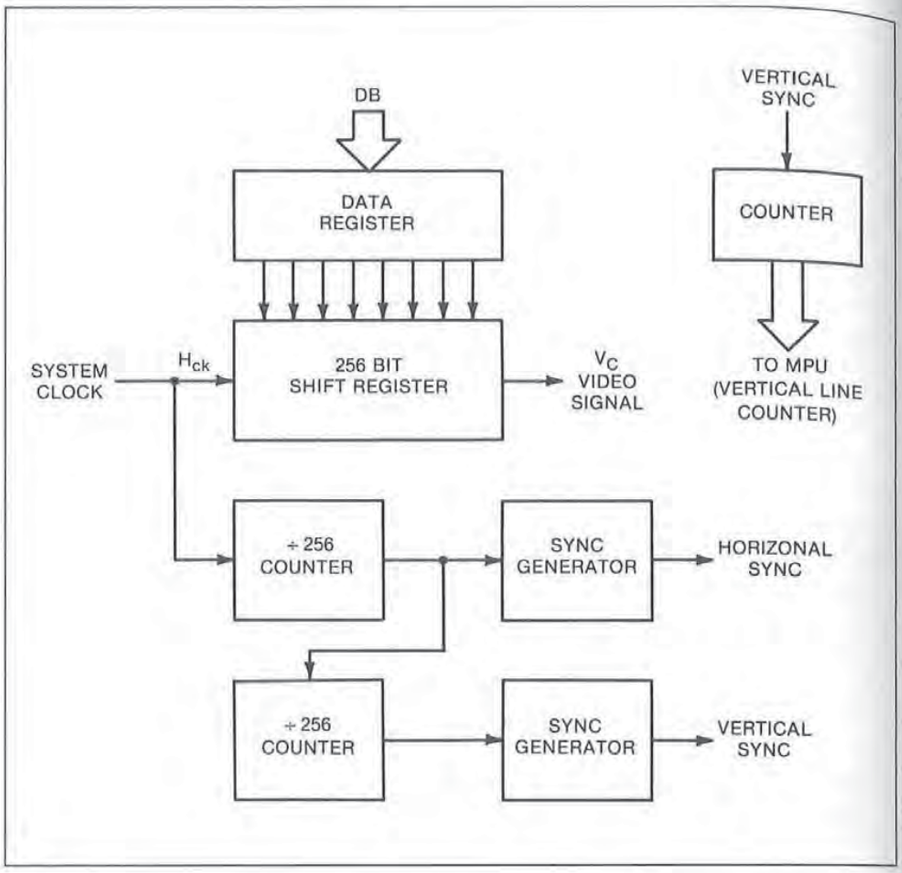


Figure 9.25 Video Signal Generation

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

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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

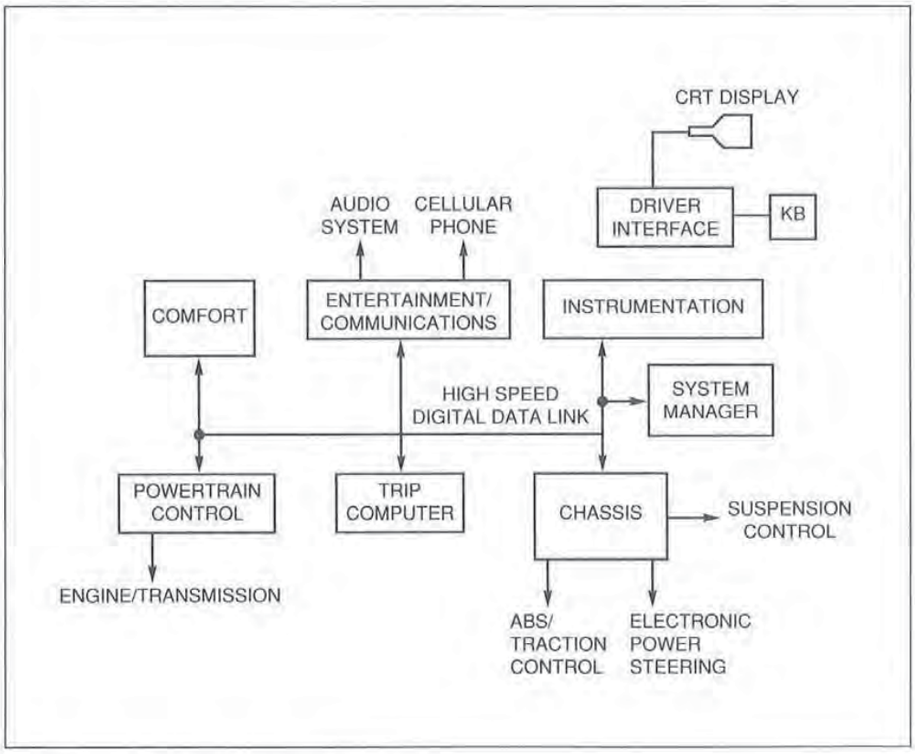


Figure 9.26 Integrated Vehicle Electronic Systems

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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

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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.

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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.

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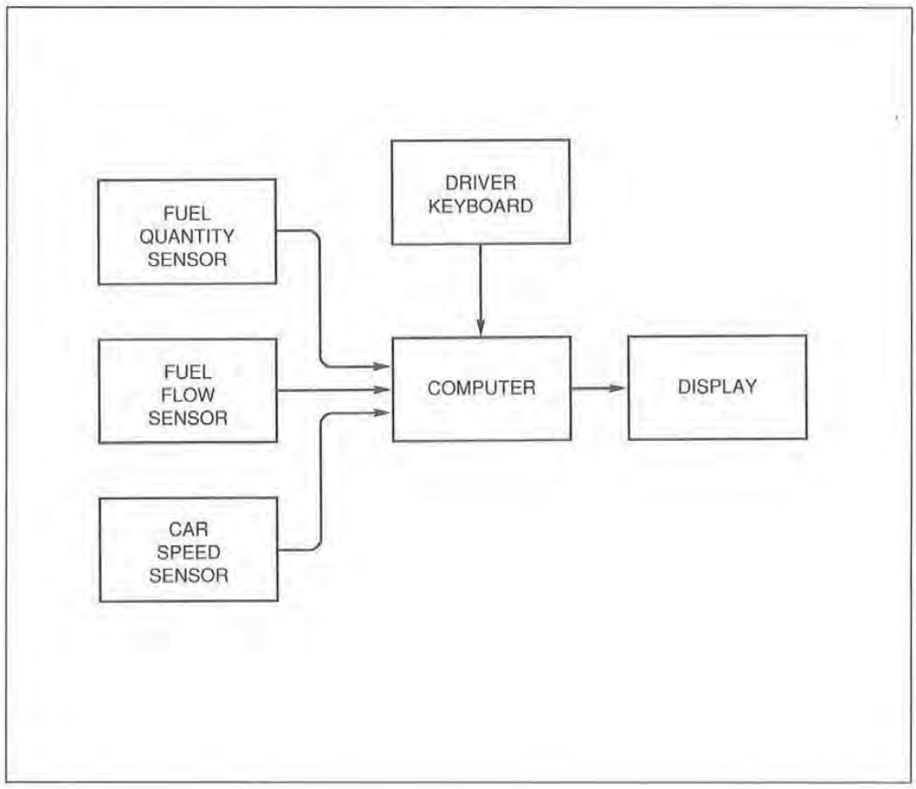


Figure 9.27
Trip Information System

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.

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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.

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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.

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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

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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

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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

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Figure 10.1
Typical Engine
Timing Light

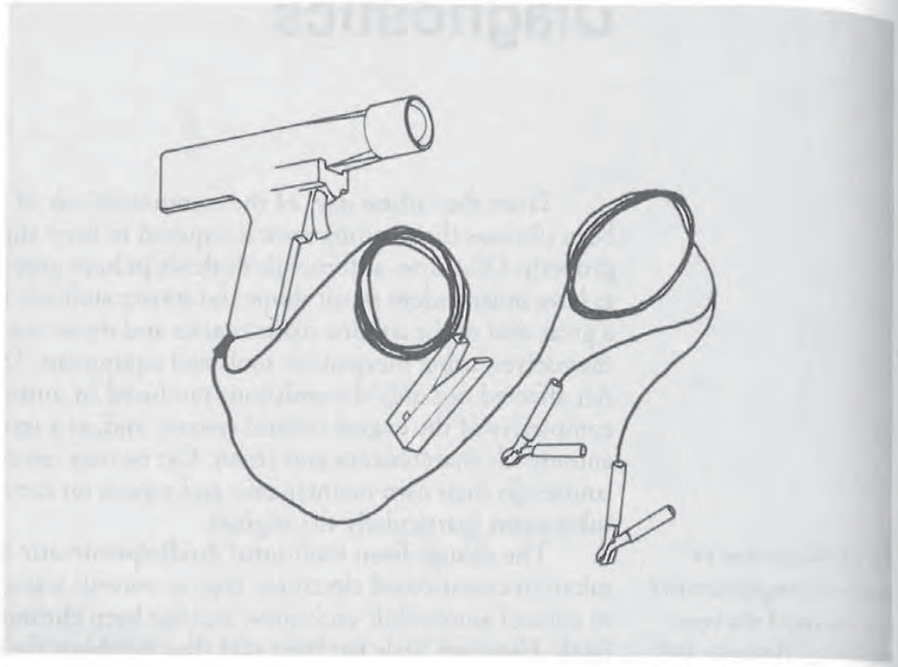
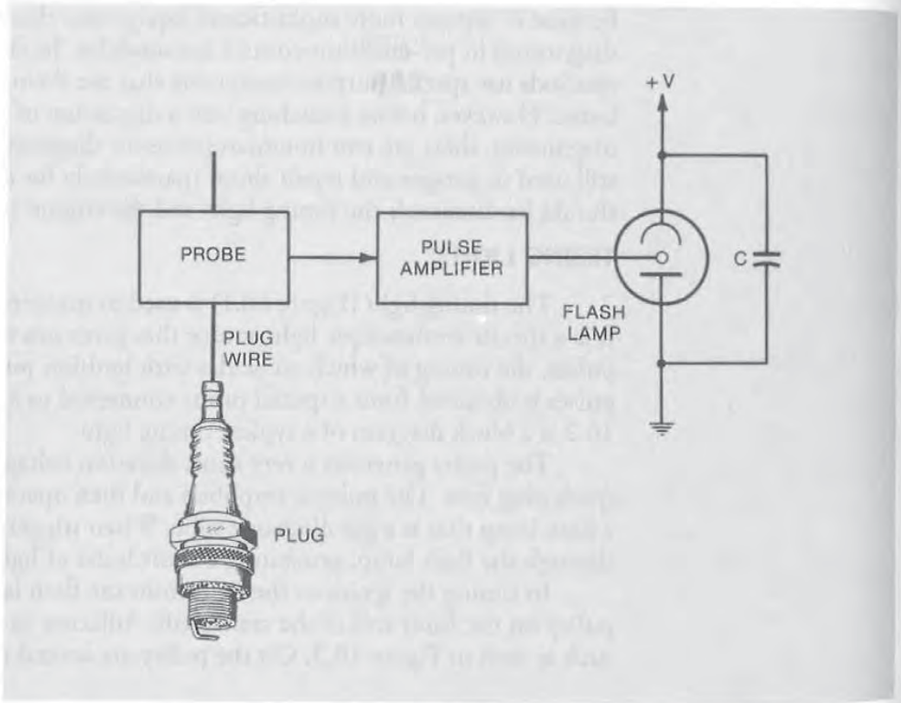
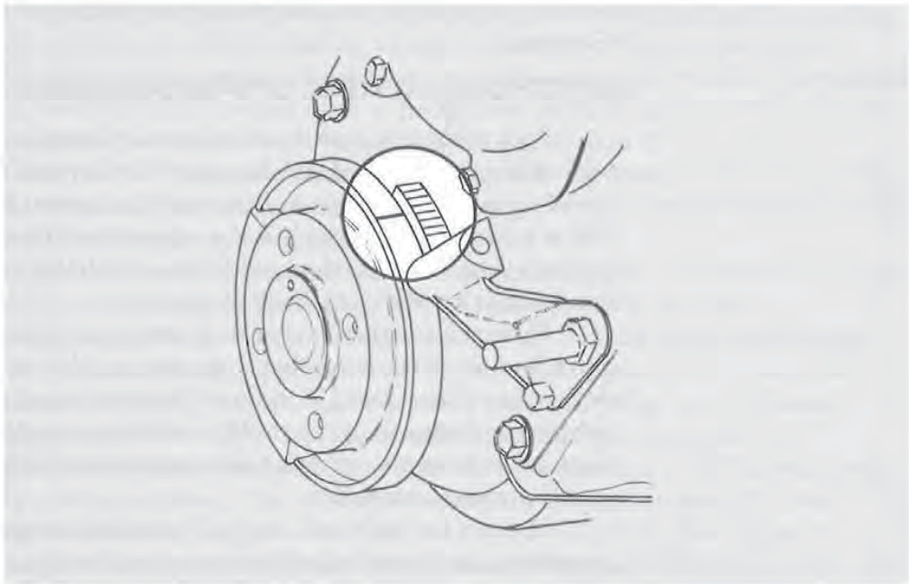


Figure 10.2
Timing Light Block
Diagram



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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

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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.

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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.

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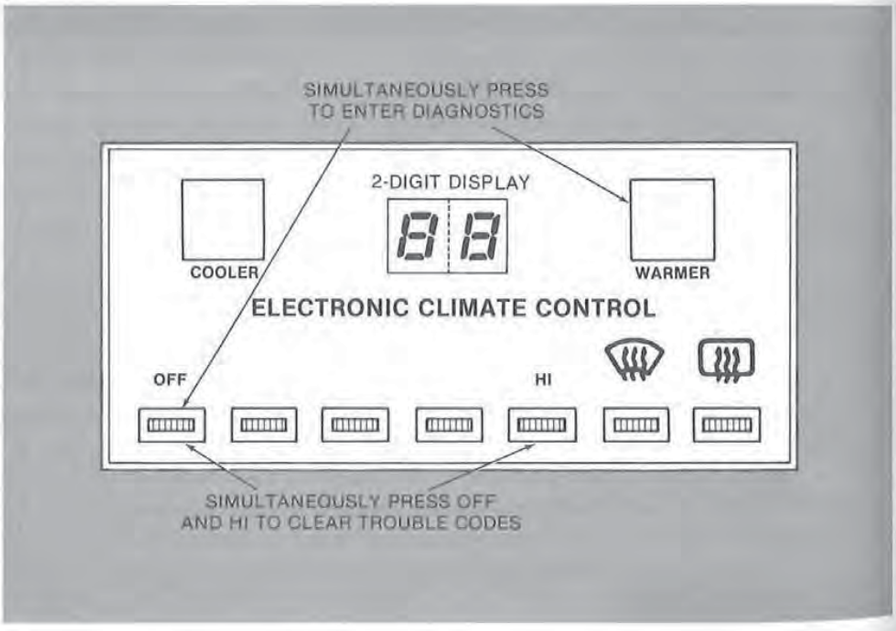
The on-board diagnostic capabilities can be manually activated by causing the engine controller to enter a diagnostic mode. The method for accomplishing this task varies from car to car. For example, in certain older-model fuel-injected Cadillac cars, the diagnostic mode is entered by first switching 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



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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

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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).

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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.

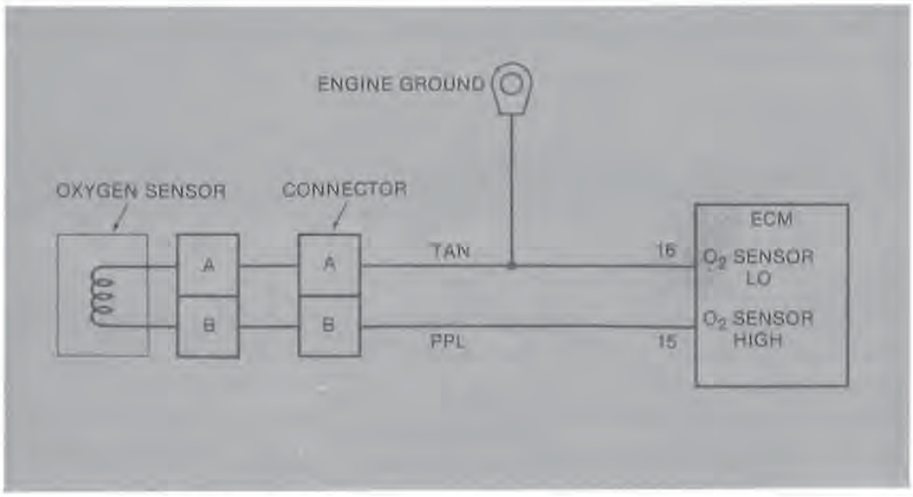


Figure 10.5
DFI Oxygen Sensor Circuit

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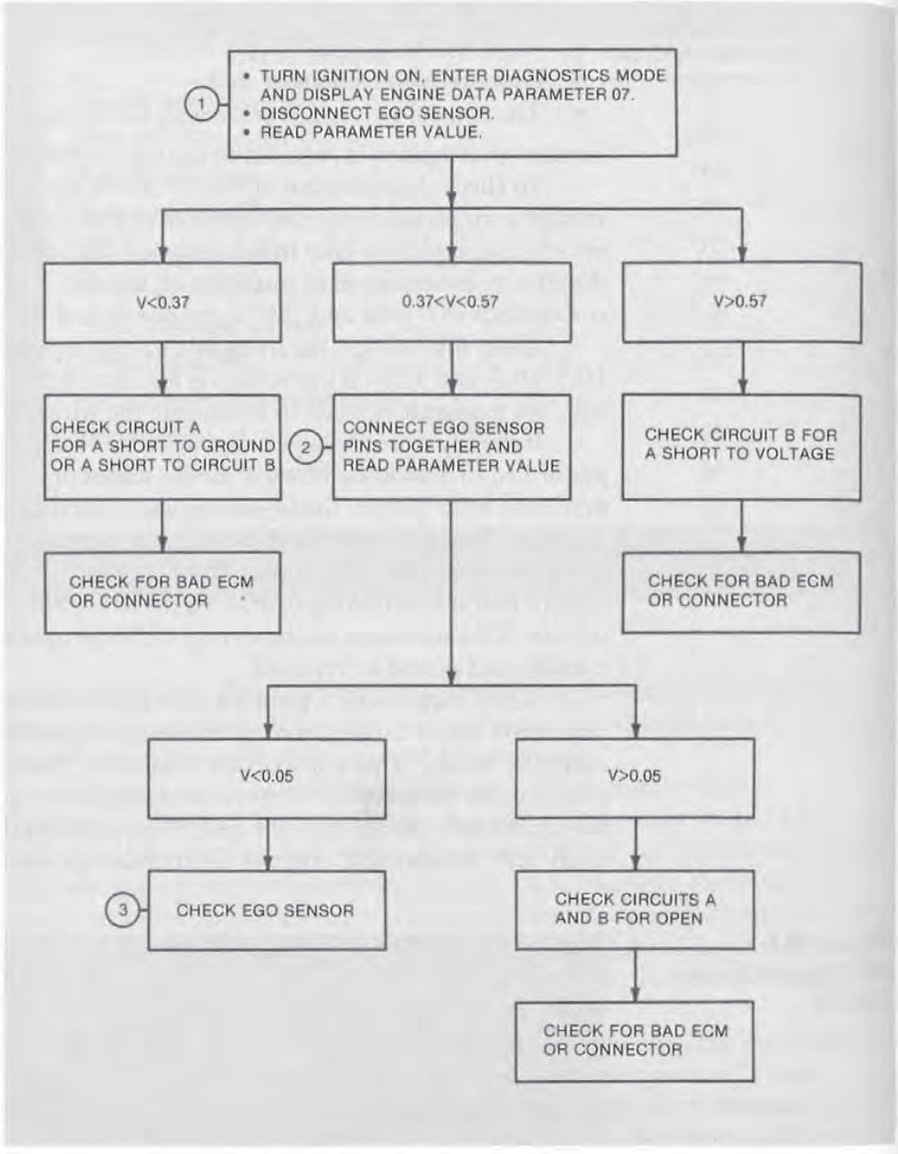


Figure 10.6
DFI Code 13: Oxygen Sensor Not Ready

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.

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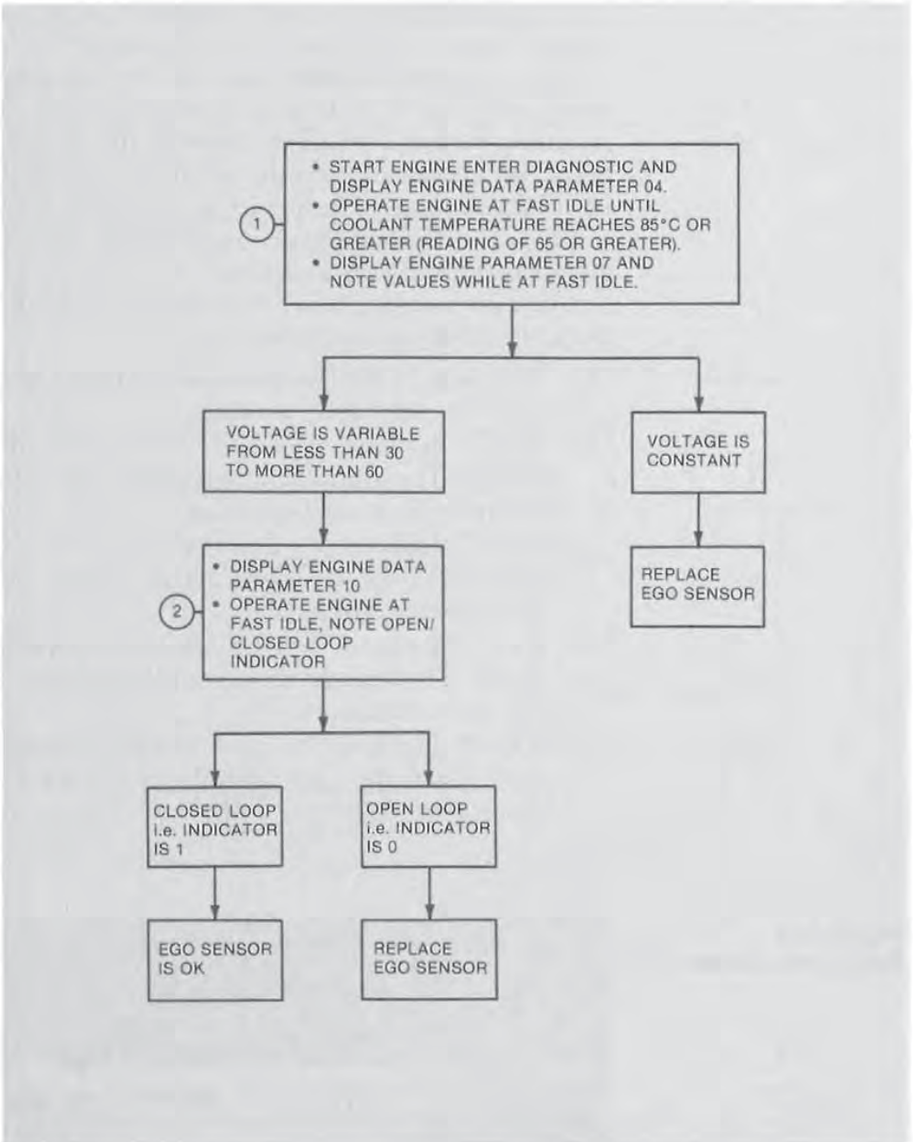


Figure 10.7
DFI Chart No. 14: Oxygen Sensor Test

Perform cylinder select tests.
Exit from diagnostic mode.

Each of the above procedures provides an important diagnostic capability to the mechanic.

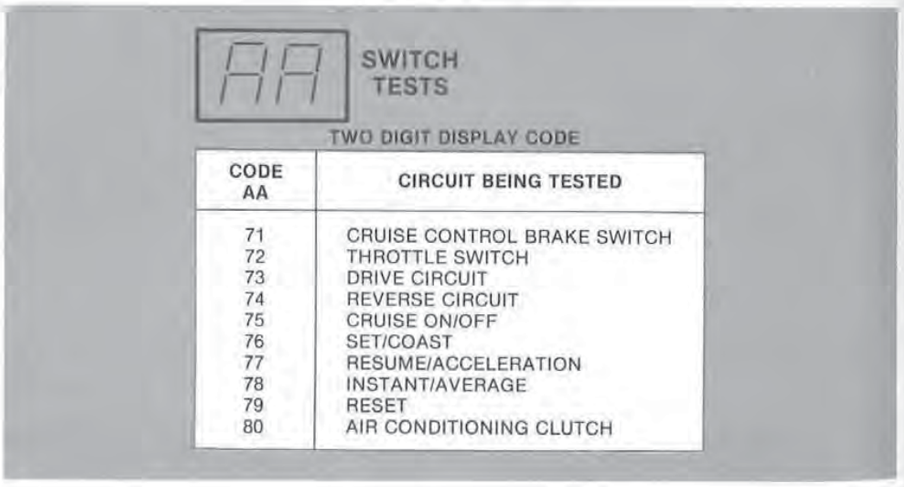
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The switch tests involve fault codes 71 to 80 and provide checks on the switches indicated in Figure 10.8. To begin the switch tests, the mechanic must depress and release the brake pedal. If there is no brake switch failure, then the code advances 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.

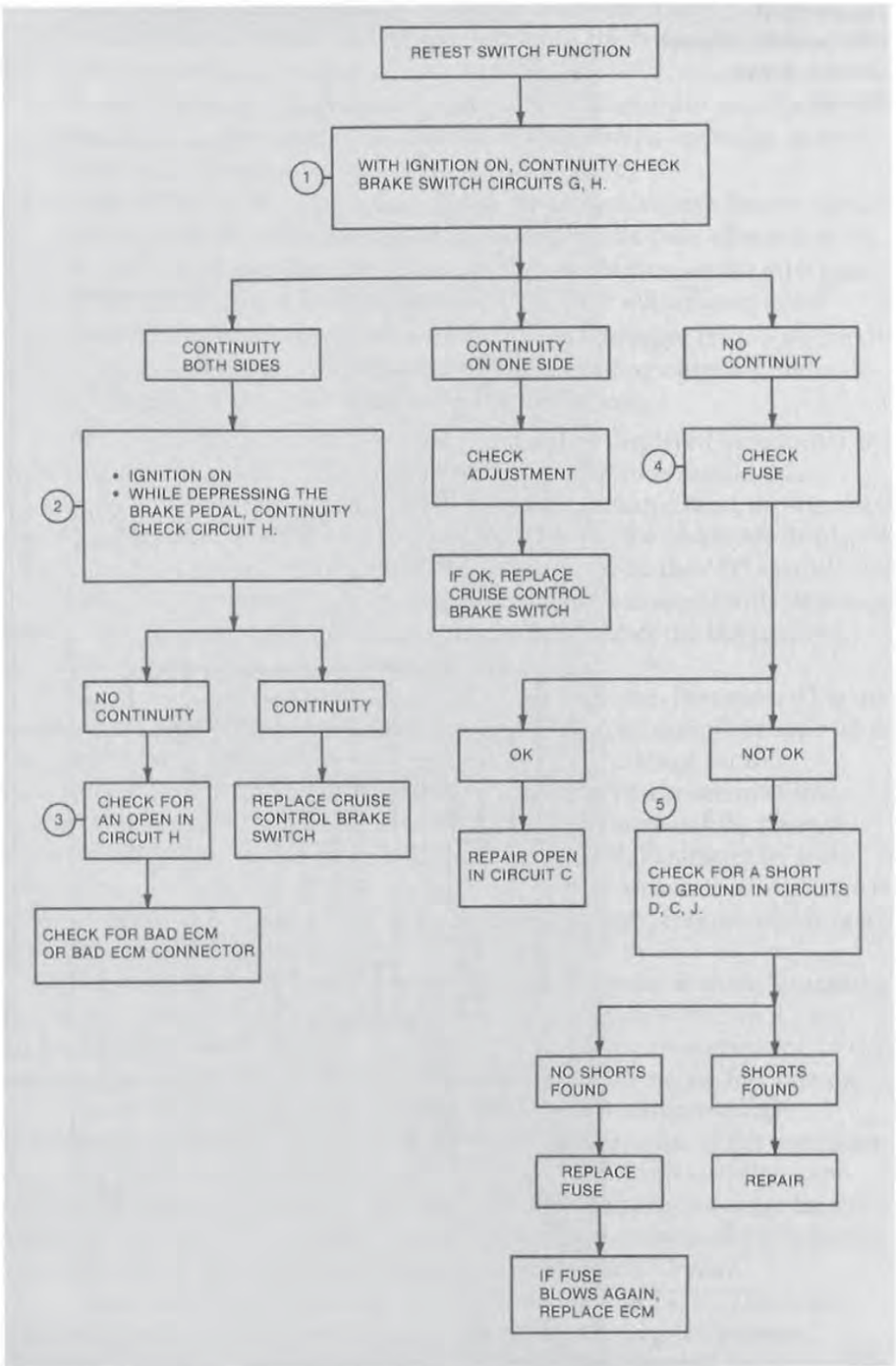
Figure 10.8
Switch Test Series



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

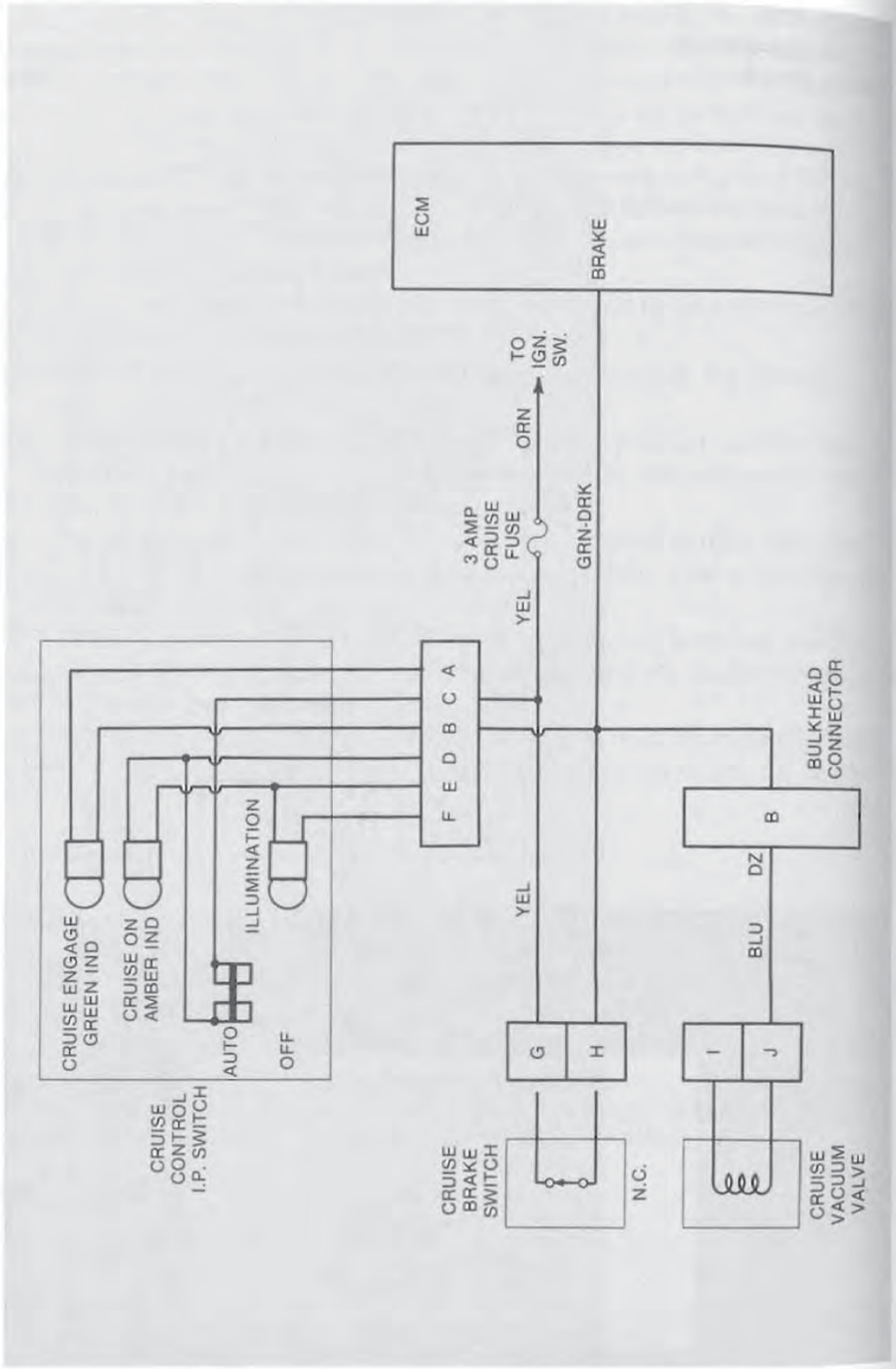
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Figure 10.9
DFI Cruise Control Brake Circuit



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Figure 10.10
DFI Code 71: Cruise Control Brake Circuit



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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

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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

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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

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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.

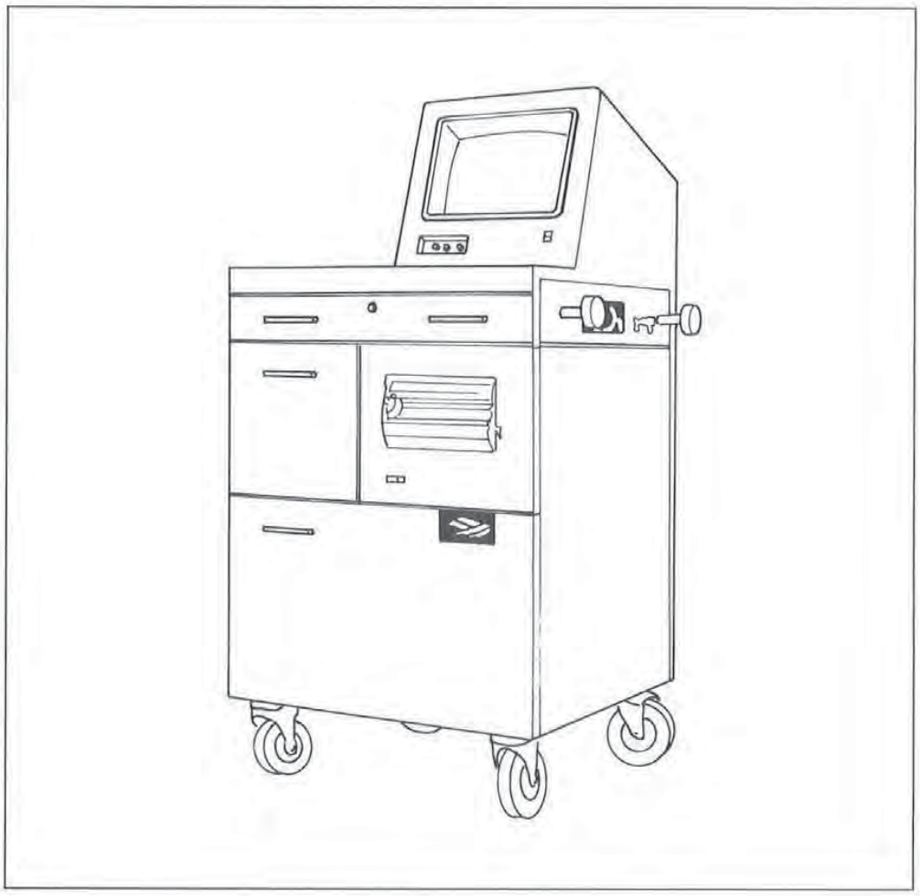
Special-purpose digital computers are coming into use in service bay diagnosis systems.

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,

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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.

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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

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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

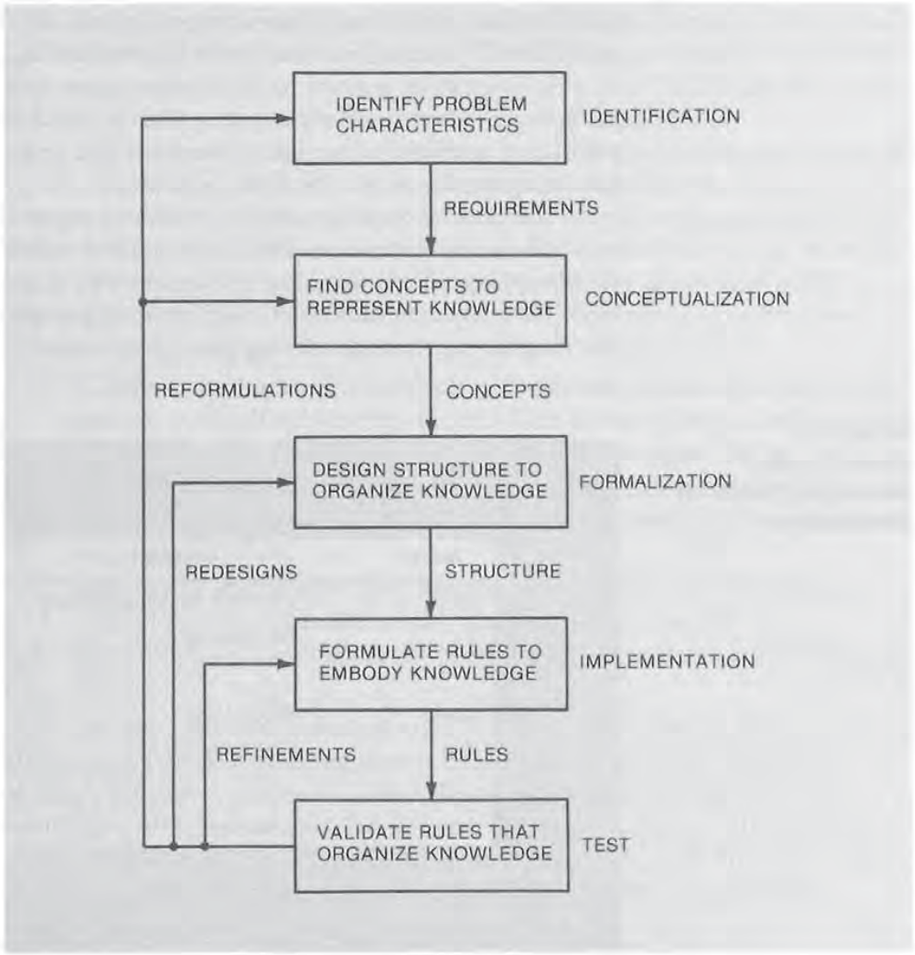


Figure 10.13 Stages of Knowledge Acquisition

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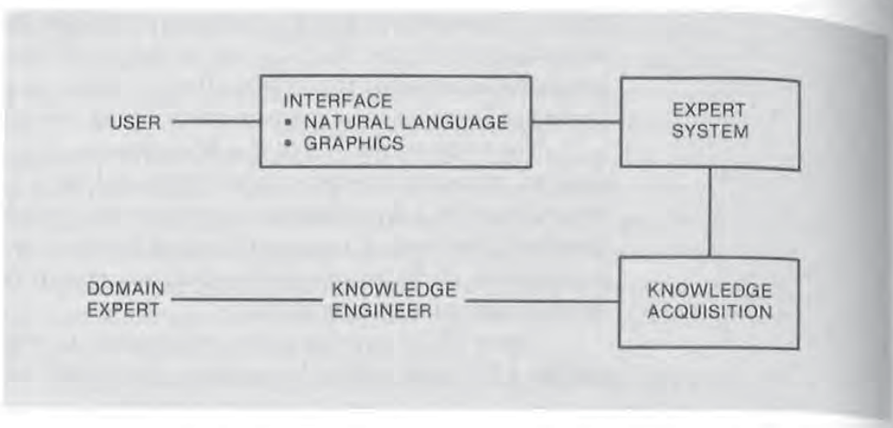


Figure 10.14 Environment of an Expert System

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

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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

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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.

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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)
```


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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.

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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

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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.

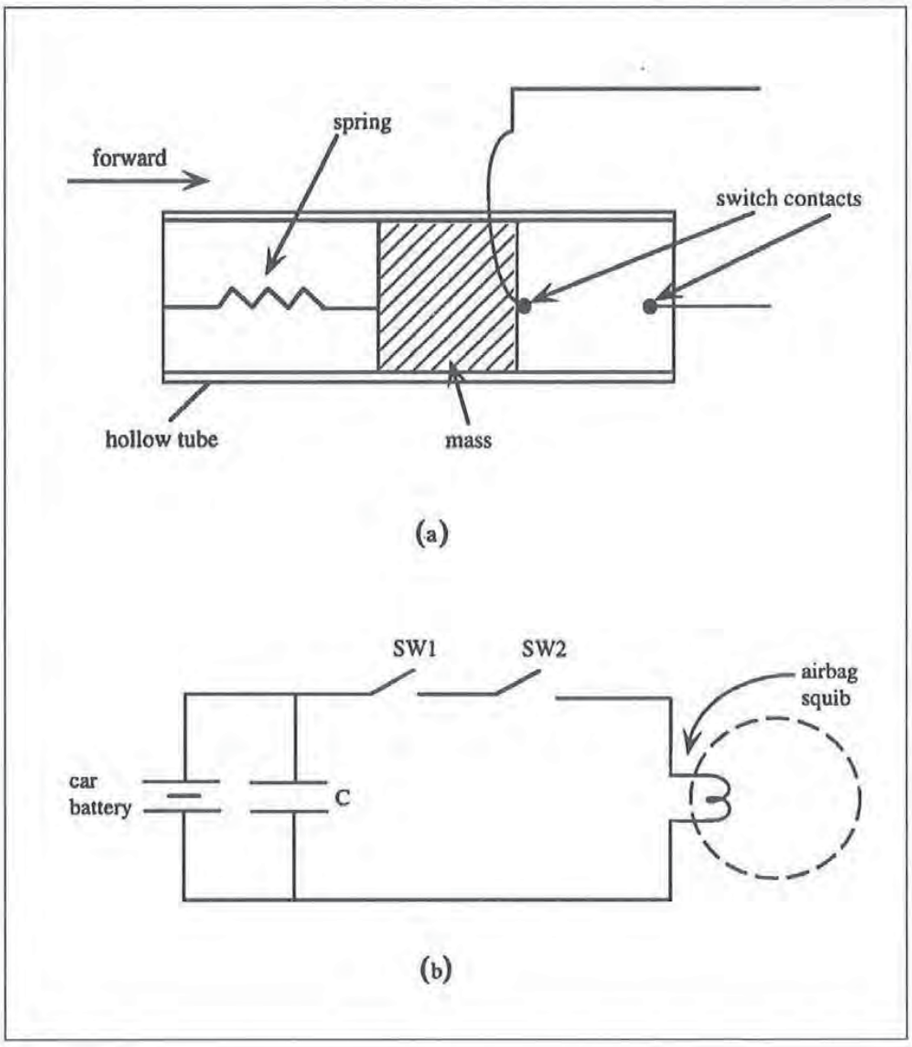
Figure 10.18b also shows a capacitor connected in parallel with the battery. This capacitor is typically located in the passenger compartment. It has sufficient capacity that in the event the car battery is destroyed early in the crash, it can supply enough current to ignite the squib.

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.

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Figure 10.18
Airbag Deployment System

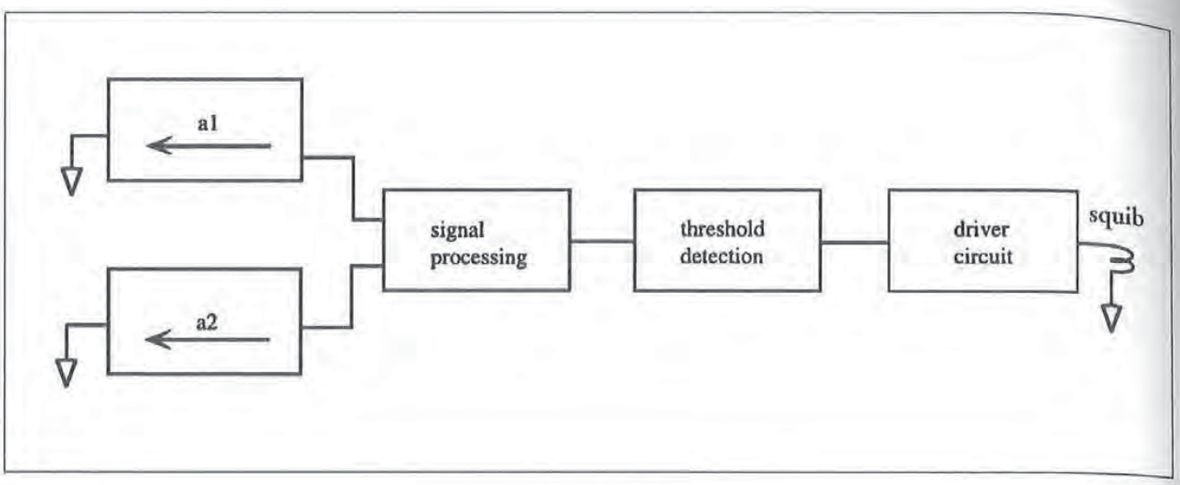


Under normal driving conditions the acceleration at the accelerometer locations is less than 1 g. However, during a collision at a sufficiently high speed the signal increases rapidly. Signal processing can be employed to enhance the collision signature in relation to the normal driving signal. Such 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

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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.

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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

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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

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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

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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

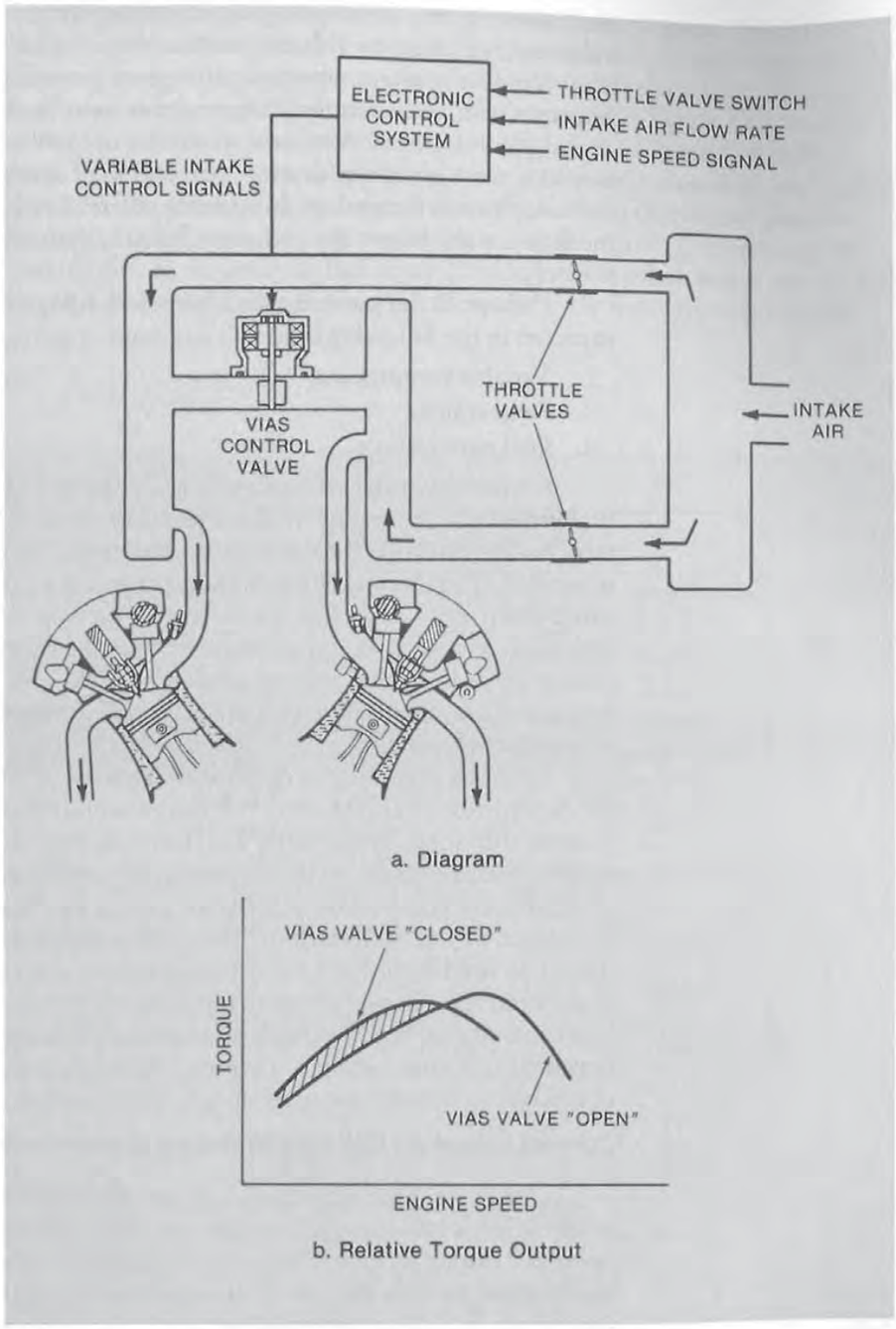
The performance and efficiency of any engine are markedly influenced by the intake system. The intake system configuration directly affects the volumetric efficiency of the engine, which is a measure of engine performance as an air pump. The design of an intake system in the past has involved many compromises 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

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Figure 11.1 Configuration of Variable-Geometry Intake System



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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.

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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.

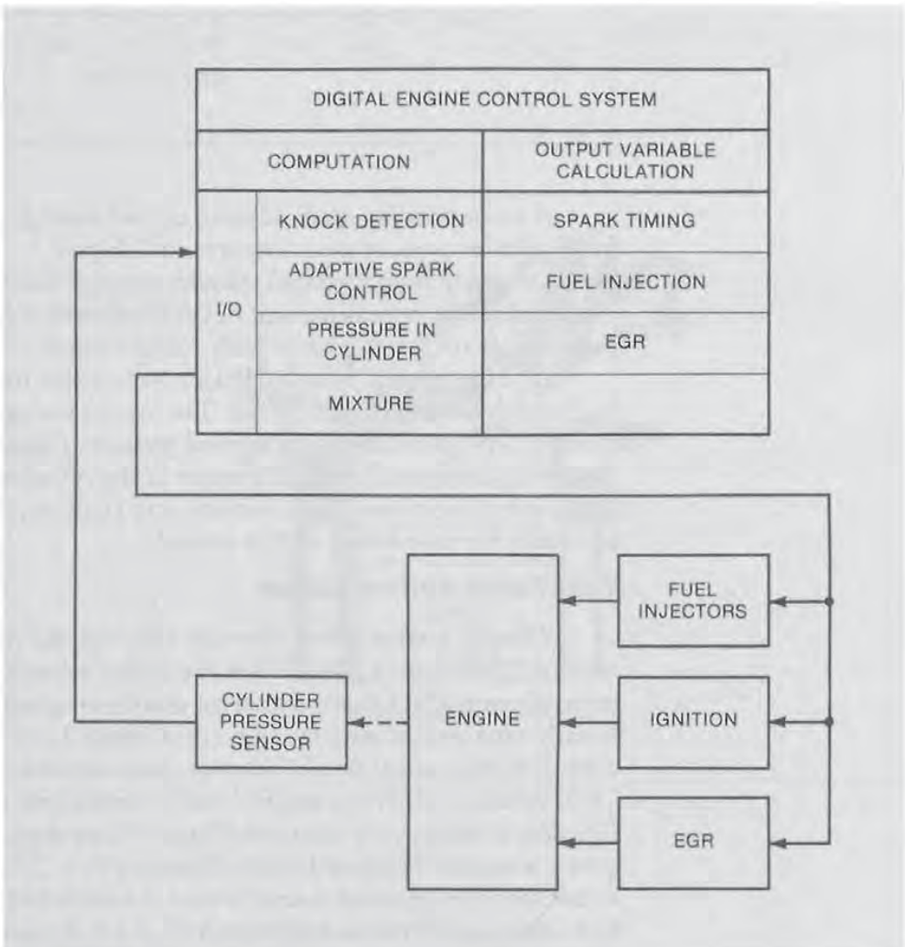


Figure 11.2 Engine Control System Based on Cylinder Pressure Measurements

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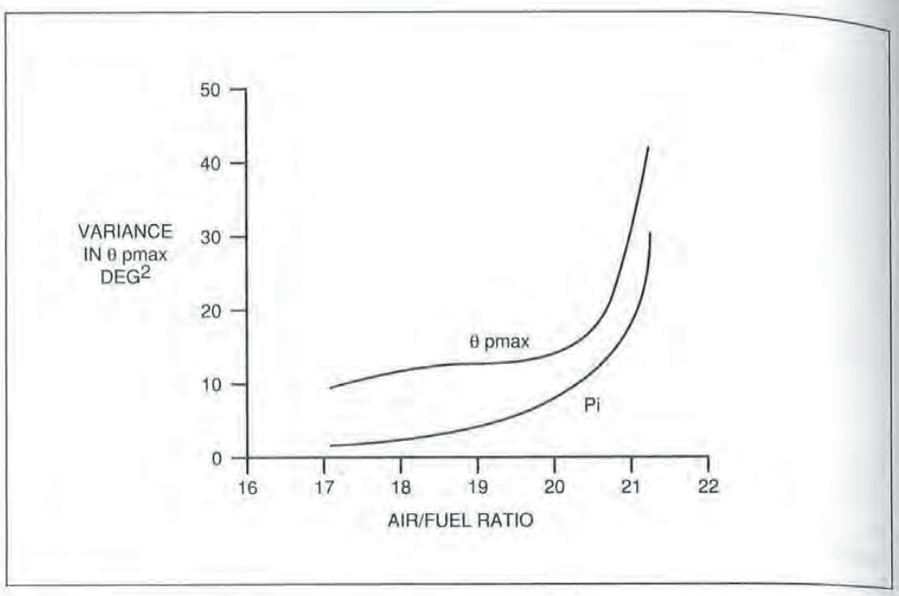


Figure 11.3 Variation in Cylinder Pressure with Air/Fuel Ratio

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.

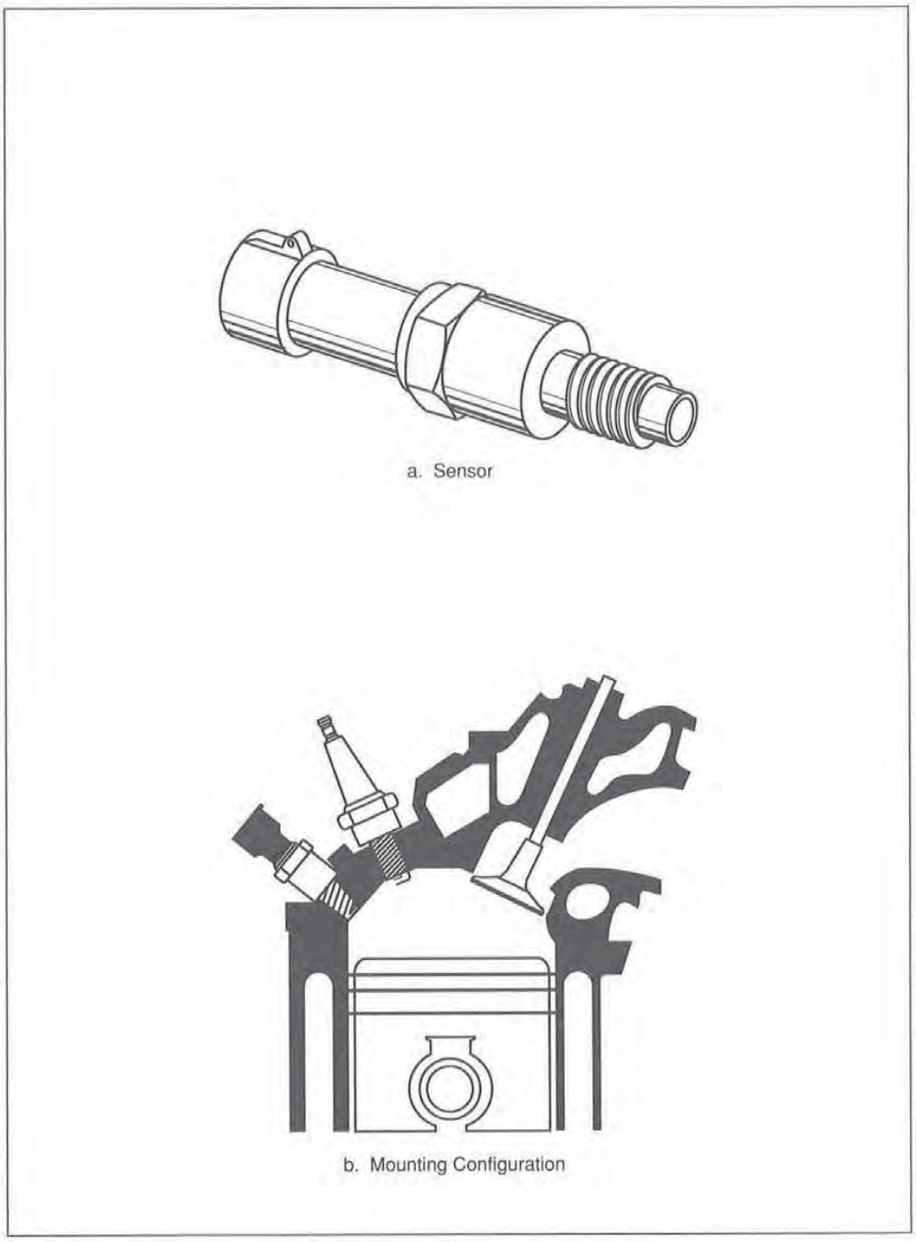
An experimental cylinder pressure sensor that uses a piezoelectric element has been developed (Figure 11.4a). The output voltage from the piezoelectric element is proportional to the applied pressure. Figure 11.4b is a sketch of the mounting configuration for this sensor in the cylinder head. Cylinder 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.

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Figure 11.4
Cylinder Pressure Sensor



a. Sensor

b. Mounting Configuration

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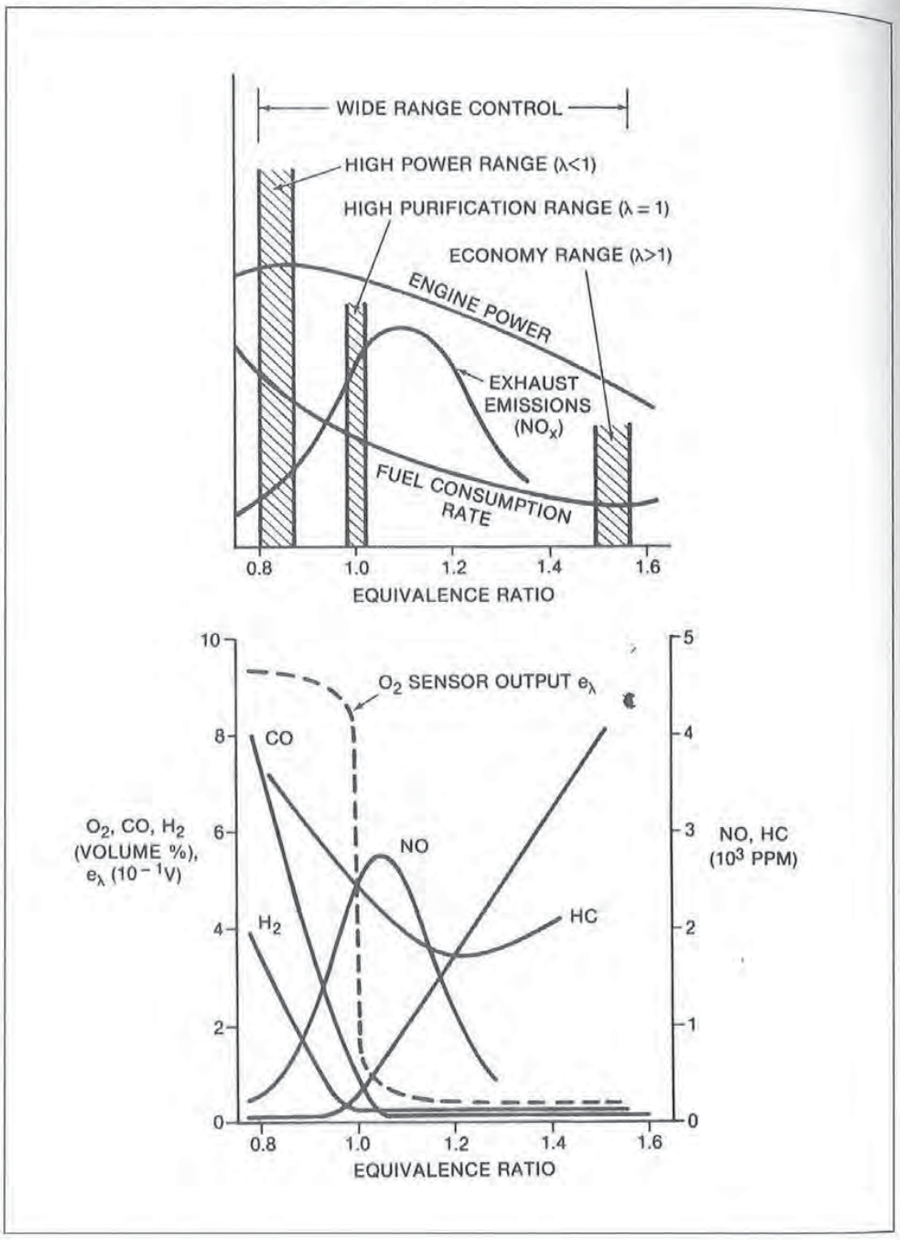


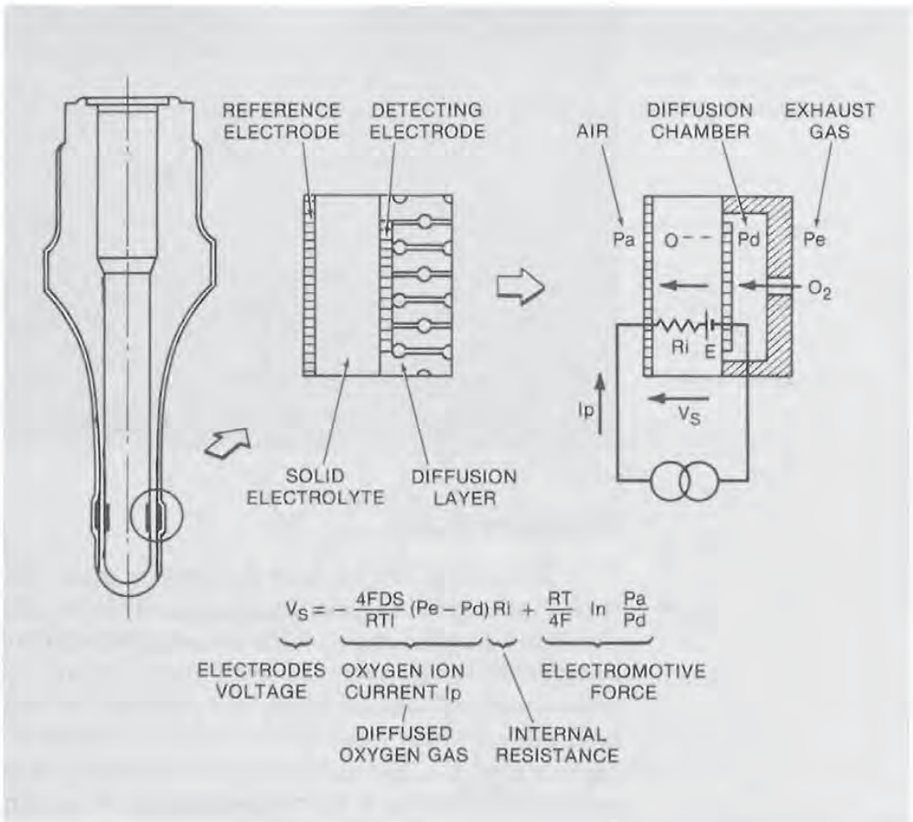
Figure 11.5 Engine Performance versus Equivalence Ratio

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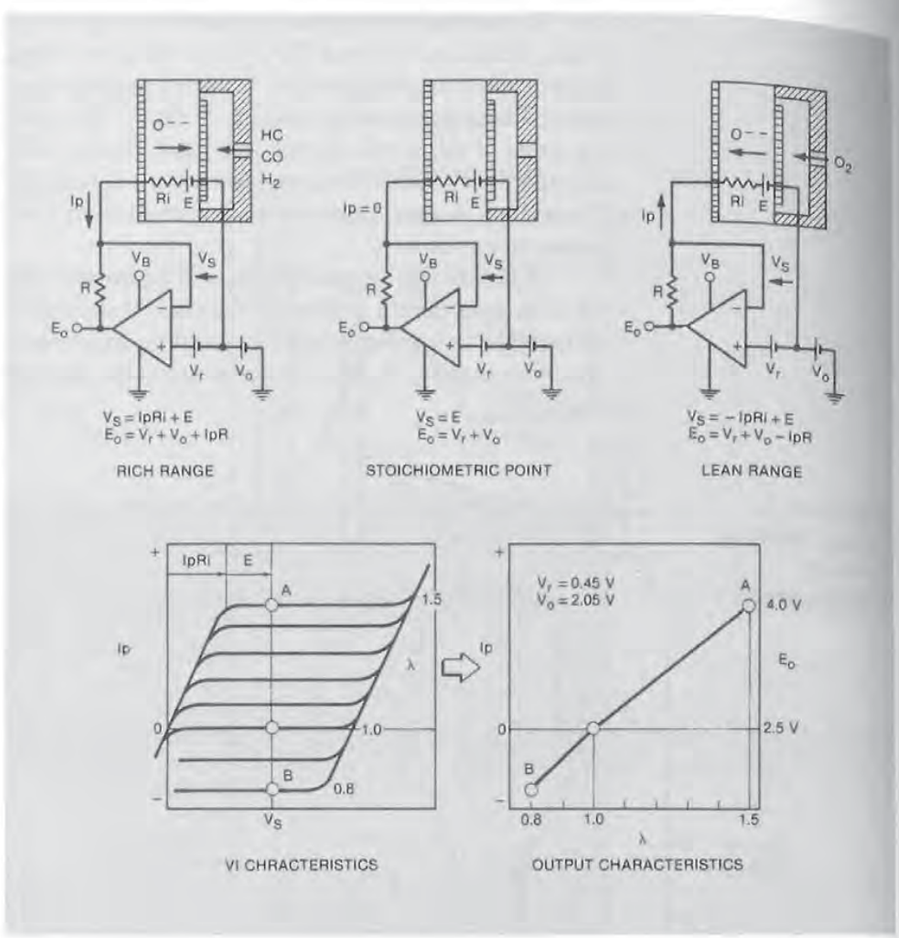
The sensor configuration is shown in Figure 11.6. This sensor uses yttria (Y_2O_3)-stabilized zirconia (ZrO_2) as a diffusion element that is preheated to a desired operating temperature. In actual operation, a voltage, V_s, is applied across this element, and a current, I_p, flows. The theory of operation 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



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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.

Figure 11.7 Functional Operation of Lambda Sensor

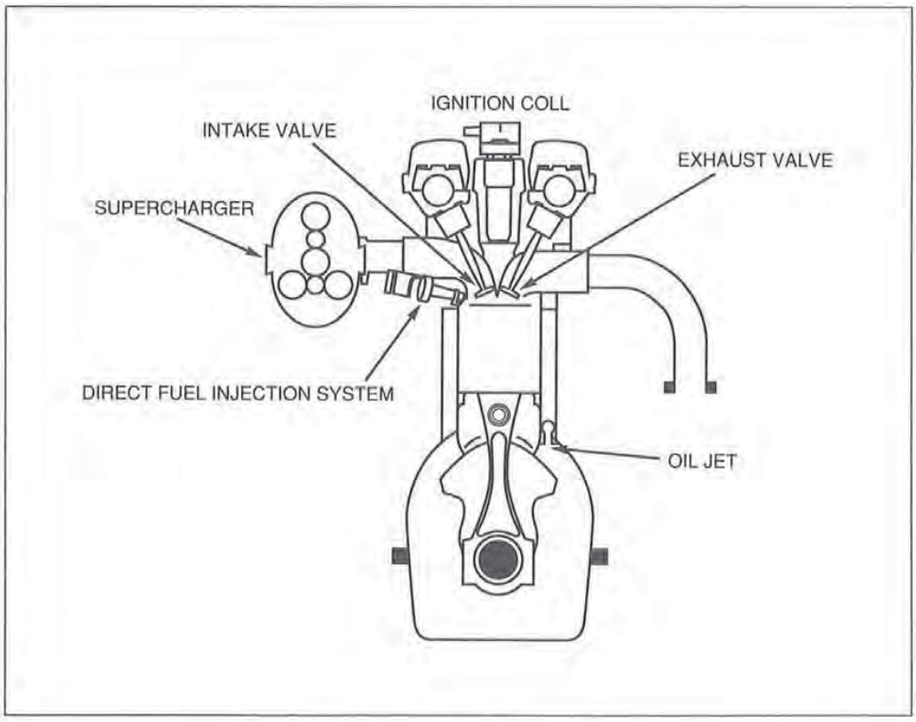
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In the past, the 2-stroke/cycle engine was virtually eliminated as a passenger car power plant due to the emission regulations of the Clean Air Act. Poor emission performance results, in part, from less efficient combustion than the 4-stroke/cycle 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



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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

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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).

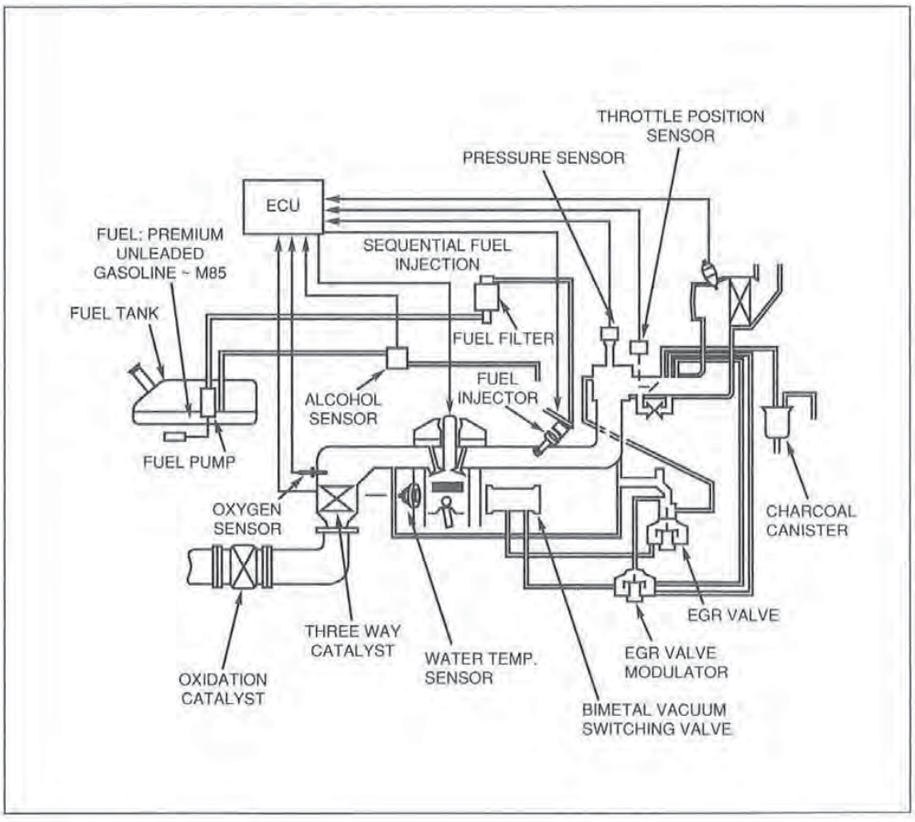
Transmission Control

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



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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.

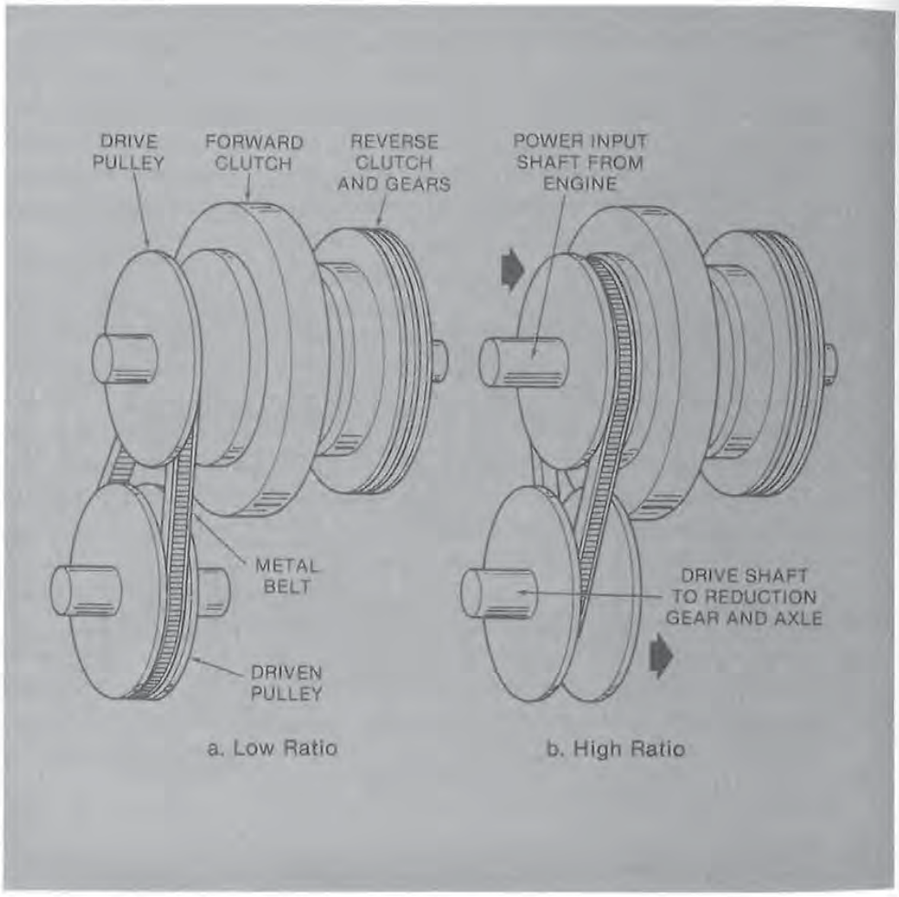


Figure 11.10 Continuously Variable Transmission

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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,

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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.

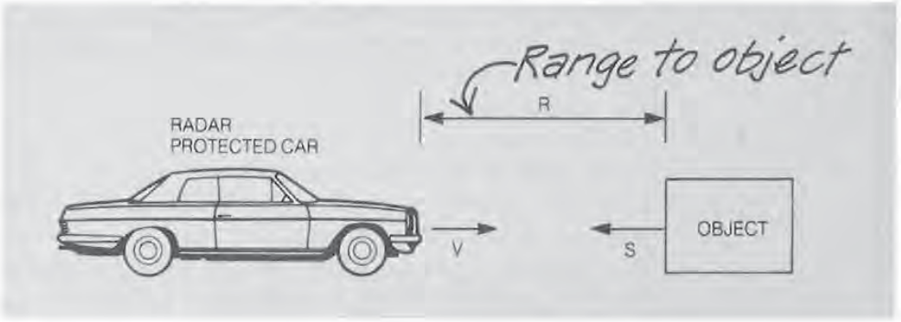
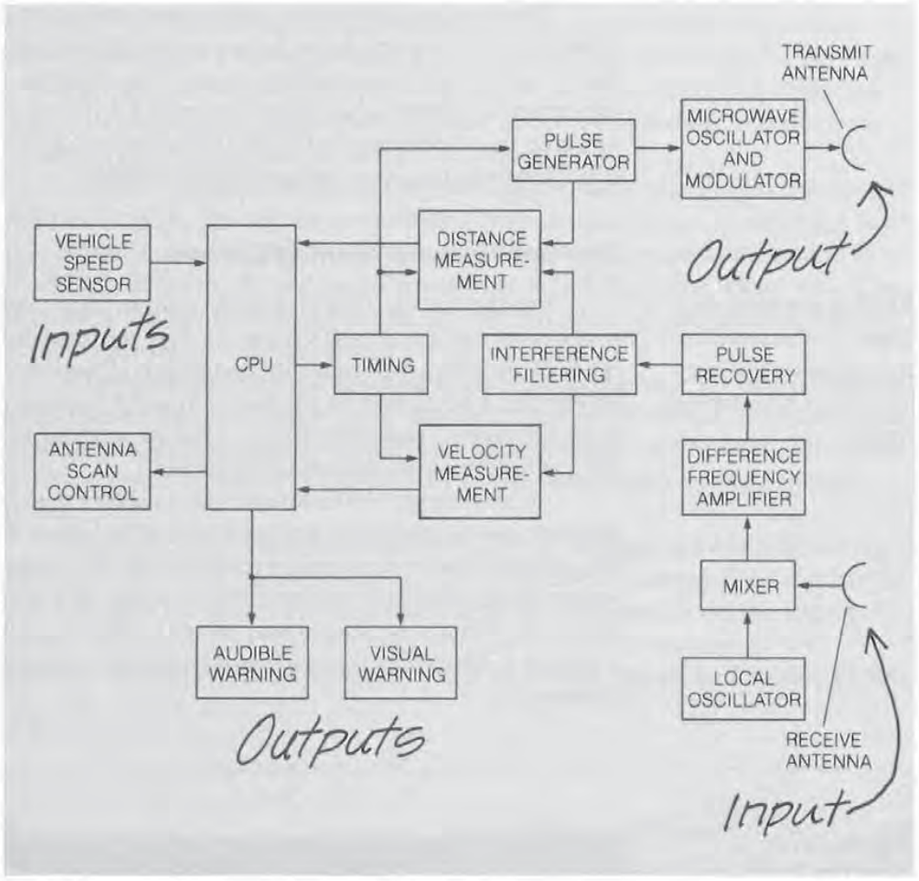


Figure 11.11 Range to Object for Anticollision Warning System

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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

$$T = \frac{R}{V+S}$$

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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.

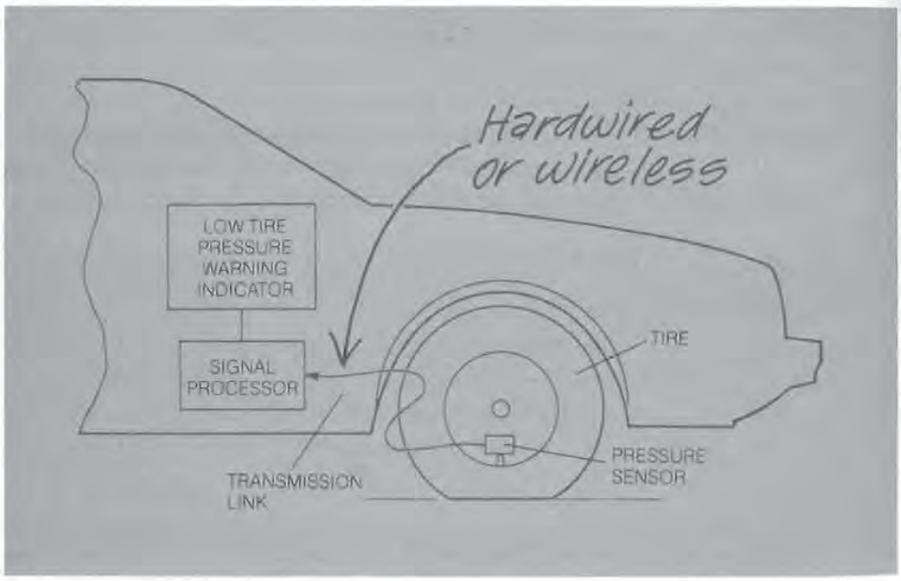
Low Tire Pressure Warning System

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



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A low tire pressure warning system utilizes a tire-mounted pressure sensor. The pressure sensor signals a loss in tire pressure.

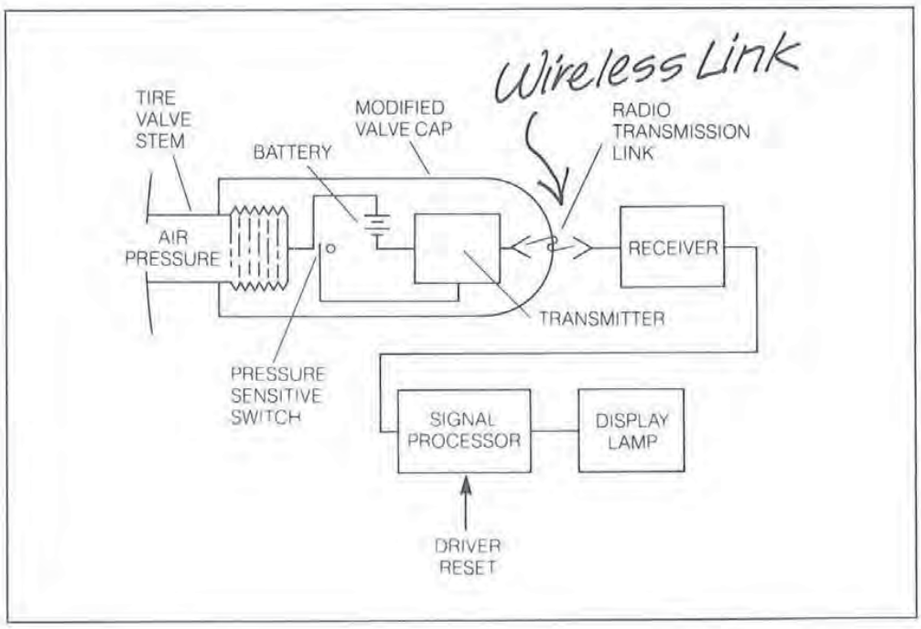
The difficult part of this system is the link from the tire pressure sensor mounted on the rotating tire to the signal processor mounted on the body. Several concepts have the potential to provide this link. For example, slip rings, which are similar to the brushes on a dc motor, could be used. However, 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



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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

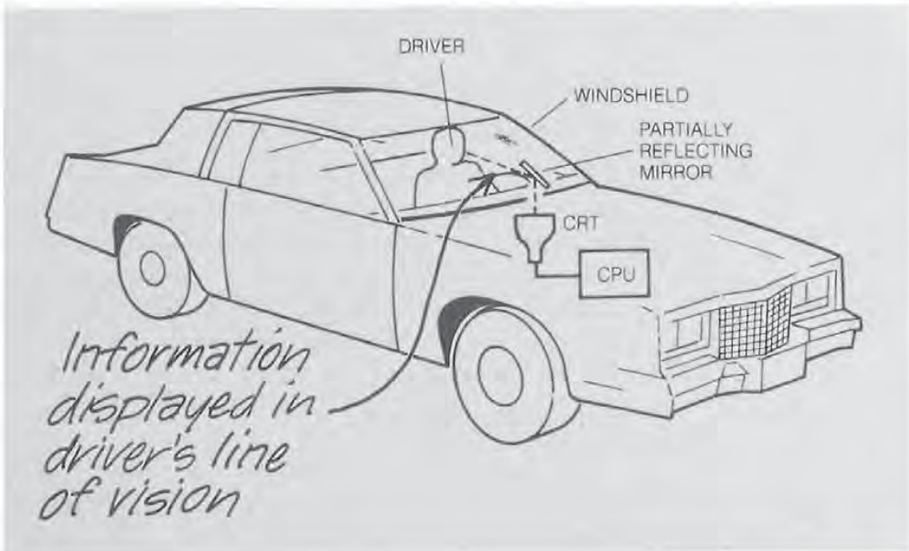
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description of the CRT display in Chapter 9. It was also speculated that the CRT might be used in conjunction with a heads up display (HUD). There is no clear sign, however, that the basic display source will be a CRT. In fact, any light-emitting display 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



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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

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CPU. However, each sensor only communicates periodically with the computer for a short time interval during sampling.

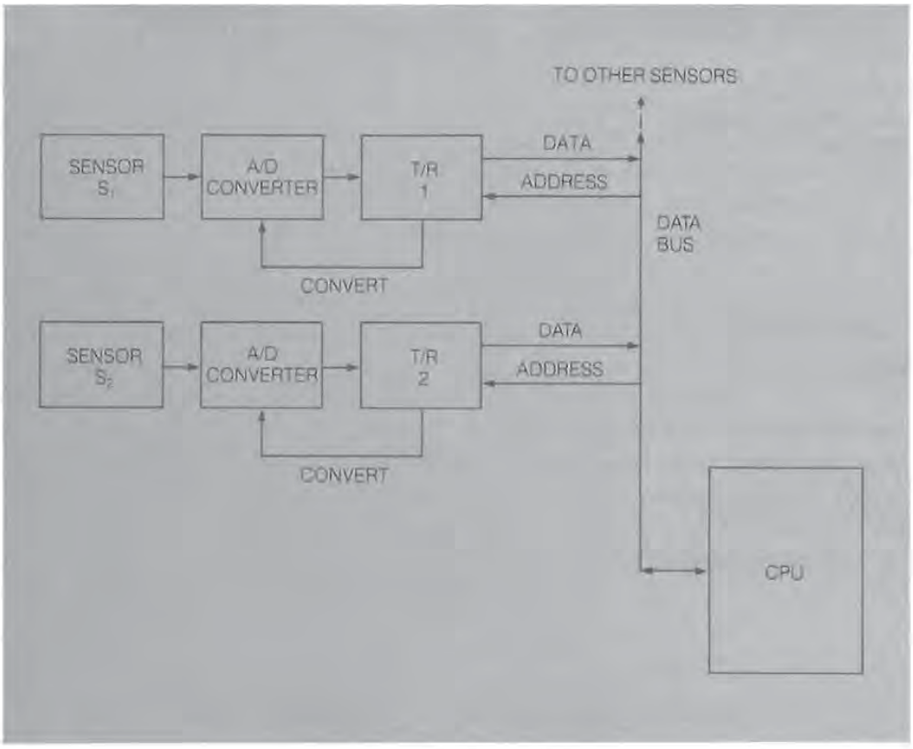
Sensor multiplexing can reduce the necessary wiring in an electrical harness by using time division multiplexing.

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



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(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.

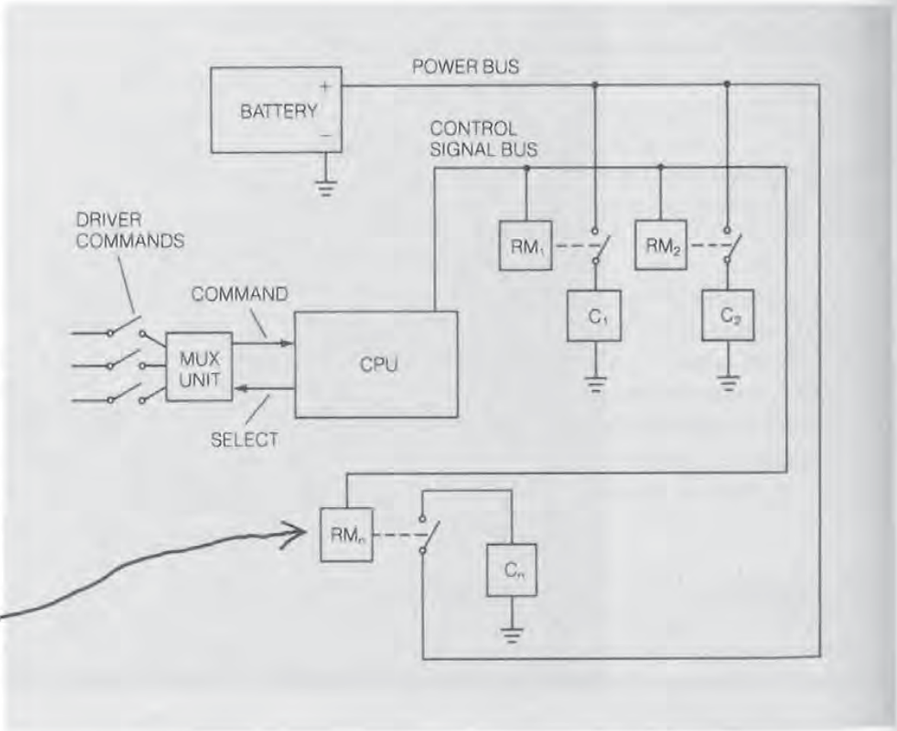
Each sensor in a multiplexing system sends its individual data over a common bus. The computer identifies the sensor by signaling each sensor with a unique address.

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.

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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

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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

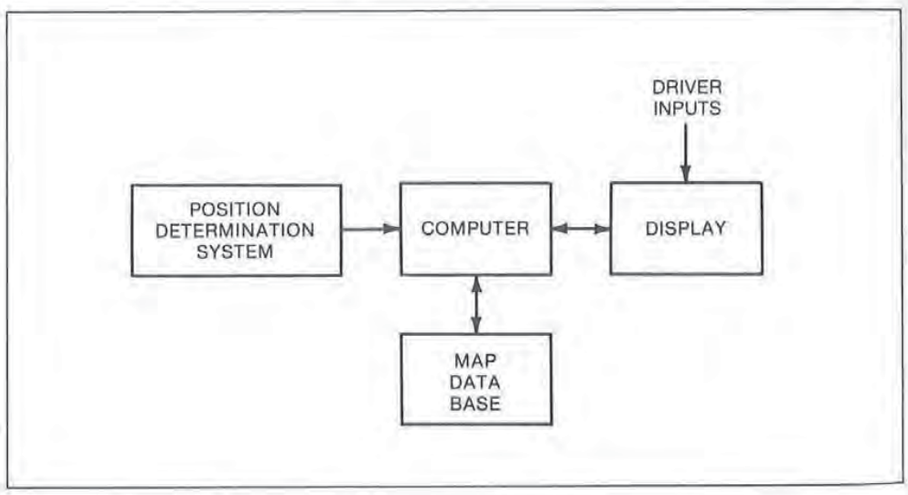


Figure 11.18 Generic Automatic Navigation System

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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.

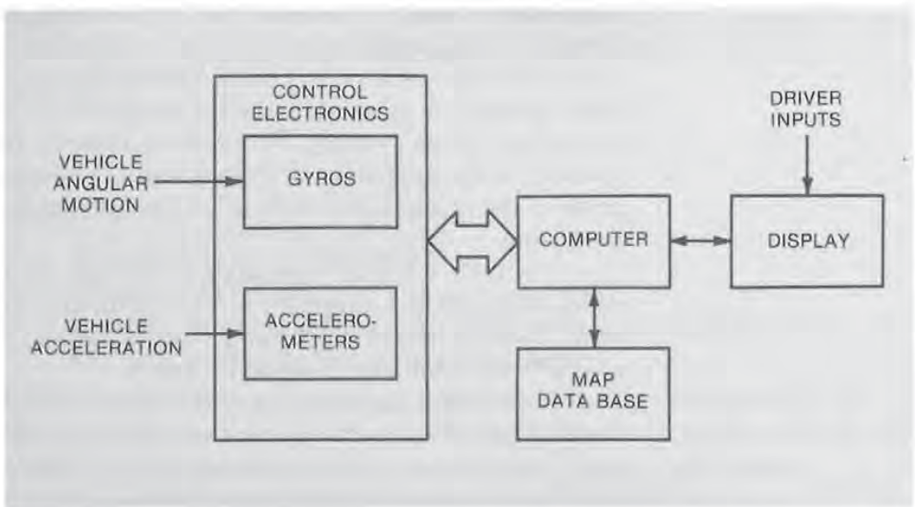


Figure 11.19 Automotive Inertial Navigation System

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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

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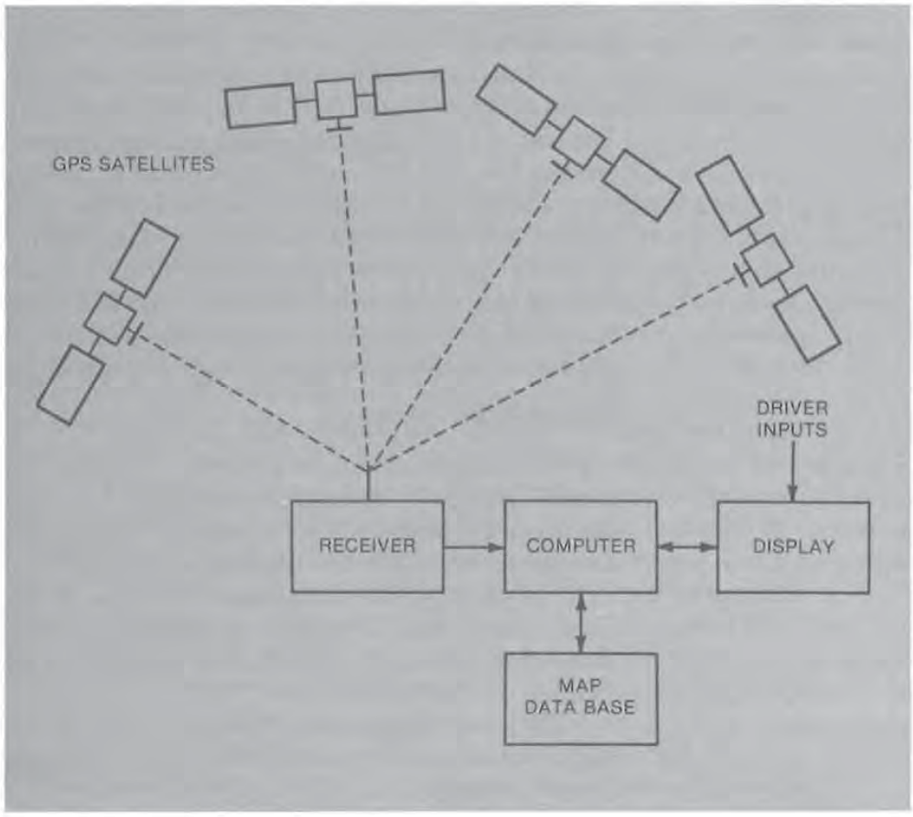


Figure 11.20 Automotive GPS Navigation System

give the time of transmission. The distance to any satellite is known by the relationship

$$R_i = c(t_i - t_r)$$

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

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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

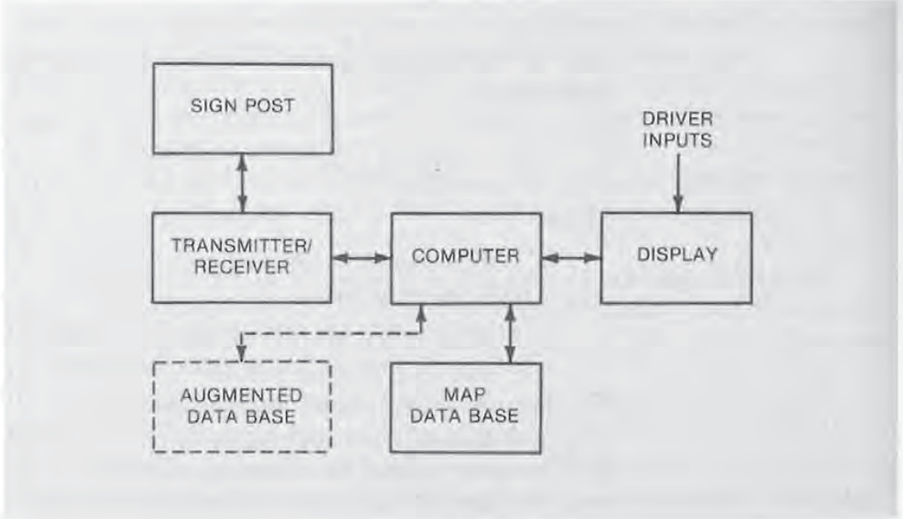


Figure 11.21 Signpost Navigation System

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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

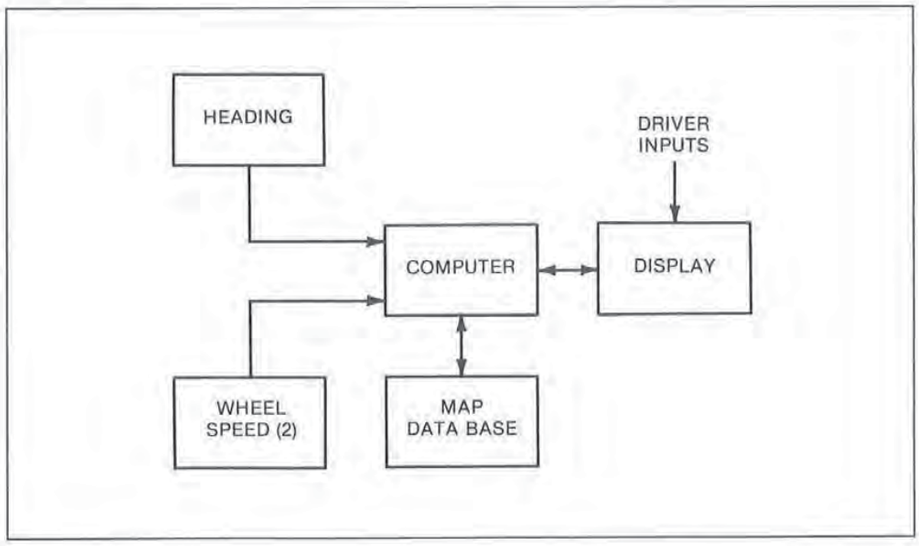


Figure 11.22 Dead Reckoning Navigation System

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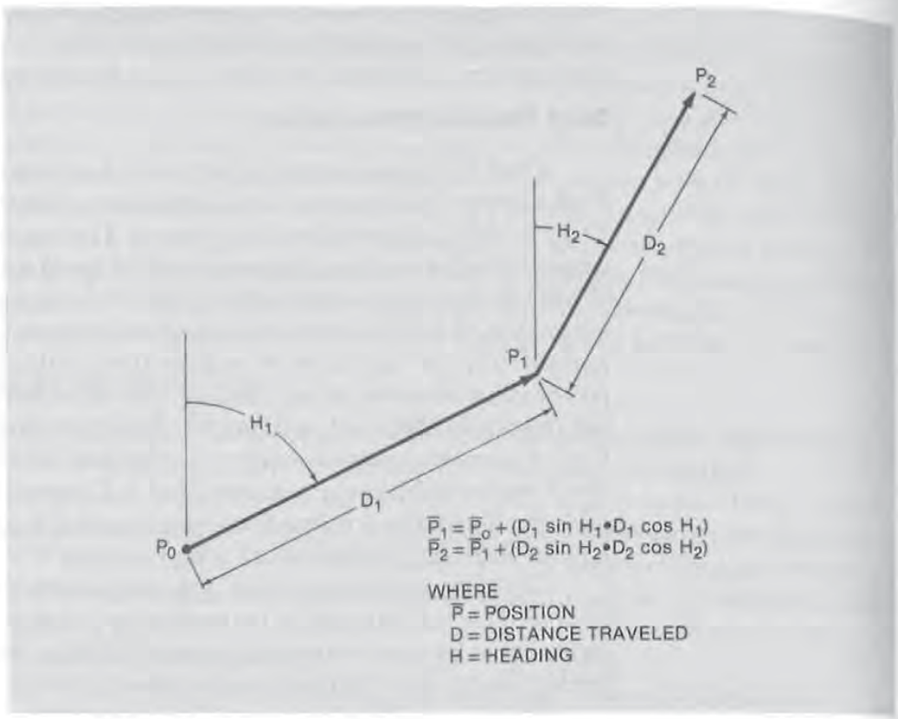


Figure 11.23 Dead Reckoning Navigation Computation

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

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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

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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.

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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.

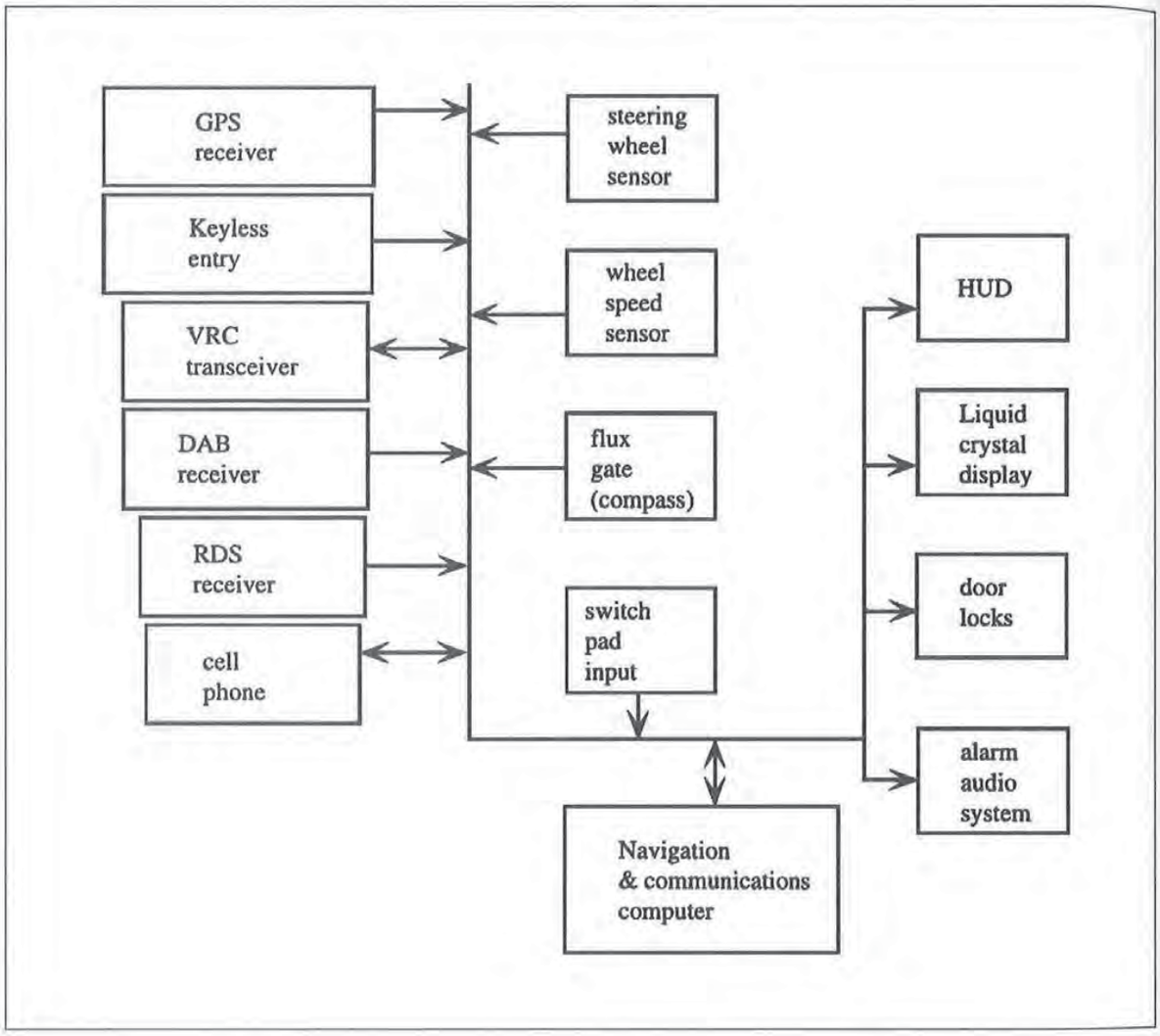
Although the long-term capabilities for ITS are unclear, the short-term application of technology will probably be in the form of an advanced driver information system. One of the most likely candidates is a radio message service system utilizing a portion of the bandwidth allotted to commercial FM radio 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

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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

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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

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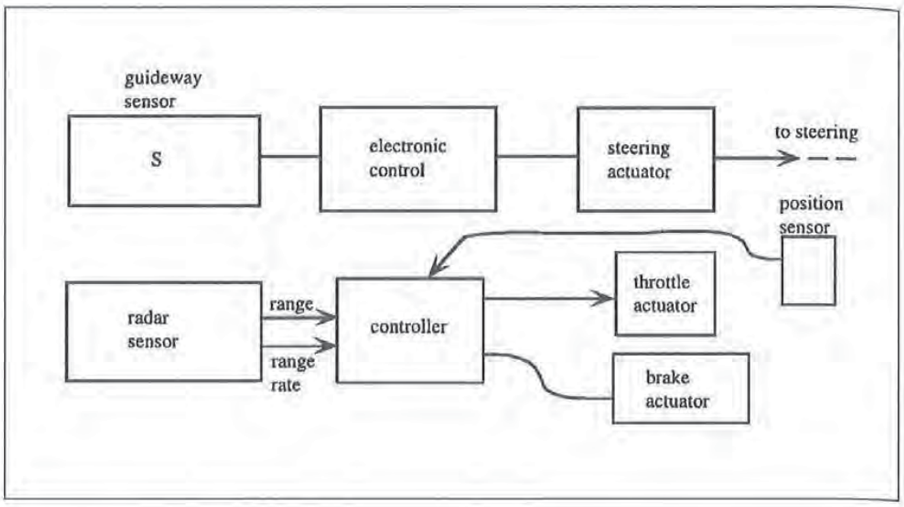


Figure 11.25
Automatic Driving Control System

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

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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.

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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

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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

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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.

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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.

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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.

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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.

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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.

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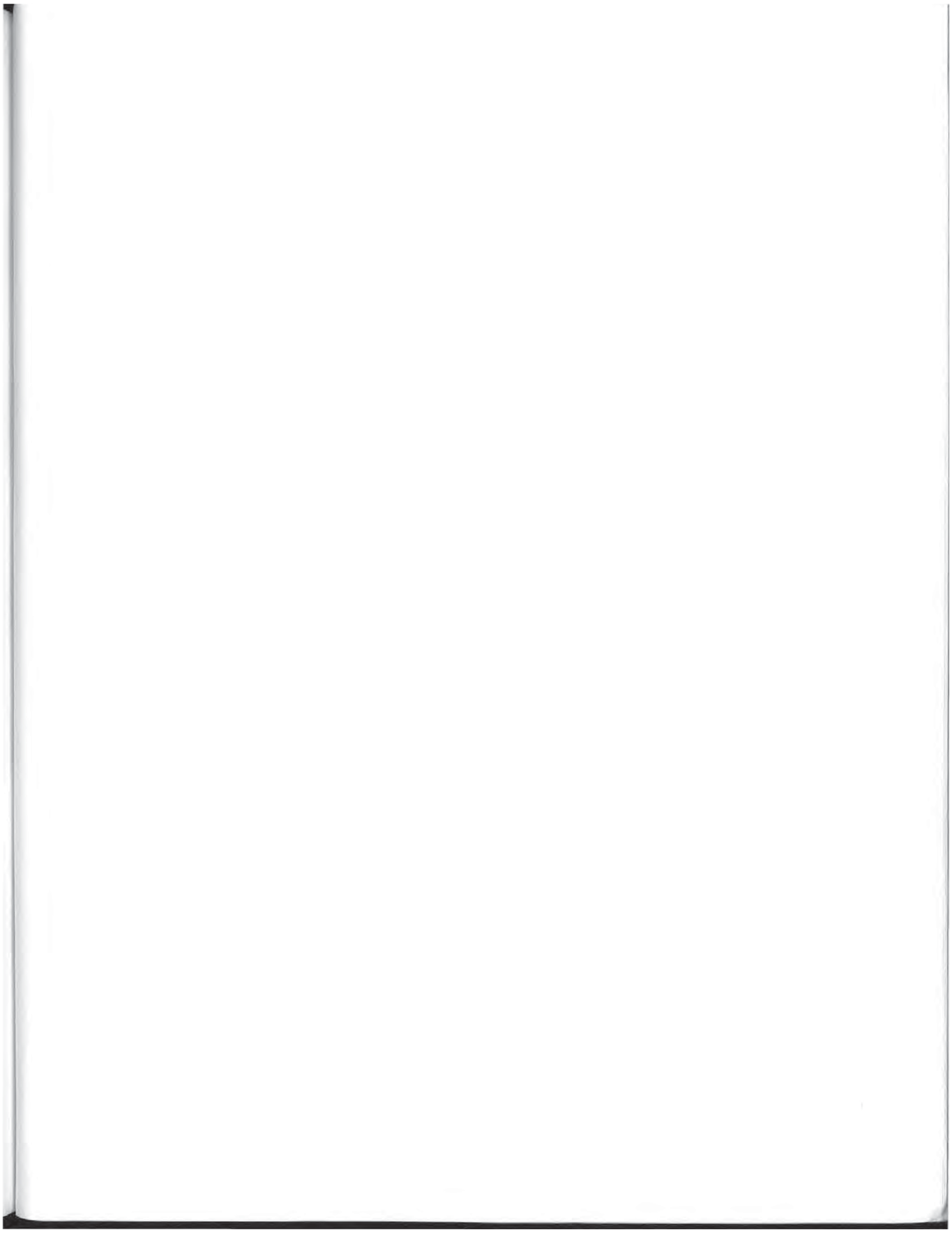
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4. c
5. d
6. d
7. d
8. a
9. b
10. b

Chapter 11

1. d
2. a
3. a
4. b
5. c
6. a
7. d
8. b
9. d
10. b
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UNDERSTANDING Automotive Electronics

FIFTH EDITION

William B. Ribbens

In today's cars, the electronic[illegible] 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[illegible]bsystems is a good grasp of mechanical aut[illegible]tures and systems of late-1990s autos. In Ch[illegible]pecifically geared to automotive systems, is [illegible]ory, and concepts are illustrated with simple [illegible] detailed theory in later chapters.

Chapters 3-10 cover specific syste[illegible]ail, with many examples and illustrations. [illegible]omotive electronics technology, some curre[illegible]may yet come to be.

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(71) Applicant:
Ford Global Technologies, Inc.
Dearborn, Michigan 48126 (US)

(72) Inventors:
- **Robichaux, Jerry Dean**
  Riverview, Michigan 48192 (US)
- **Pallett, Tobias John**
  Ypsilanti, Michigan 48197 (US)

(74) Representative:
Messulam, Alec Moses et al
A. Messulam & Co. Ltd,
43-45 High Road
Bushey Heath, Herts WD23 1EE (GB)

(54) system and method for controlling engine torque

(57) A system and method for controlling an engine include determining a desired engine brake torque and modifying the desired engine brake torque based on current engine operating conditions to determine a requested engine brake torque prior to determination of control parameters, including at least one of an airflow and a fuel quantity, to effect the requested engine brake torque. Preferably, the desired engine brake torque is modified by combining the desired engine brake torque with an idle speed torque to generate a first intermediate torque, comparing the first intermediate torque to an actual engine brake torque to generate a second intermediate torque, generating a feedback correction torque based on the second intermediate torque, and combining the first intermediate torque, the feedback correction torque, and a third intermediate torque to determine the requested engine brake torque, where the third intermediate torque represents accessory load or a frictional torque loss which varies with temperature.

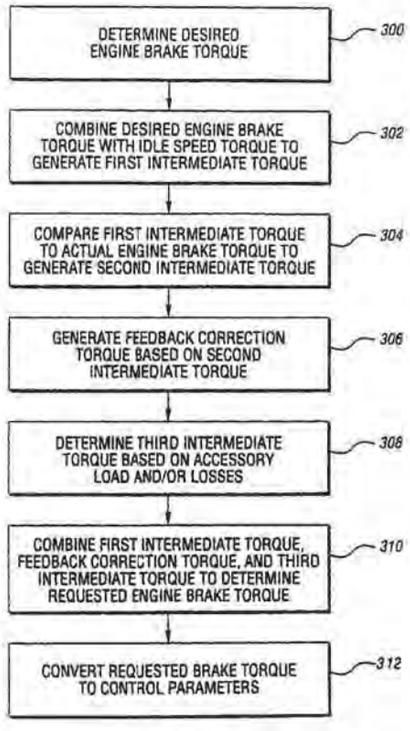


Fig. 4

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Description

[0001] The present invention is directed to a system and method for controlling engine torque using feedback and feed forward control.

[0002] Electronic airflow control systems, such as variable cam timing systems and electronic throttle control systems, replace traditional mechanical throttle cable systems with an "electronic linkage" provided by sensors and actuators in communication with an electronic controller. This increases the control authority of the electronic controller and allows the airflow and/or fuel flow to be controlled independently of the accelerator pedal position.

[0003] To control the actual output engine brake torque to achieve the driver demanded engine brake torque, it is desirable to calculate a corresponding desired airflow and fuel flow. Preferably, this computation accounts for variations in engine operating parameters, such as engine operating temperature and accessory losses.

[0004] Prior art approaches convert the desired engine torque to a desired airflow using a two-dimensional lookup table with inputs for desired torque and engine speed. However, such lookup tables are typically calibrated for stoichiometric operation and for maximum brake torque (MBT). The resulting desired airflow is then modified by a function which relates engine operating temperature and air/fuel ratio to engine torque to generate a modified or corrected airflow. The corrected desired airflow is then achieved via an appropriate airflow rate controller. This approach may be seen by reference to U.S. Pat. Nos. 5,351,776, 5,383,432, and 5,501,989, for example.

[0005] While the prior art approaches may be acceptable for many applications and operating conditions, it is desirable to provide a more robust engine torque controller which improves powertrain performance for current applications and is more amenable to new engine technologies and control strategies such as direct injection, lean burn, variable cam timing, and variable displacement applications.

[0006] Preferably, the control parameters include at least one of an airflow and a fuel quantity, to effect the requested engine brake torque. Preferably, the desired engine brake torque is modified by combining the desired engine brake torque with an idle speed torque to generate a first intermediate torque, comparing the first intermediate torque to an actual engine brake torque to generate a second intermediate torque, generating a feedback correction torque based on the second intermediate torque, and combining the first intermediate torque, the feedback correction torque, and a third intermediate torque to determine the requested engine brake torque, where the third intermediate torque represents accessory load or a frictional torque loss which varies with temperature.

[0007] The embodiment of the present invention provides a system and method for engine torque control in an engine having electronically controlled airflow and/or fuel flow.

[0008] The embodiment of the present invention is has an advantage that it provides a system and method for engine torque control which more accurately compensate for current operating conditions such as additional frictional losses when the engine is cold and for variable accessory losses which correct for variations between desired and actual torque using a torque feedback signal.

[0009] The embodiment of the present invention provides a number of other advantages. It compensates the input to the engine torque controller prior to determination of the control parameters, such as airflow and fuel flow, rather than modifying the output of the engine torque controller as described in the prior art. This provides a more robust torque controller which is more easily applied to various engine technologies.

[0010] The invention will now be described further, by way of example, with reference to the accompanying drawings, in which:

Figure 1 is a block diagram illustrating a system and method for controlling engine torque according to the present invention;
Figure 2 is a block diagram illustrating an output torque based powertrain control strategy including determination of a desired engine torque according to the present invention;
Figure 3 is a block diagram illustrating an engine torque controller according to the present invention; and
Figure 4 is a flowchart illustrating a system and method for controlling engine torque according to the present invention.

[0011] Figure 1 provides a block diagram illustrating operation of a system or method for controlling engine torque according to the present invention.

[0012] System 10 includes a vehicular powertrain 12 having an internal combustion engine 14 coupled to an automatic transmission 16. Of course, the present invention is equally applicable to manual transmission applications. Powertrain 12 may also include a controller 18 in communication with engine 14 and transmission 16 for providing various information and control functions. Engine 14 is connected to transmission 16 via crankshaft 20 which is connected to transmission pump 22 and/or torque converter 24. Preferably, torque converter 24 is a hydrodynamic torque converter including a pump or impeller 26 which is selectively fluidly coupled to a turbine 28. Torque converter 24 may also include a frictional converter clutch or bypass clutch 30 which provides a selective frictional coupling between turbine shaft 32

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and input shaft 34.

[0013] Automatic transmission 16 includes a plurality of input-to-output ratios or gear ratios effected by various gears, indicated generally by reference numeral 36, and associated frictional elements such as clutches, bands, and the like, as well known in the art. Gears 36 provide selective reduction or multiplication ratios between turbine shaft 32 and output shaft 38. Automatic transmission 16 is preferably electronically controlled via one or more shift solenoids, indicated generally by reference numeral 40, and a converter clutch control (CC) 41 to select an appropriate gear ratio based on current operating conditions. Transmission 16 also preferably includes an actuator for controlling pump pressure (PP) 42 (or line pressure), in addition to a shift lever position sensor (PRN) 44 to provide an indication of the operator's selected gear or driving mode, such as drive, reverse, park, etc. A line pressure sensor (LP) 46 can be provided to facilitate closed loop feedback control of the hydraulic line pressure during shifting or ratio changing.

[0014] Depending upon the particular application, output shaft 38 may be coupled to one or more axles 48 via a final drive reduction or differential 50 which may include one or more gears, as indicated generally by reference numeral 52. Each axle 48 may include two or more wheels 54 having corresponding wheel speed sensors 56.

[0015] In addition to the sensors described above, powertrain 12 preferably includes a plurality of sensors, indicated generally by reference numeral 60, in communication with corresponding input ports 62 of controller 18 to sense or monitor the current operating and ambient conditions of powertrain 12. A plurality of actuators, indicated generally by reference numeral 64, communicate with controller 18 via output ports 66 to effect control of powertrain 12 in response to commands generated by controller 18.

[0016] The sensors preferably include a throttle valve position sensor (TPS) 68 which monitors the position of throttle valve 70 which is disposed within intake 72. A mass airflow sensor (MAF) 74 provides an indication of the air mass flowing through intake 72. A temperature sensor (TMP) 76 provides an indication of the engine temperature which may include engine coolant temperature or engine oil temperature, for example.

[0017] As also illustrated in Figure 1, an engine speed sensor (RPM) 80 monitors rotational speed of crankshaft 20. Similarly, a turbine speed sensor 82 monitors the rotational speed of the turbine 28 of torque converter 24. Another rotational speed sensor, vehicle speed sensor (VSS) 84, provides an indication of the speed of output shaft 38 which may be used to determine the vehicle speed based on the ratio of differential 50 and the size of wheels 54. Of course, wheel speed sensors (WS1 and WS2) 56 may be used to provide an indication of the vehicle speed as well.

[0018] Depending upon the particular application requirements, various sensors may be omitted or alternative sensors provided which generate signals indicative of related sensed parameters. Values corresponding to ambient or operating conditions may be inferred or calculated using one or more of the sensed parameters without departing from the spirit or scope of the present invention.

[0019] An accelerator pedal 58 is manipulated by the driver to control the output of powertrain 12. A pedal position sensor 59 provides an indication of the position of accelerator pedal 58, preferably in the form of counts. In one embodiment, an increasing number of counts indicates a request for increased power output. Preferably, redundant position sensors are used with at least one position sensor having a negative slope such that a decreasing number of counts corresponds to a request for increased power output. A manifold absolute pressure (MAP) sensor, or equivalent, may be used to provide an indication of the current barometric pressure.

[0020] Actuators 64 are used to provide control signals or to effect movement of various devices in powertrain 12. Actuators 64 may include actuators for timing and metering fuel (FUEL) 90, controlling ignition angle or timing (SPK) 92, controlling intake/exhaust valve actuators 93 (VCT) to implement variable cam timing ,setting the amount of exhaust gas recirculation (EGR) 94, and adjusting the intake air using throttle valve 70 with an appropriate servomotor or actuator (TVA) 96. As described above, automatic transmission 16 may be selectively controlled by controlling transmission pump or line pressure using an appropriate actuator (PP) 42 in combination with shift solenoids (SS1 and SS2) 40 which are used to select an appropriate gear ratio, and a converter clutch actuator or solenoid (CC) 41 used to lock, unlock or control slip of the torque converter clutch 30. Also preferably, a temperature sensor 106 is provided to determine the transmission oil temperature (TOT).

[0021] Controller 18 is preferably a microprocessor-based controller which provides integrated control of engine 14 and transmission 16 of powertrain 12. Of course, the present invention may be implemented in a separate engine or transmission controller depending upon the particular application. Controller 18 includes a microprocessor 110 in communication with input ports 62, output ports 66, and computer readable media 112 via a data/control bus 114. Computer readable media 112 may include various types of volatile and non-volatile memory such as random access memory (RAM) 116, read-only memory (ROM) 118, and keep-alive memory (KAM) 119. These "functional" descriptions of the various types of volatile and non-volatile storage may be implemented by any of a number of known physical devices including but not limited to EPROMs, EEPROMs, PROMs, flash memory, and the like. Computer readable media 112 include stored data representing instructions executable by microprocessor 110 to implement the method for controlling engine torque according to the present invention.

[0022] Figure 2 provides a block diagram of a representative control architecture for use with a system and method for engine control according to the present invention. As will be understood by one of ordinary skill in the art, one of the

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advantages of the present invention is its adaptability and robustness to various control architectures and engine technologies. As such, the present invention may be utilised in any of a number of applications and is independent of the particular strategy illustrated for determining a desired engine brake torque and for effecting a requested engine brake torque.

[0023] In one embodiment of the present invention, a driver demand is interpreted as represented by block 120 of Figure 2 based on the vehicle speed 122 accelerator pedal position 124 and barometric pressure 126. In this embodiment, the driver demand is interpreted as a wheel torque (TQWH_DD) and is provided as an input to block 130 which arbitrates the final wheel torque among various other torque requesters, indicated generally by reference numeral 132. Such torque requesters may include, for example, a cruise control torque 134, a traction assist torque 136, and/or a vehicle speed limiting torque 138. Block 130 selects the appropriate torque depending upon the current operating conditions and provides this final wheel torque (TQ_WHEEL) to block 140 which performs a number of functions including scheduling the gear ratio and ratio changes. Block 140 preferably includes determination of a torque converter slip, and calculation of a desired engine brake torque based on the final desired wheel torque. Inputs used in these determinations include vehicle speed 122, barometric pressure 126, current gear ratio 142, current torque converter slip 144, and bypass clutch duty cycle 145. Determination of the desired engine torque is explained in greater detail below.

[0024] The engine torque requested from block 140 is arbitrated with various other engine torque limiting functions 146 as represented by block 150. Transmission controller 152 may also request torque limiting or modulation to provide cancellation of the inertia phase to improve shift feel. Transmission controller 152 communicates with transmission solenoid control module 154 which energises the appropriate shift solenoids to effect the ratio change. Solenoid control module 154 preferably dynamically controls the line pressure via transmission pump pressure actuator 42 during a ratio change to improve shift feel. Alternatively, the apply and release pressures for individual clutches or shifting elements may be controlled during the ratio change to further improve shift feel. Transmission controller 152 is also in communication with bypass clutch controller 155 which controls the duty cycle of the torque converter bypass clutch to control the state of the clutch.

[0025] The final engine torque determined by block 150 is communicated as a desired engine brake torque to engine controller 156, illustrated and described in greater detail with reference to Figure 3. The engine controller modifies the desired engine brake torque based on current engine operating conditions to determine a requested engine brake torque prior to determination of control parameters such as air flow, spark, EGR, and fuel as represented by blocks 158, 160, 162, and 164, respectively. Various other control parameters may also be used, such as air/fuel ratio, and the like, depending upon the particular application.

[0026] While the present invention is described with reference to a system based on desired wheel torque, the present invention is independent of the particular strategy used to determine the desired engine brake torque. For example, the present invention could be easily applied to a system which uses a desired tractive effort or wheel power to determine a desired engine brake torque. Likewise, the present invention is applicable to systems which determine a desired engine brake torque directly from the operator via an accelerator pedal or similar device.

[0027] Figure 3 is a block diagram illustrating an engine torque controller 156 according to the present invention. Engine torque controller 156 includes three functional sections represented generally by reference numerals 200, 202, and 204. Block 200 receives a desired engine brake torque (TQ_ENG) and adjusts the desired engine brake torque to generate a requested engine brake torque (TQ_SUM2) based on current operating conditions. The requested engine brake torque is provided to block 202 which controls at least one operating parameter of the engine based on the requested engine brake torque to deliver the desired engine brake torque. Block 204 includes an airflow-based idle speed controller which generates an idle speed torque determined at least in part based on a desired engine speed, preferably stored in a lookup table.

[0028] Idle speed controller 204 determines the required airflow to provide idle speed control and dashpot modes of operation. As known in the art, dashpot mode operates to modify the engine deceleration rate to smoothly approach the desired idle speed when the accelerator pedal is released. Idle speed controller 204 includes a feed forward idle speed control 206 having various inputs including a desired engine idle speed (N_BASE), engine coolant temperature (ECT), air charge temperature (ACT), and flags or switches to determine the state of various accessories such as air conditioning (A/C) and power steering (P/S).

[0029] PID and adaptive control feedback block 208 generates an appropriate output based on an RPM error which is combined with the output from block 206 and a dashpot input to determine a desired airflow (DESMAF). This value is provided to section 202 as explained in greater detail below. The desired airflow is also used to generate a torque trim term to provide smooth transitions between idle speed control and other operation modes. The torque trim term is produced by generating an airflow error which is operated on by PID controller 210 to reduce the error toward zero. The airflow value is converted to a torque trim value by block 212 which is then combined with the desired engine brake torque value at summing junction 214. As such, the desired engine brake torque (TQ_ENG) is adjusted or modified first by combining the desired engine brake torque with an idle speed torque (TQ_TRIM) to generate a first intermediate torque (TQ_ SUM) according to:

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$$TQ\_SUM = TQ\_ENG + TQ\_TRIM$$

[0030] The first intermediate torque is compared at block 218 to an actual engine brake torque (TQ_NET) generated by block 216 to generate a torque error (second intermediate torque) according to:

$$TQ\_ERROR = TQ\_SUM - TQ\_NET$$

[0031] The actual engine brake torque (TQ_NET) may be an estimated or a measured value for actual torque. The second intermediate torque or torque error is provided to a PID controller 220 which generates a feedback correction torque based on the second intermediate torque.

[0032] Preferably, controller 220 includes proportional, integral, and derivative terms but is not active during certain transient torque limiting control modes, which may include idle speed control, dashpot, engine speed limiting, traction asist, transmission gear shifting, and fail safe cooling, among others. In one embodiment, controller 220 sets the proportional and derivative terms to zero while holding the integral term constant during these control modes. Alternatively, the integral term of controller 220 may be reset during transient torque control modes while setting the proportional and derivative terms to zero. The torque feedback controller is preferably deactivated during these transient modes to prevent interference between the control parameters for air and fuel flow and the transient torque control parameters such as spark retard or injector/cylinder cutout. An example of a method for reducing engine torque through co-ordinated control of spark retard, cylinder cutout, and air/fuel scheduling can be seen in U.S. Patent No. 5,479,898, for example.

[0033] Block 216 preferably provides an estimate of the actual engine brake torque based on current engine operating parameters including ignition angle, air/fuel ratio, number of cylinders, variable CAM timing angle, engine coolant temperature, engine speed, airflow, and operation state of accessories such as the air conditioning compressor. Of course, various other parameters may be included in determining the actual engine brake torque. Alternatively, an appropriate sensor may be provided to directly determine the actual engine brake torque. Determination of an estimated actual torque is described in greater detail in U.S. Patent No. 5,241,855, assigned to the Assignee of the present invention.

[0034] The feedback correction torque generated by PID controller 220 (TQ_PID) is provided to a summing block 222 where it is combined with the first intermediate torque and a third intermediate torque (ETC_TQ_LOSS) to determine the final requested engine brake torque according to:

$$TQ\_ENG\_DES = TQ\_SUM + TQ\_PID + ETC\_TQ\_LOSS$$

[0035] The third intermediate torque may represent an accessory brake torque and/or the additional torque required to overcome increased frictional losses during cold engine operation. Preferably, the third intermediate torque is the sum of the estimated accessory brake torques including the air conditioning compressor, front end accessory friction, power steering pump losses, and additional rotational friction attributable to cold engine operation. The output of block 222 is then the requested final engine brake torque which is provided to section 202 to control the engine output. In the embodiment illustrated in Figure 3, section 202 uses airflow as the primary control parameter. Of course, fuel delivery or fuel flow may also be controlled to control the engine output torque. As such, the input to the torque controller section 202 is compensated to request additional torque to compensate for accessory losses and cold friction losses as opposed to modifying the output of the torque controller as seen in various prior art references.

[0036] As stated above, the present invention is independent of the particular strategy or controller used to deliver the requested engine brake torque. In this embodiment, airflow is used as the primary control parameter to deliver the requested torque for stoichiometric operation. Various other operational modes and/or engine technologies, such as lean burn, may utilise airflow control, fuel flow control, spark or ignition angle control, and the like as well known in the art.

[0037] Once the requested brake torque is determined by section 200, it is provided to block 230 which provides feed forward compensation to compensate for the non-linear effects of the air/fuel ratio being rich or lean of stoichiometry, i.e., an air/fuel ratio between about 12:1 and about 18:1. Likewise, block 230 compensates for the non-linear effects of the spark or ignition angle being retarded from the steady-state operation conditions, such as when in idle speed control mode. This is considered a feed forward compensation because these terms modify the control input to cause total or partial cancellation of the non-linear functions of the model. Improved transient and steady-state control is provided by combining the feed forward compensation of block 230 with the feedback operation of block 220.

[0038] Block 230 includes inputs representing the operating air/fuel equivalence ratio (LAMBSE), spark retard from MBT (SPK_DELTA), engine speed (RPM), and load. A lookup table is used to generate a torque ratio parameter which defines a relationship between indicated torque at a given air/fuel ratio relative to the indicated torque at a stoichiometric air/fuel ratio according to:

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TQ_RATIO_LAMBSE = FN(LAMBSE

[0039] This function is described in greater detail in U.S. Patent No. 5,241,855 assigned to the Assignee of the present invention. Because this function is preferably defined for maximum brake torque (MBT) ignition timing, any variation from MBT requires an additional compensation. The effect of spark retard, such as may occur during idle speed control, is preferably calculated from a tabular function and is represented as a scalar determined according to:

TQ_RATIO_SPK = FN(SPK_DELTA)

[0040] Such a function is described in greater detail in U.S. Patent No. 5,241,855. Preferably, this value represents the reduction in torque due to an ignition timing which is varied from MBT during steady-state conditions. Thus, the input torque to block 230 (TQ_ENG_DES) can be compensated for the effects of spark retard and lean or rich LAMBSE according to:

$$TQ\_ENG\_TOT = \frac{TQ\_ENG\_DES}{TQ\_RATIO\_LAMBSE * TQ\_RATIO\_SPK}$$

[0041] The output of block 230 (TQ_ENG_TOT) is provided to block 232 which converts the torque to a required airflow (load) to achieve the requested value of engine brake torque. Preferably, this model (FNTQETC) is in the form of a lookup table referenced by requested engine brake torque and engine speed. In one embodiment, this model assumes minimal accessory losses, stoichiometric operation, warm engine operation, and standard temperature and pressure calibrations. The output of block 232 is in the form of a desired engine cylinder load which may be represented by:

ETC_DES_LOAD = FNTZETC(TQ_ENG_TOT, RPM)

where load is defined as the percentage of maximum theoretical cylinder air mass in the combustion chamber for a naturally aspirated engine (SARCHG).

[0042] Block 234 converts the load to a desired intake airflow (ETC_TQ_MAF) according to:

ETC_TQ_MAF = ETC_DES_LOAD * ENGCYL * RPM * SARCHG

where ENGCYL represents the number of intake strokes per engine revolution. Block 236 operates as a multiplexer or switch to switch between the real-time controller and the idle speed or dashpot mode control. The appropriate input is selected and passed to the output based on the APP (at part pedal) flag which is set to zero or one when the accelerator pedal is either partly depressed or fully depressed and equal to minus one when the accelerator pedal is not depressed. Block 238 selects the higher value for the airflow from the idle speed controller or the real-time engine torque controller to ensure that the final requested airflow (ETC_DESMAF) does not decrease below the idle speed control setting (DESMAF) due to any modelling errors in the torque-to-load table (FNTQETC) represented by block 232. As such, block 238 always selects the maximum of its two inputs which is then provided at the output.

[0043] Referring now to Figure 4, a flowchart illustrating control logic of one embodiment of a system or method according to the present invention is shown. As will be appreciated by one of ordinary skill in the art, the flowchart illustrated in Figure 4 may represent any of a number of known processing strategies such as event-driven, interrupt-driven, multi-tasking, multi-threading, and the like. As such, various steps or functions illustrated may be performed in the sequence illustrated, in parallel, or in some cases omitted. Likewise, the order of processing is not necessarily required to achieve the objects, features, and advantages of the invention, but is provided for ease of illustration and description. Preferably, the control logic is implemented in software which is executed by a microprocessor-based controller. Of course, the control logic may be implemented in software, hardware, or a combination of software and hardware. The flowchart of Figures 4 illustrate one "loop" and its operations are preferably repeated at predetermined time intervals as known by those of skill in the art.

[0044] Block 300 represents determining a desired engine brake torque. As described above, various techniques may be used to determine the desired engine brake torque. Preferably, the desired engine brake torque is determined based on the vehicle speed, accelerator pedal position, and current barometric pressure. Depending upon the particular application, a driver demanded torque may be represented by a wheel torque, wheel power, engine power, or various other parameters which are converted to a desired engine brake torque. Blocks 302-308 adjust the desired engine brake torque to generate a requested engine brake torque based on current operating conditions. Blocks 310-312 represent controlling at least one of the operating parameters of the engine based on the requested engine brake torque to deliver the desired engine brake torque.

[0045] In particular, block 302 represents combining the desired engine brake torque with an idle speed torque to

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generate a first intermediate torque. Preferably, the idle speed torque is a torque trim value which is used to provide smooth transitions between the idle speed controller and the engine torque controller. The first intermediate torque is compared to the actual engine brake torque to generate a second intermediate torque as represented by block 304. Preferably, the first intermediate torque is also used in a feed forward arrangement as illustrated in Figure 3 and represented by block 308.

[0046] Block 306 represents generating a feedback correction torque based on the second intermediate torque. Preferably, a proportional-integral-derivative (PID) controller is used to generate the feedback correction torque. Preferably, the proportional and derivative terms are set to zero while the integral term is held constant during at least one engine control mode where transient torque control is necessary, such as during idle speed control, traction assist, and the like. The output of the feedback correction torque block is used to adjust the requested engine brake torque to drive the torque error toward zero.

[0047] A third intermediate torque based on accessory loads and/or engine frictional losses is determined as represented by block 308. Preferably, block 308 represents determination of an estimated accessory brake torque which includes the torque required to operate various vehicle accessories including an air conditioning compressor, power steering pump, and the like. Various losses may also be compensated for by block 308 including the frictional losses. As known, frictional losses generally vary as a function of engine temperature and engine speed. As such, block 308 preferably includes a term for frictional losses based on engine temperature and engine speed.

[0048] The first intermediate torque, feedback correction torque, and third intermediate torque are combined to determine the requested engine brake torque as represented by block 310. The requested engine brake torque is then compensated for the torque reducing effects of spark retard and LAMBSE being rich or lean of stoichiometry. The compensated requested engine brake torque is then provided to block 312 where it is converted to appropriate control parameters to control the engine as represented by block 312. The control parameters may include airflow, fuel, ignition angle (spark), CAM timing, and the like, depending upon the particular application.

[0049] As such, the present invention compensates the input to the engine torque controller prior to determination of the control parameters rather than modifying the output of the engine torque controller as described in the prior art. This provides a more robust torque controller which is more easily applied to various engine technologies including lean burn, variable CAM timing, and the like.

Claims

1. A method for controlling an engine, the method comprising:

   determining a desired engine brake torque;
   adjusting the desired engine brake torque to generate a requested engine brake torque based on current operating conditions; and
   controlling at least one operating parameter of the engine based on the requested engine brake torque to deliver the desired engine brake torque.

2. A method as claimed in claim 1, wherein the step of determining a desired engine brake torque comprises determining a desired engine brake torque based on accelerator pedal position, barometric pressure, and vehicle speed.

3. A method as claimed in claim 1, wherein the step of determining a desired engine brake torque comprises determining a desired engine brake torque based on accelerator pedal position, barometric pressure, and engine speed.

4. A method as claimed in claim 1, wherein the step of adjusting the desired engine brake torque comprises: combining the desired engine brake torque with an idle speed torque, the idle speed torque determined at least in part based on a desired engine speed.

5. The method of claim 1 wherein the step of adjusting the desired engine brake torque comprises:

   determining an actual engine brake torque; and
   comparing the actual engine brake torque to the desired engine brake torque to generate a torque error.

6. A method as claimed in claim 5, wherein the step of determining an actual engine brake torque comprises estimating an actual engine brake torque based on current engine operating parameters.

7. A method as claimed in claim 6, wherein the step of estimating an actual engine brake torque comprises estimating an actual engine brake torque based on at least engine speed, engine temperature, airflow, ignition angle, and rel-

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ative camshaft timing.

8. A method as claimed in claim 5, wherein the step of adjusting the desired engine brake torque further comprises generating a requested brake torque based on the torque error to drive the torque error toward zero.

9. A method as claimed in claim 8, wherein the step of generating a requested brake torque based on the torque error comprises applying the torque error to a PID feedback controller.

10. A method as claimed in claim 8, wherein the PID feedback controller includes a proportional term, an integral term, and a derivative term, and wherein the proportional and derivative terms are set to zero and the integral term is held constant during transient torque control modes.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565
Page 7497

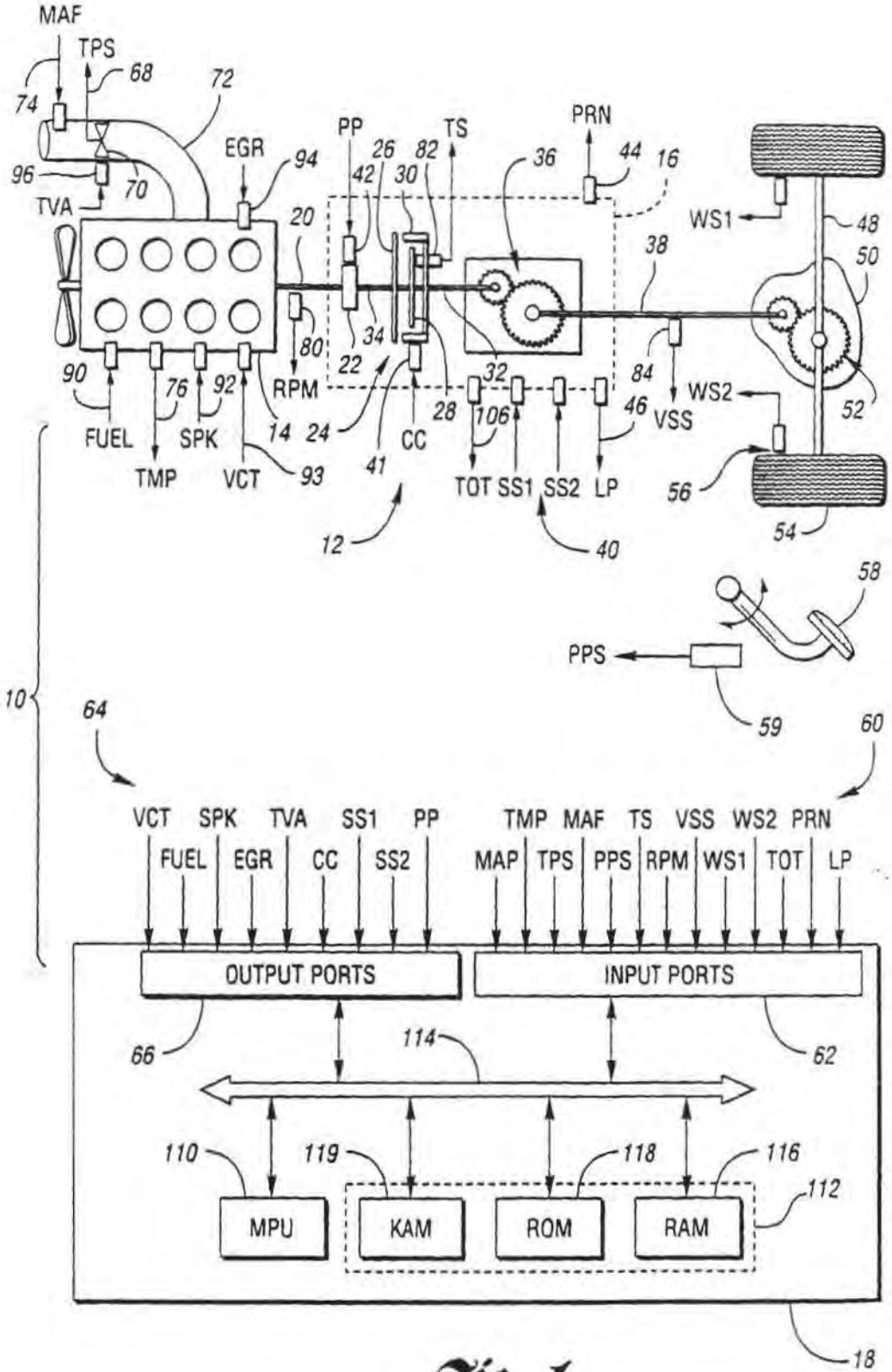


Fig. 1

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565
Page 7498

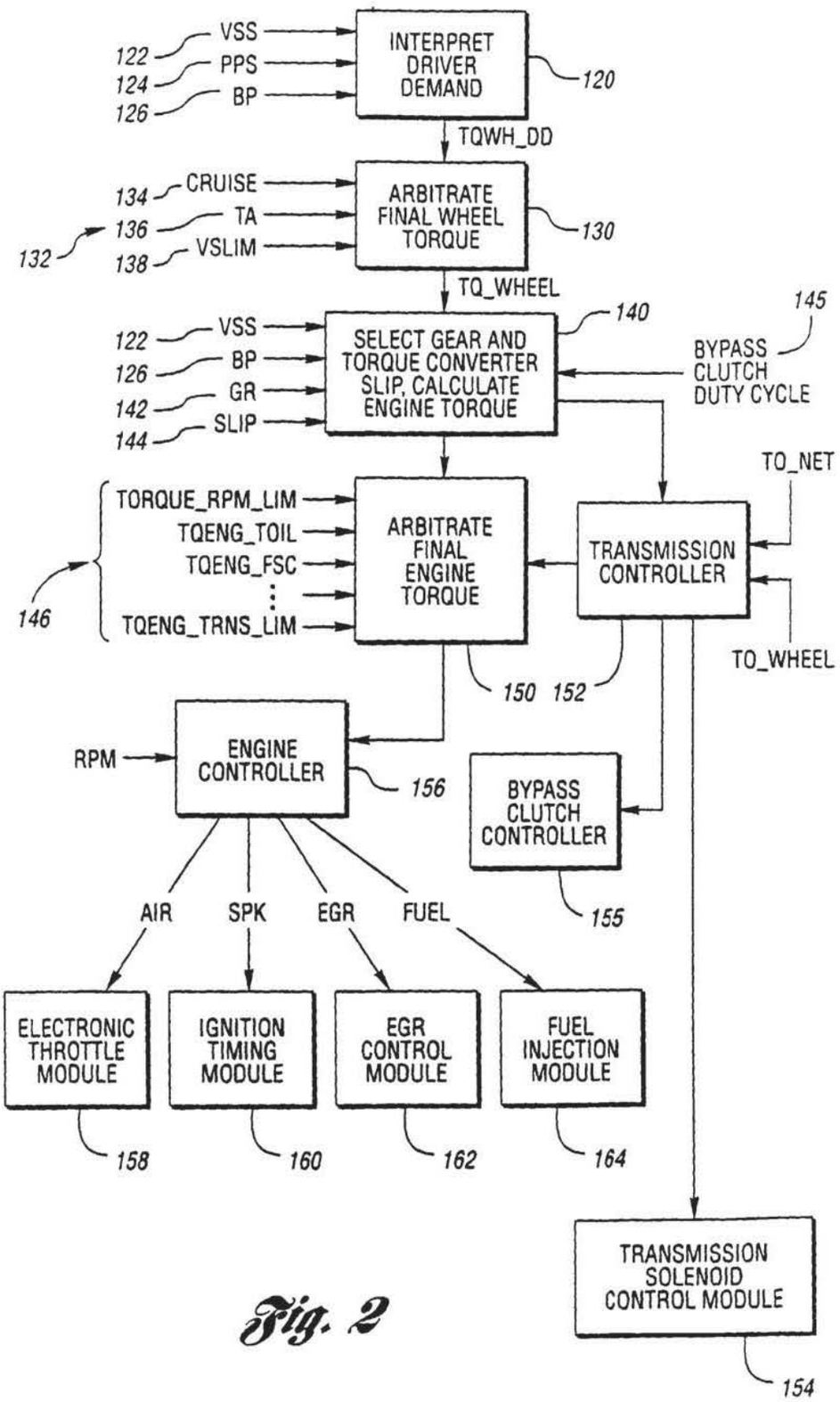


Fig. 2

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565
Page 7499

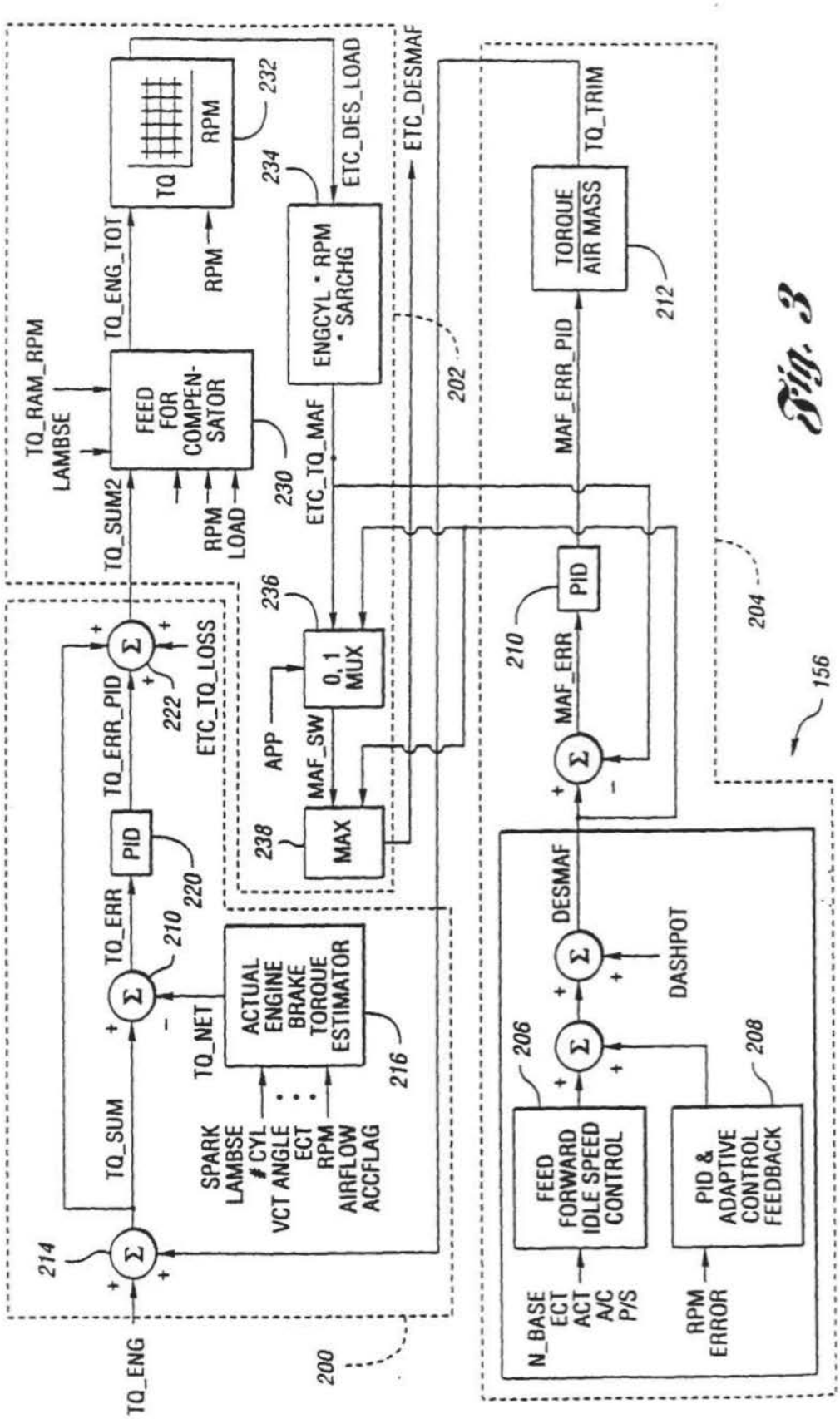


Fig. 3

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565
Page 7500

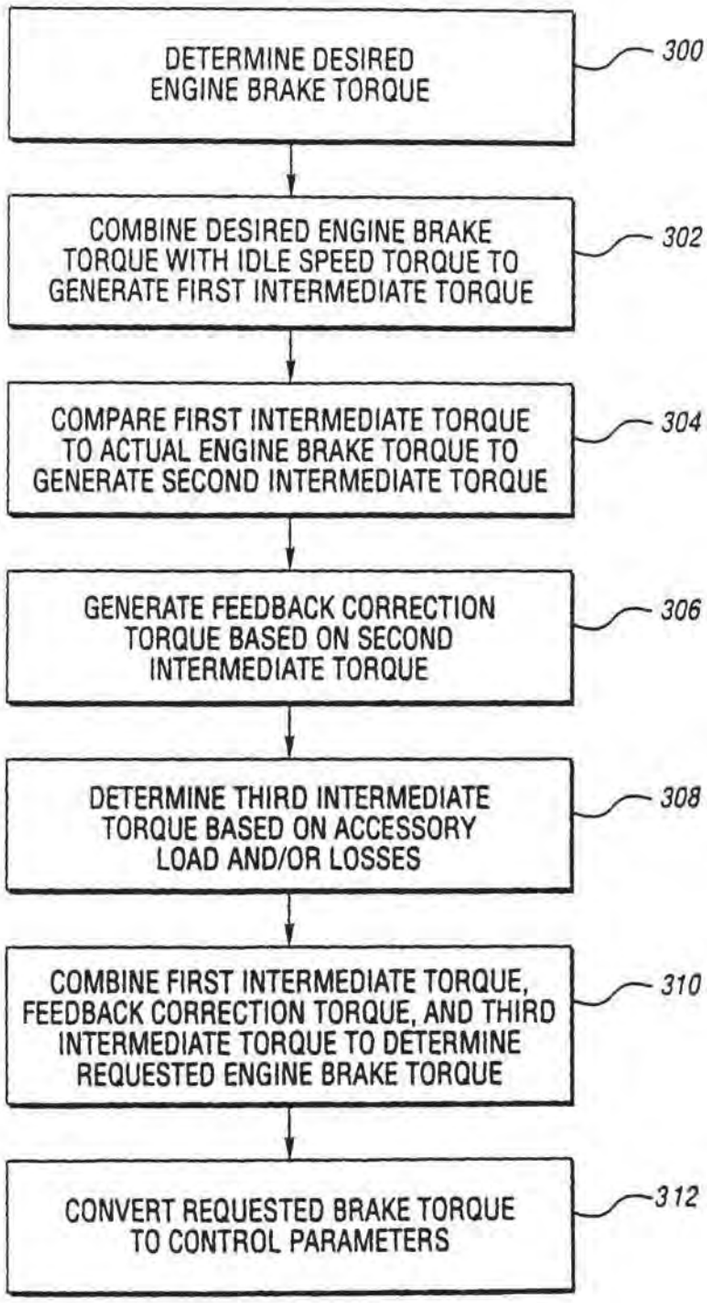


Fig. 4

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565
Page 7501

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

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

States Patent and Trademark Office. A true and correct copy of the ’260 patent is attached as Exhibit 1.

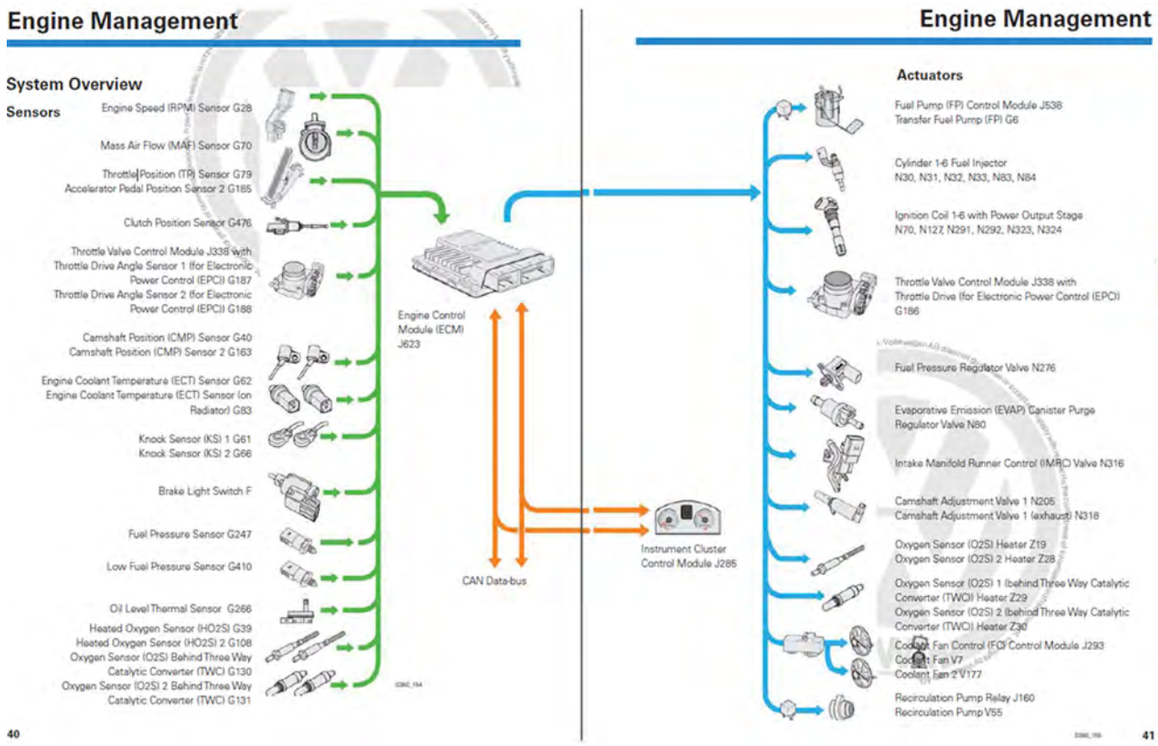
12. Plaintiff is the assignee and owner of the right, title and interest in and to the ’260 patent, including the right to assert all causes of action arising under said patents and the right to any remedies for infringement of them.

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*),

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

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		

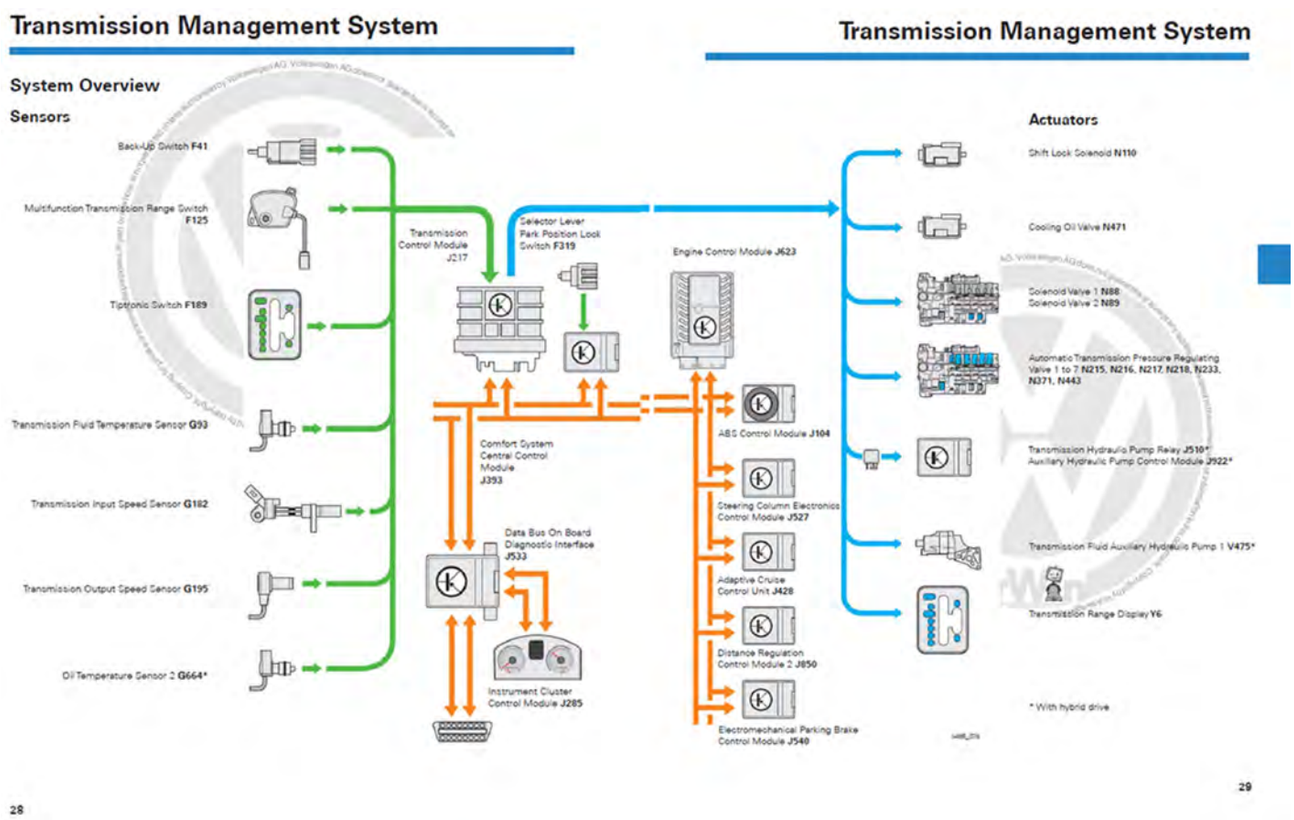
testing integrity of a motor drive electronics disable feature

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

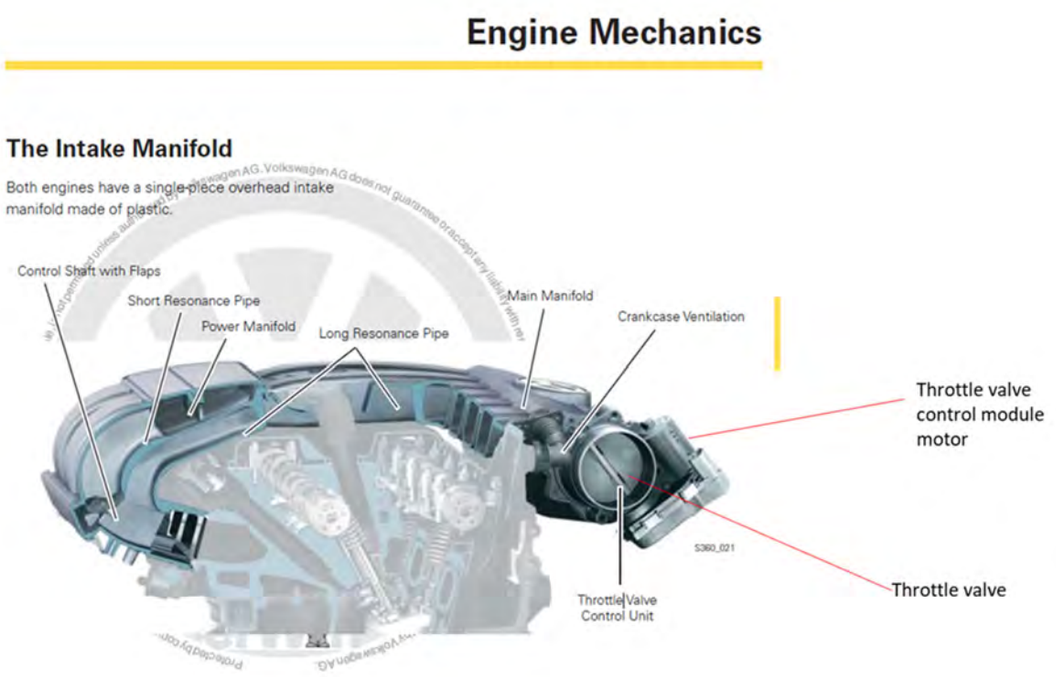
Figure 2



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).



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.

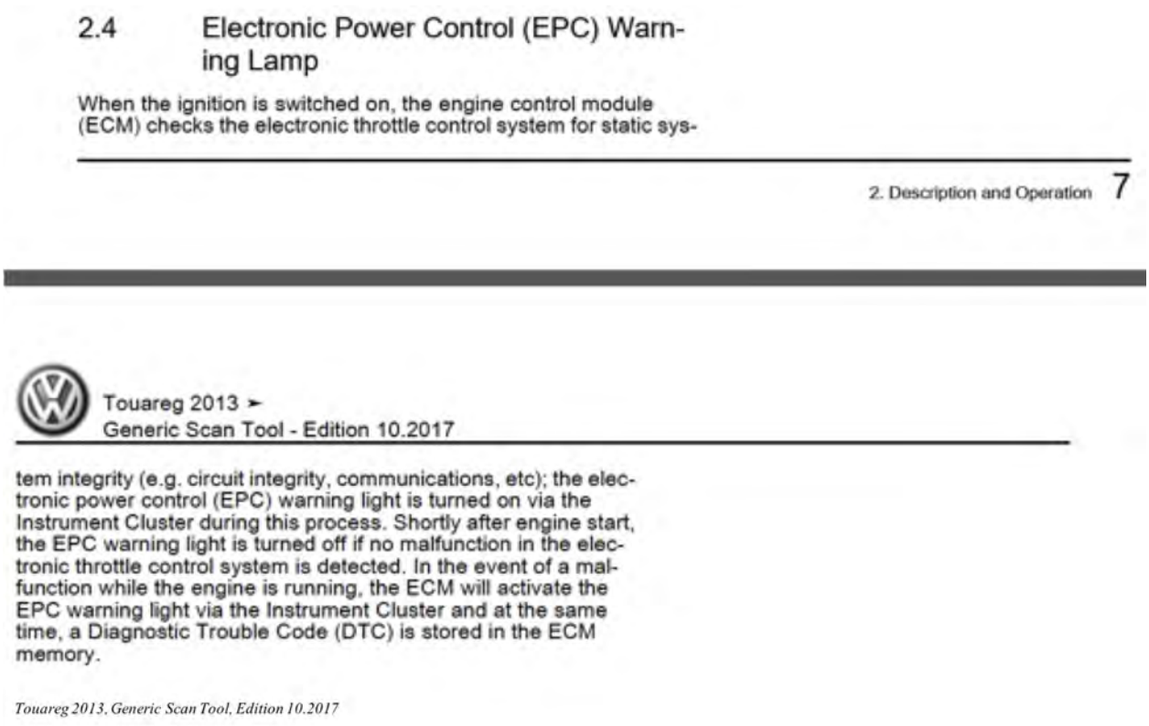
https://www.obd-codes.com

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.

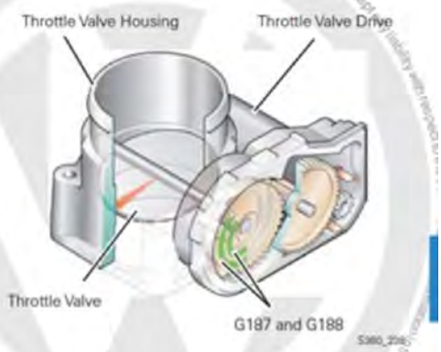
Figure 5

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.

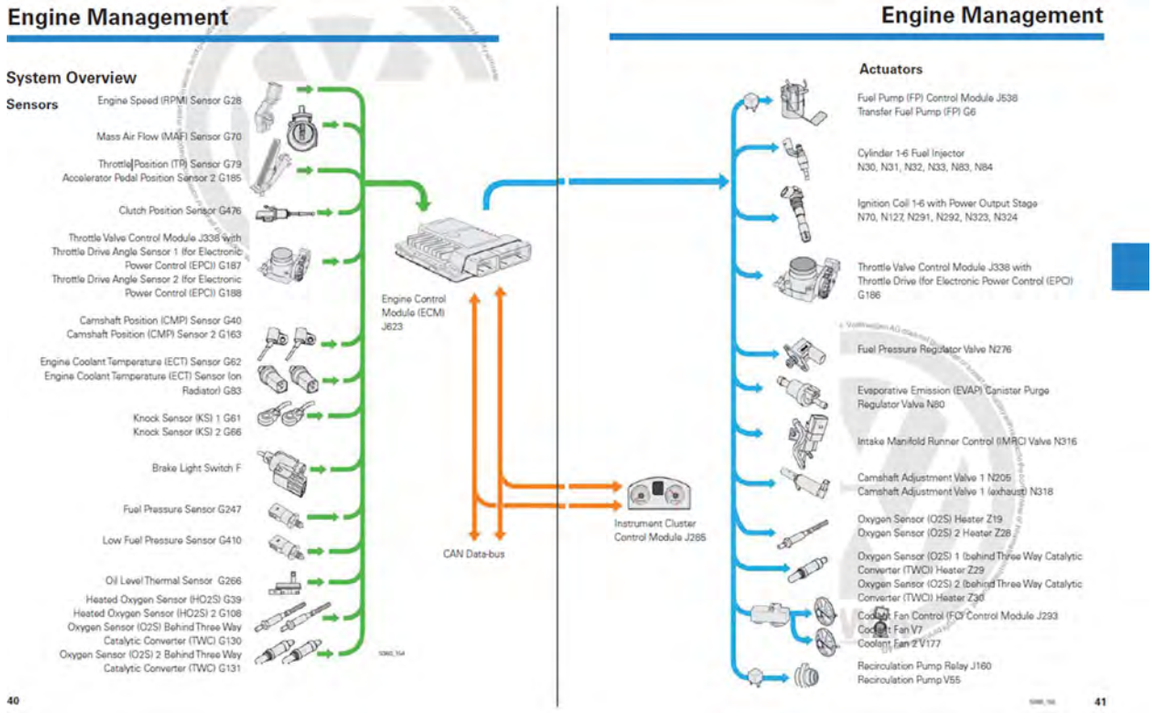
18. Plaintiff is the assignee and owner of the right, title and interest in and to the '128 patent, including the right to assert all causes of action arising under said patents and the right to any remedies for infringement of them.

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

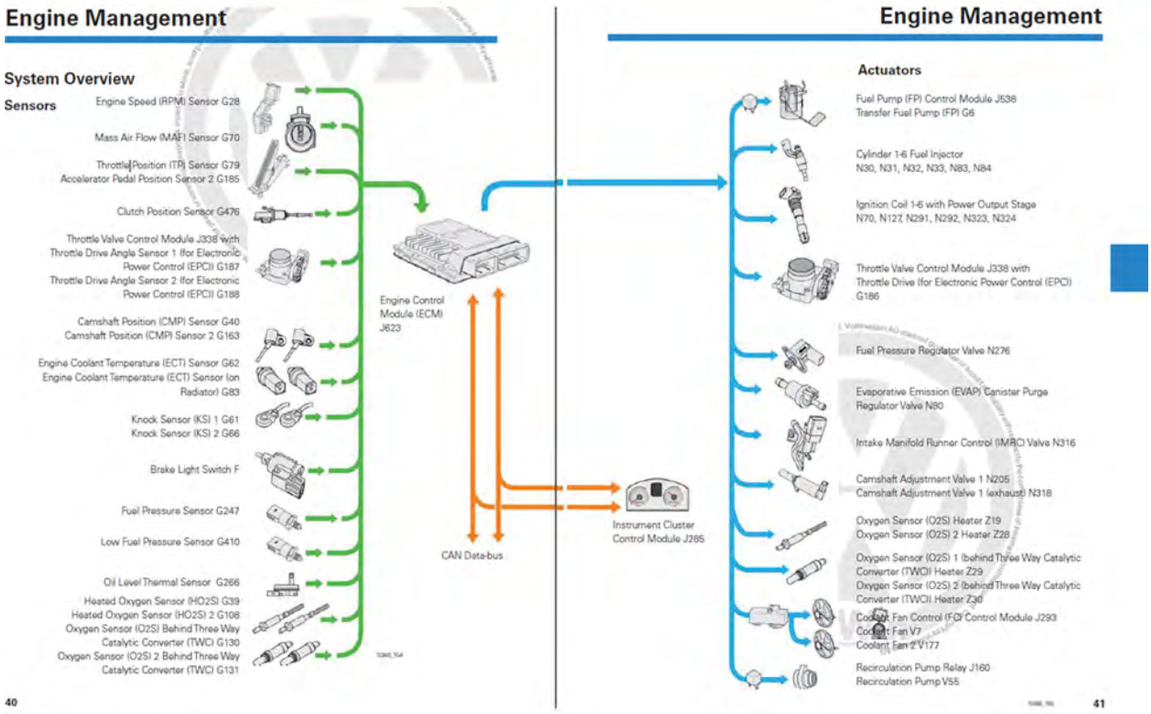
position command; and applying the clipped throttle position command to the throttle control motor with the throttle control circuit.

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*).

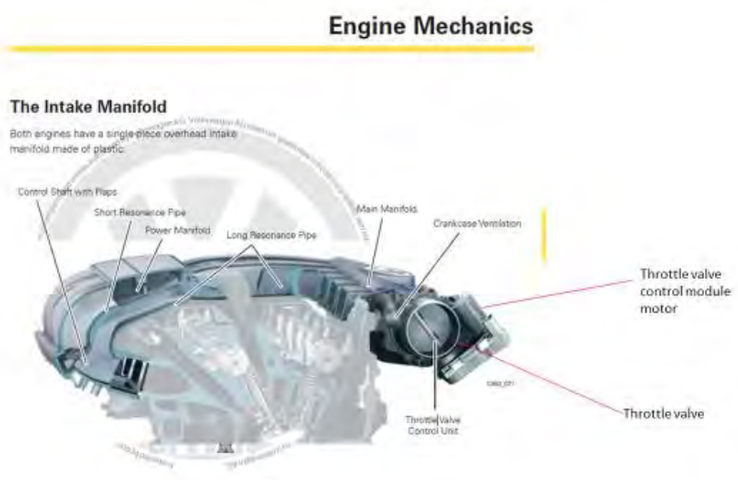


The Engine Control Module (J623) provides a method of controlling an internal combustion engine.

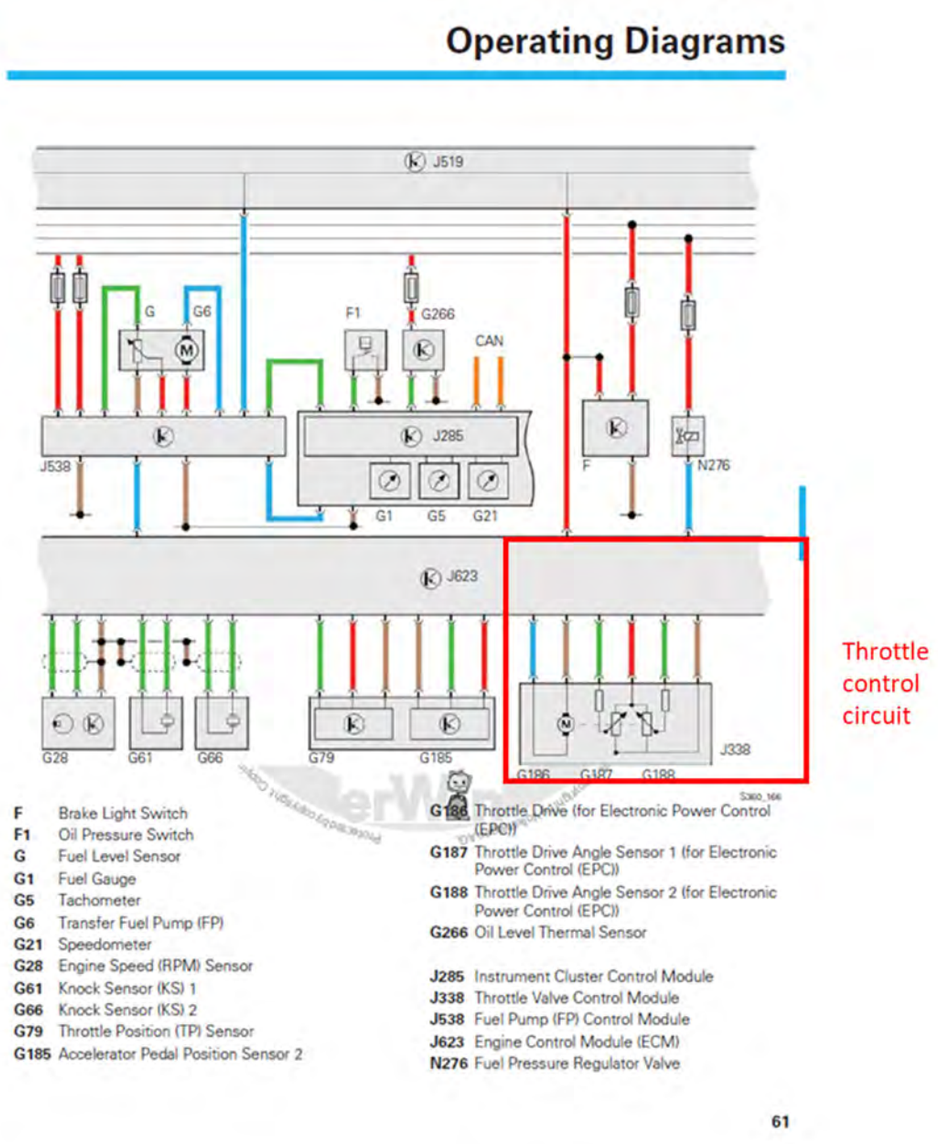
Figure 7



The ’128 patent Infringing Instrumentalities comprise an Engine controller, the ECM (J623) and an electronically controlled throttle (J338).

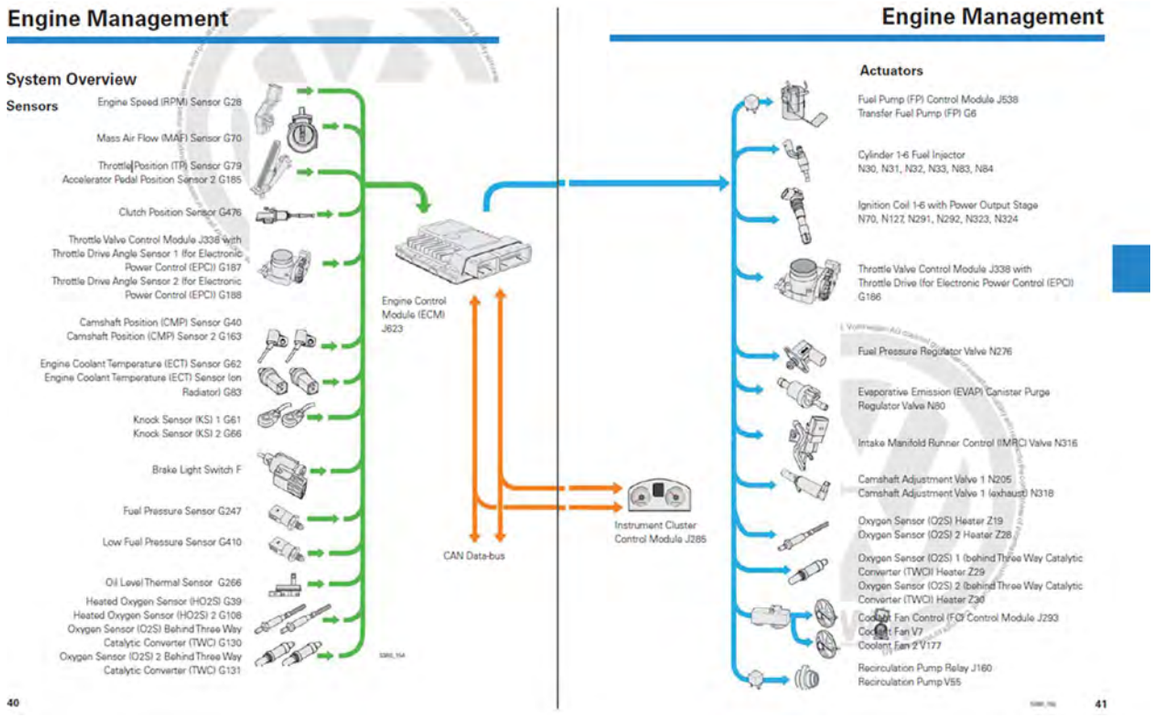


The method practiced by the ’128 patent Infringing Instrumentalities comprises an electronically controlled throttle (J338) including a throttle control motor driven by a throttle control circuit.



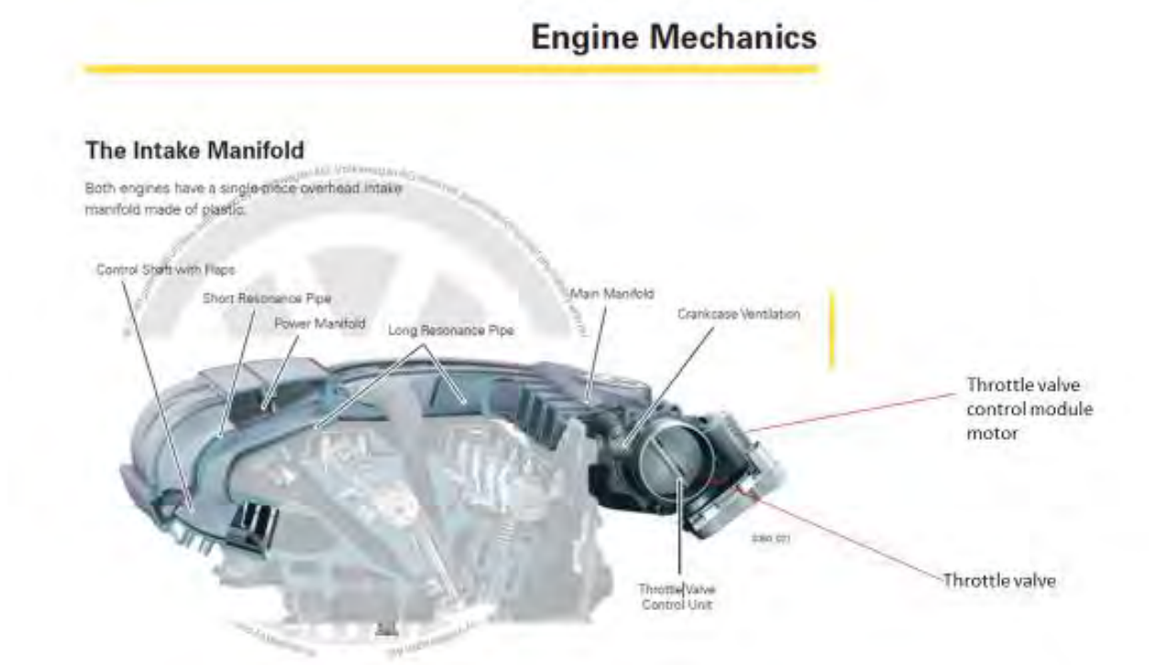
The electronically controlled throttle includes a throttle control motor (J338) driven by a throttle control circuit. *See above*.

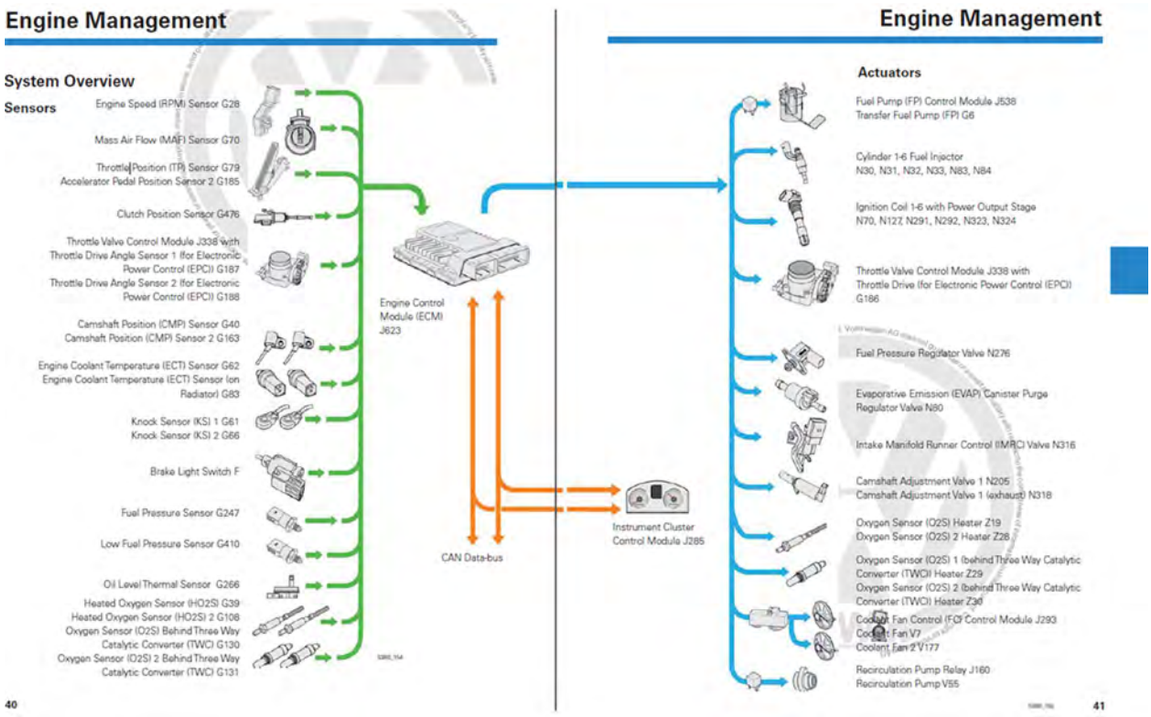
Figure 8



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





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

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.

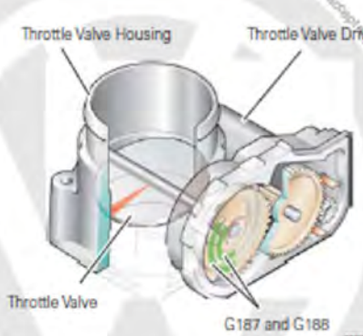
Figure 11

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

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

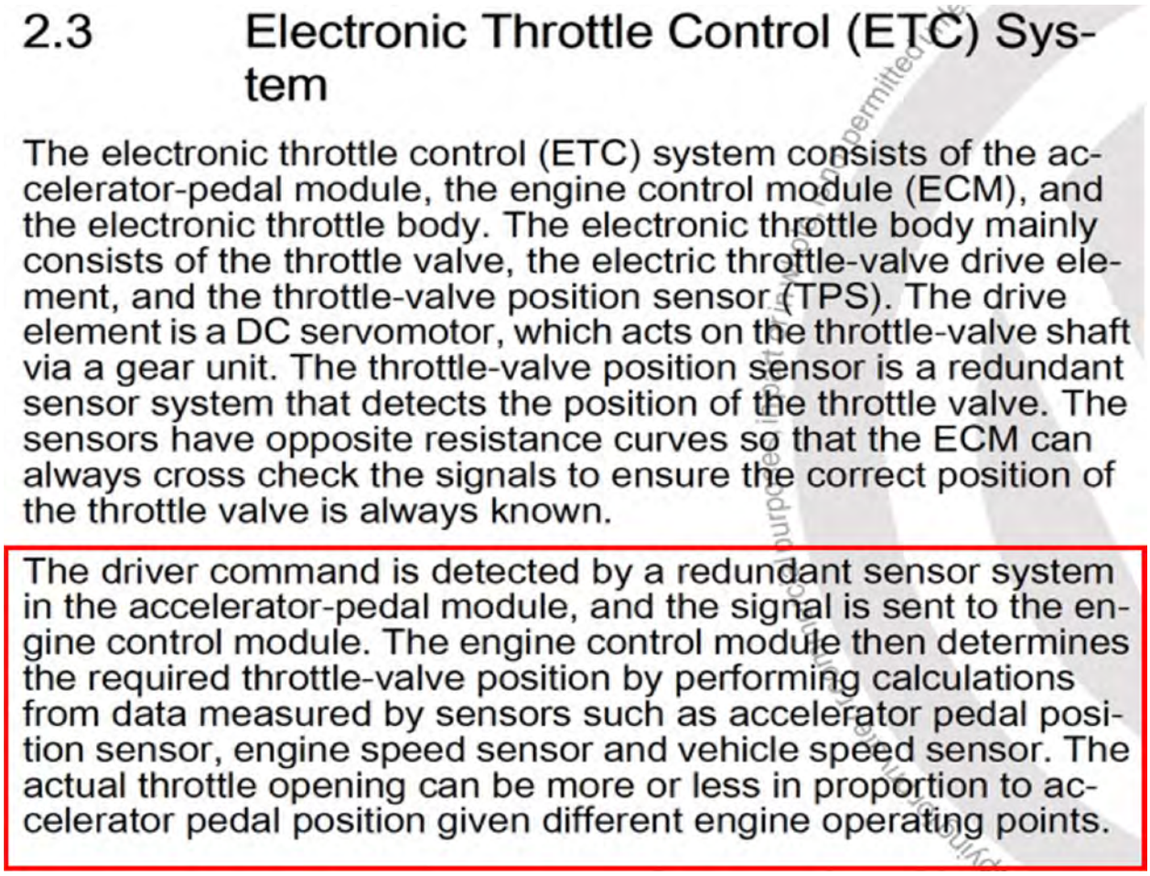


A circuit which removes the peak of a waveform is known as a clipper. A clipper is designed to prevent the output of a circuit from exceeding a predetermined voltage level. *https://www.allaboutcircuits.com/textbook/semiconductors/chpt-3/clipper-circuits/*

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.

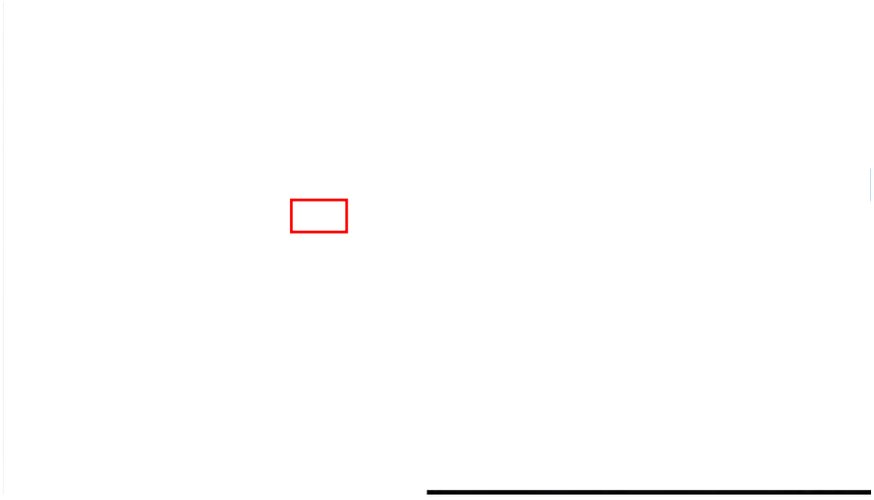
24. Plaintiff is the assignee and owner of the right, title and interest in and to the '565 patent, including the right to assert all causes of action arising under said patents and the right to any remedies for infringement of them.

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*).



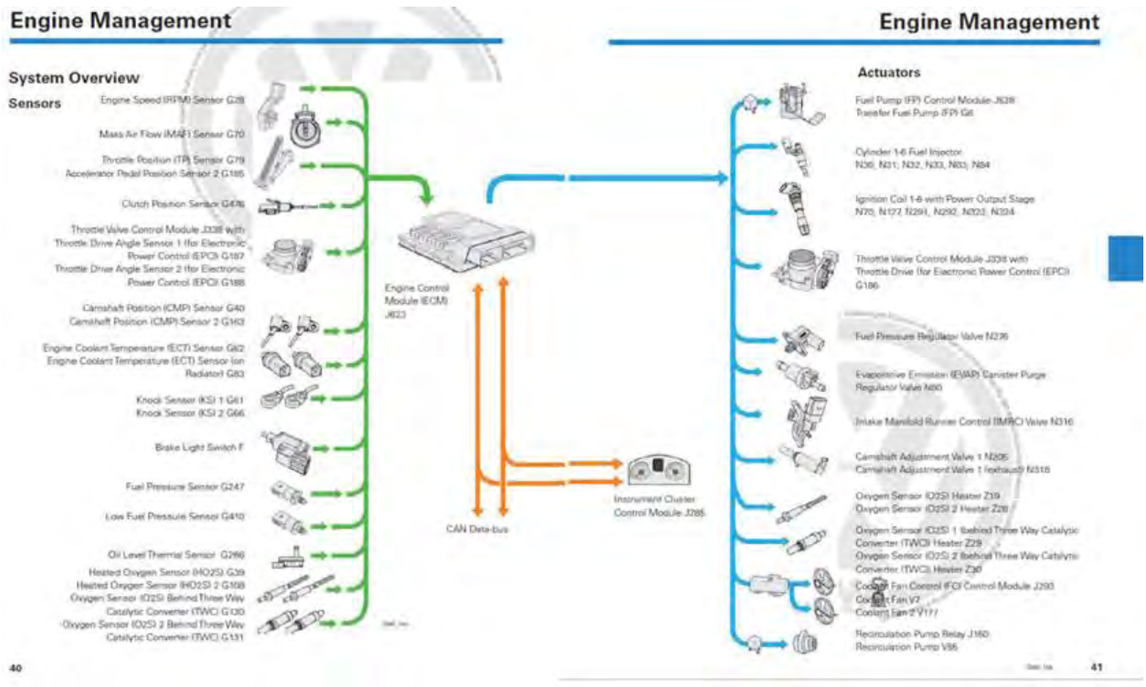
For example, as shown above, the Engine Control Module (ECM) J623 is a device for controlling the torque output of the engine.

Figure 13

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.

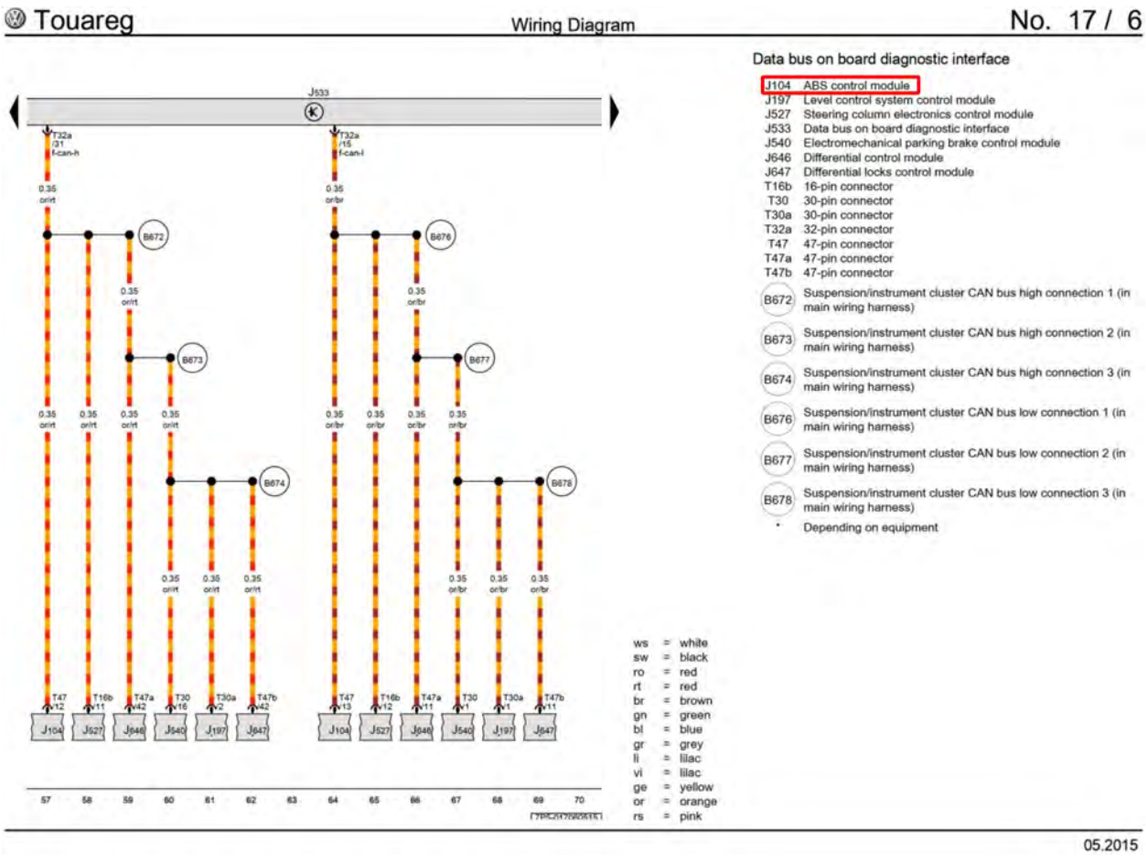
Figure 15



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



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
Page 7531

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
Page 7533

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				

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

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.

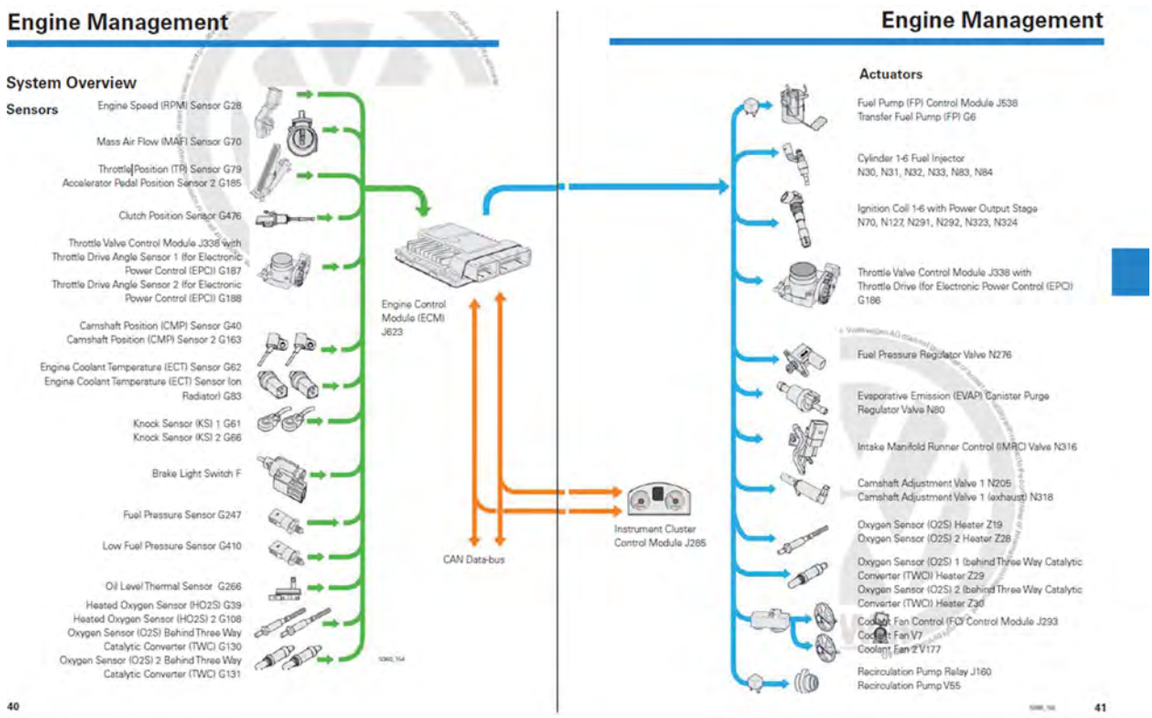
30. Plaintiff is the assignee and owner of the right, title and interest in and to the '281 patent, including the right to assert all causes of action arising under said patents and the right to any remedies for infringement of them.

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

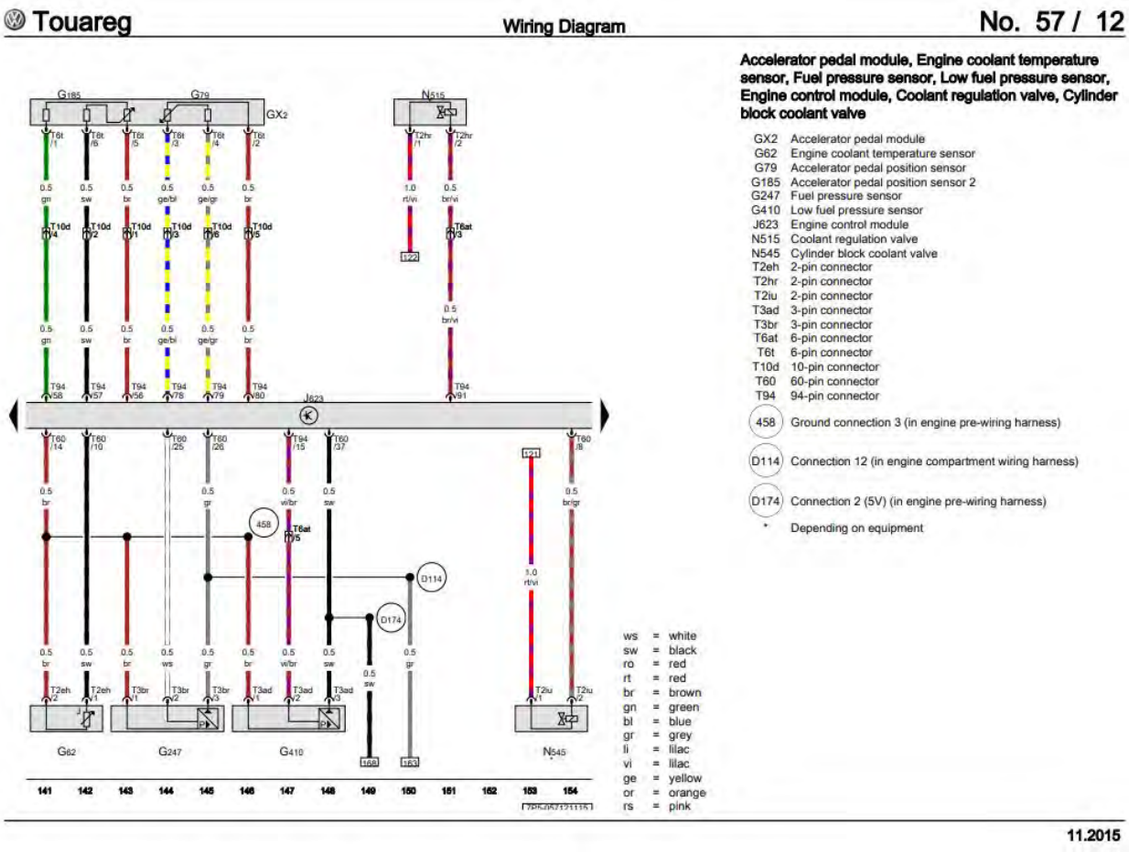
output control method for a vehicle having a drive by wire engine system (*Figure 20*) responsive to a desired engine torque signal (*Figure 20*), the method comprising the steps of: generating a driver demanded acceleration value corresponding to an operator input (*Figure 21*); generating a gear value 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.

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.

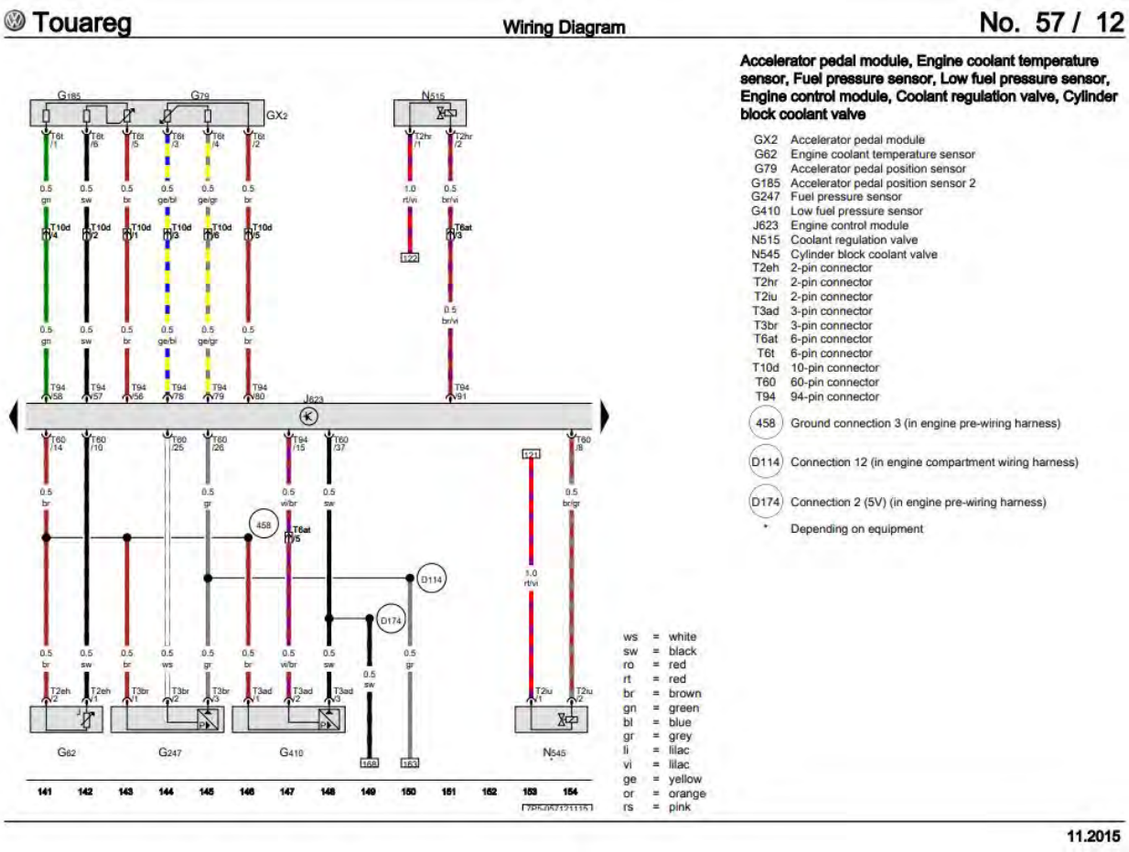
Figure 20



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



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

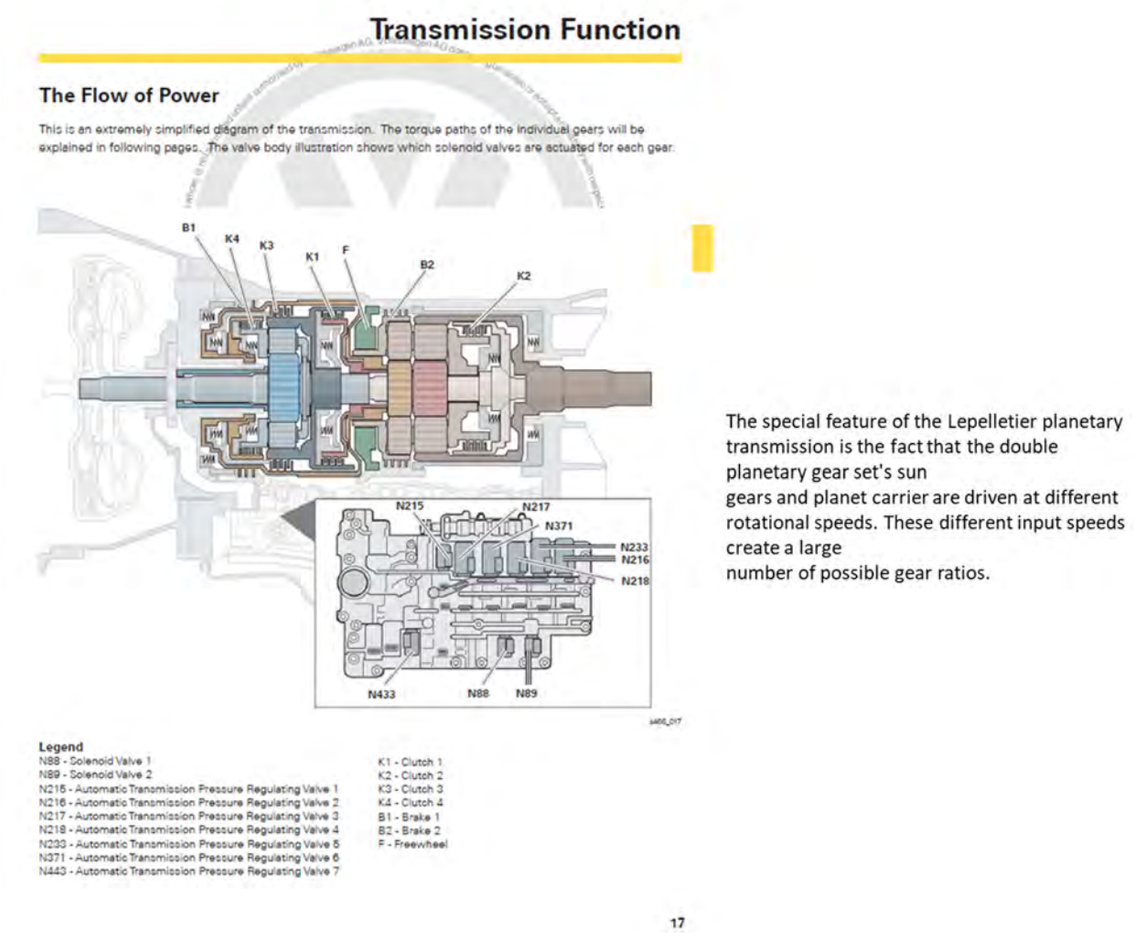
If the actual gear position is higher than the position supposed by the TCM, the slip ratio will be more than normal. In case the ratio exceeds the specified value, the TCM judges this diagnosis malfunction.

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

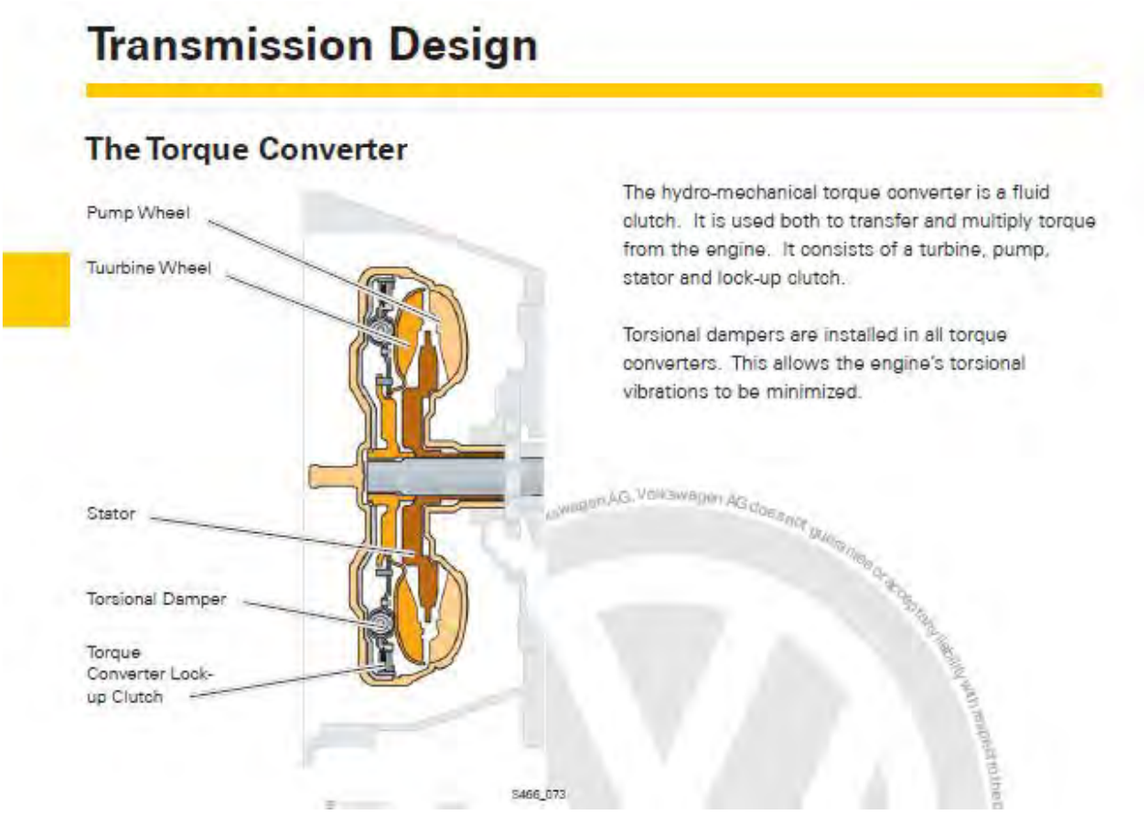


Additionally, adaptations are used to allow the system to learn during vehicle operation.

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)

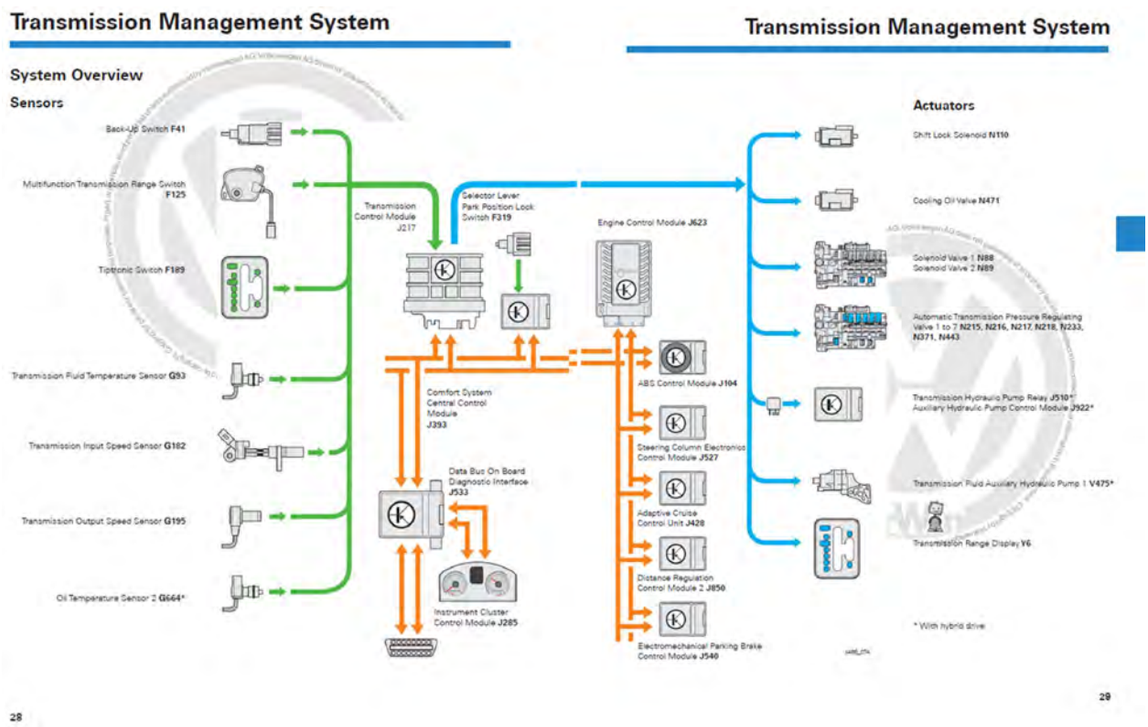
N_{in} = speed of turbine (torque converter output) = transmission input speed (RPM)

$R_{TQ} = f_3\frac{N_{in}}{N_e}$ = 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.

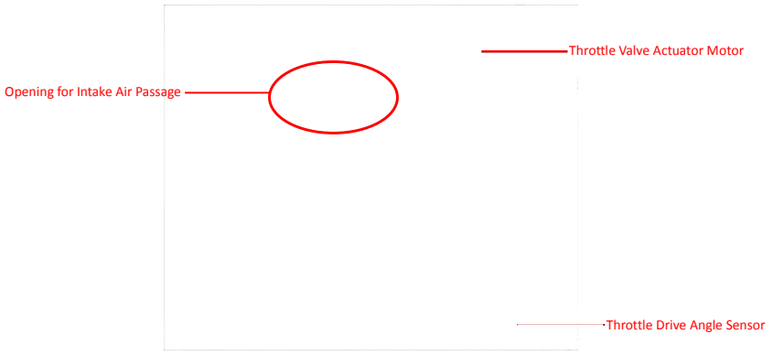
39. On information and belief, the '804 patent Accused Instrumentalities infringe at least claim 1 of the '804 patent. The '804 patent Accused Instrumentalities practice a method for controlling a positioning device of an internal combustion engine (*Figure 26*), the method

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



For example, as shown above, a positioning device, the Throttle Valve Control Module J338 of an internal combustion engine (VW 3.2L & 3.6L), is actuated via a Throttle Valve Actuator Motor.

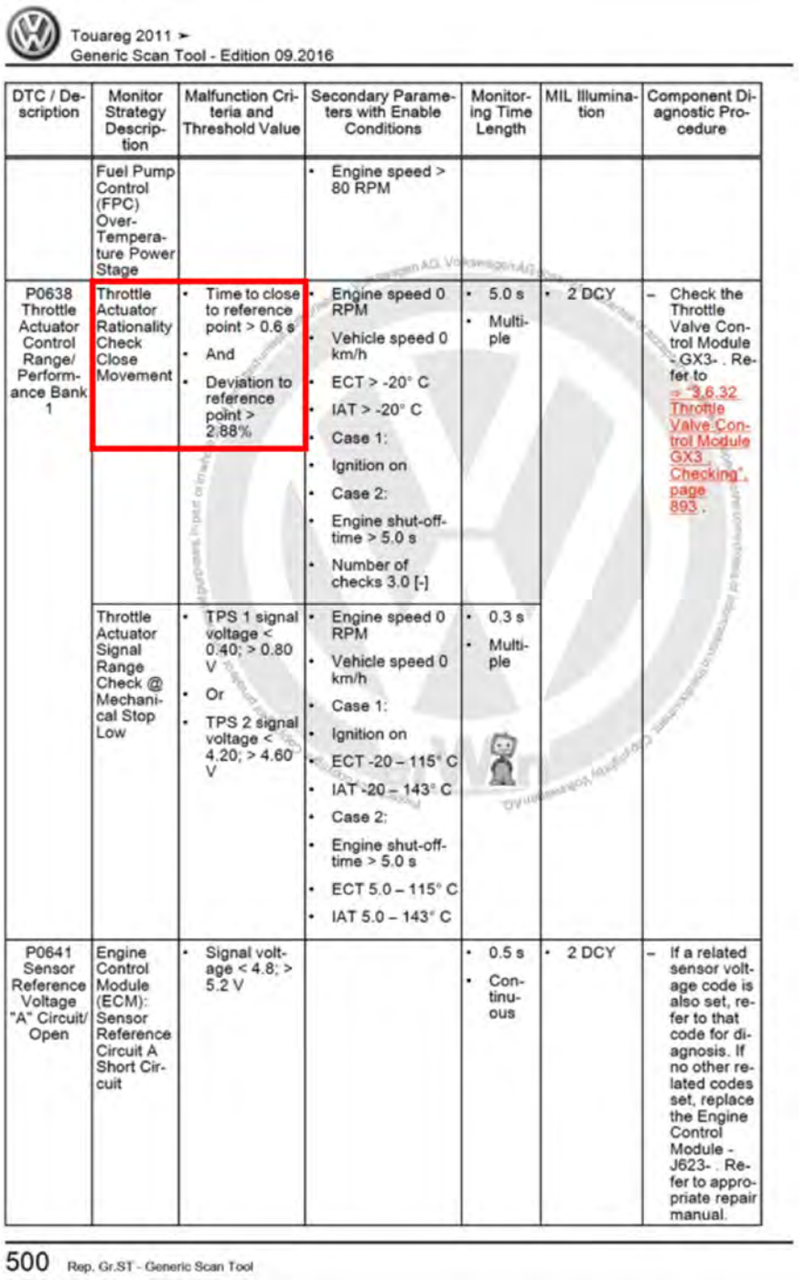
Figure 27



For example, as shown above, a positioning device, the Throttle Valve Control Module J338 of an internal combustion engine (VW 3.2L & 3.6L), is actuated via a Throttle Valve Actuator

Motor as commanded by the ECM, to change to a commanded position (based on the driver demand commanded from the Accelerator Position Sensor 2 G185).

Figure 28



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DTC / Description	Monitor Strategy Description	Malfunction Criteria and Threshold Value	Secondary Parameters with Enable Conditions	Monitoring Time Length	MIL Illumination	Component Diagnostic Procedure
	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 ⇒ "3.6.32 Throttle Valve Control Module GX3 Checking", page 893 .
	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: • Engine shut-off-time > 5.0 s • ECT 5.0 – 115° C • IAT 5.0 – 143° C	• 0.3 s • Multiple		
P0641 Sensor Reference Voltage "A" Circuit/ Open	Engine Control Module (ECM): Sensor Reference Circuit A Short Circuit	• Signal voltage < 4.8; > 5.2 V		• 0.5 s • Continuous	• 2 DCY	– If a related sensor voltage code is also set, refer to that code for diagnosis. If no other related codes set, replace the Engine Control Module - J623- . Refer to appropriate repair manual.

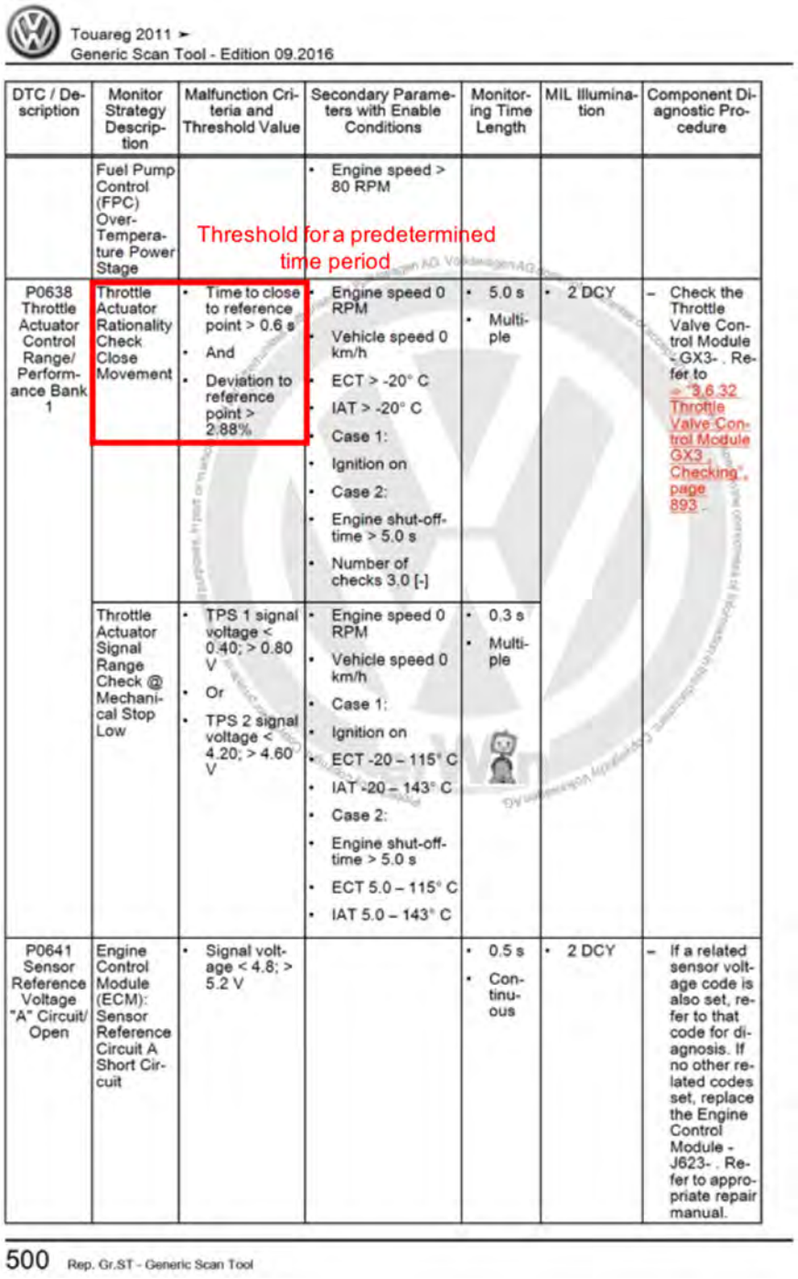
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For example, control effort corresponds to the amount of motor torque that the Throttle Valve Control Module J338 requires to change the position of the throttle valve and this is related to the time it takes the Throttle Valve Control Module J338 to close to a reference point. The

commanded position is determined by the Engine Control Module (ECM) J623 based on information from the Accelerator Position Sensor 2 G185 derived from driver demand, to change to a commanded position (based on the driver demand commanded from the Accelerator Position Sensor 2 G185).

Figure 29



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DTC / Description	Monitor Strategy Description	Malfunction Criteria and Threshold Value	Secondary Parameters with Enable Conditions	Monitoring Time Length	MIL Illumination	Component Diagnostic Procedure
	Fuel Pump Control (FPC) Over-Temperature Power Stage	Threshold for a predetermined time period	• 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 ⇒ "3.6.32 Throttle Valve Control Module GX3 , Checking", page 893 .
	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: • Engine shut-off-time > 5.0 s • ECT 5.0 – 115° C • IAT 5.0 – 143° C	• 0.3 s • Multiple		
P0641 Sensor Reference Voltage "A" Circuit/ Open	Engine Control Module (ECM): Sensor Reference Circuit A Short Circuit	• Signal voltage < 4.8; > 5.2 V		• 0.5 s • Continuous	• 2 DCY	– If a related sensor voltage code is also set, refer to that code for diagnosis. If no other related codes set, replace the Engine Control Module - J623- . Refer to appropriate repair manual.

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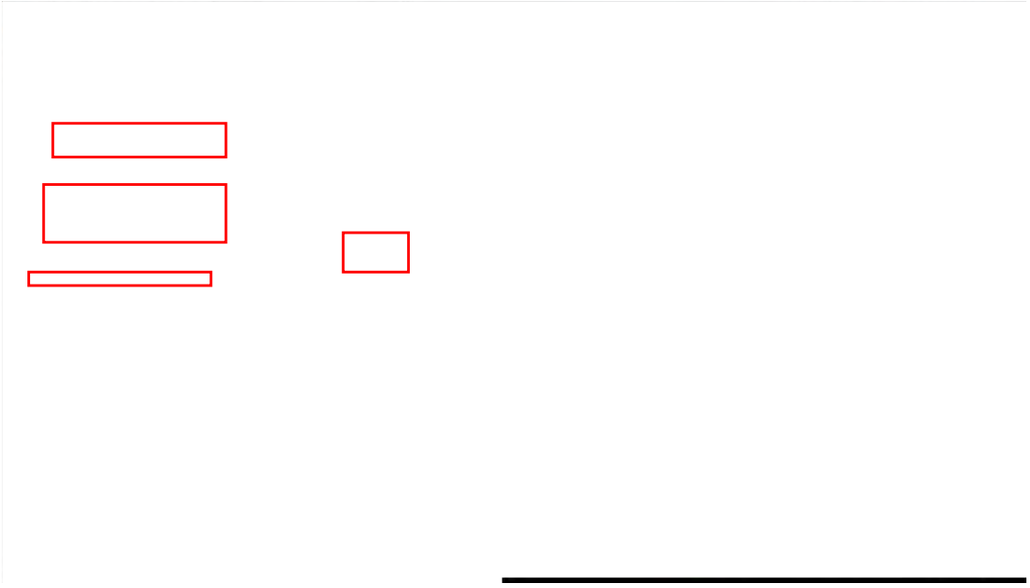
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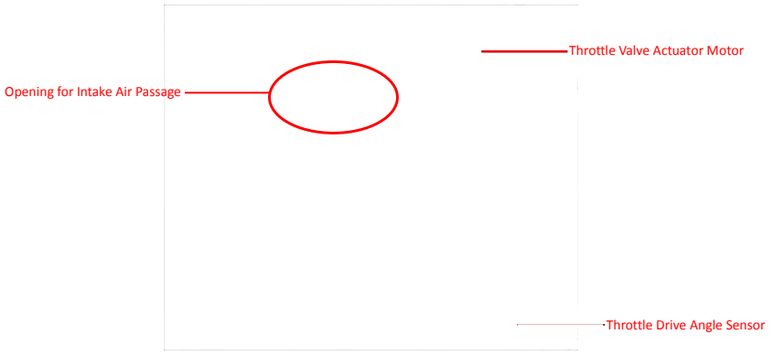
PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565
Page 7548

For example, as shown above, the threshold value demonstrates a determination being made by the Engine Control Module (ECM) J623 regarding whether a control effort exceeds a threshold for a predetermined time period.

Upon information and belief, the claim limitation “determining whether said control effort exceeds a threshold for said predetermined time period” is satisfied.

Figure 30

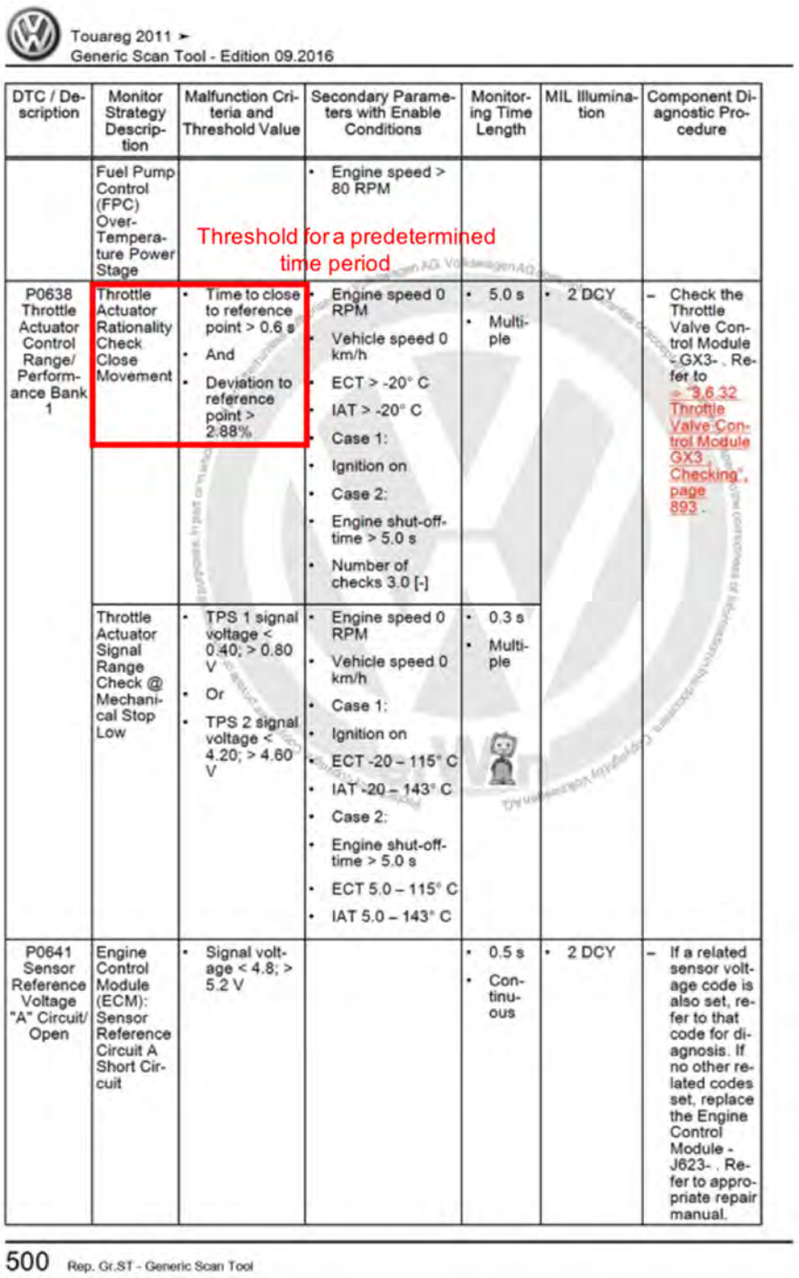




2.3 Electronic Throttle Control (ETC) System

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.



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DTC / Description	Monitor Strategy Description	Malfunction Criteria and Threshold Value	Secondary Parameters with Enable Conditions	Monitoring Time Length	MIL Illumination	Component Diagnostic Procedure
	Fuel Pump Control (FPC) Over-Temperature Power Stage	Threshold for a predetermined time period	• 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 ⇒ "3.6.32 Throttle Valve Control Module GX3 , Checking", page 893 .
	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: • Engine shut-off-time > 5.0 s • ECT 5.0 – 115° C • IAT 5.0 – 143° C	• 0.3 s • Multiple		
P0641 Sensor Reference Voltage "A" Circuit/ Open	Engine Control Module (ECM): Sensor Reference Circuit A Short Circuit	• Signal voltage < 4.8; > 5.2 V		• 0.5 s • Continuous	• 2 DCY	– If a related sensor voltage code is also set, refer to that code for diagnosis. If no other related codes set, replace the Engine Control Module - J623- . Refer to appropriate repair manual.

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Control effort is provided by the Throttle Valve Actuator Motor based on the signal sent by the Engine Control Module (ECM) J623. The ECM signal is derived from the Accelerator Position Sensor 2 G185 based on driver demanded acceleration input. The throttle valve is actuated by the Throttle Valve Actuator Motor, sending a Throttle Drive Angle Sensor signals (1 & 2) to the ECM. The Throttle Actuator Control Rationality check shows a threshold valve. The Throttle Valve Actuator Motor will attempt to close the throttle valve within a time limit with feedback

from the Throttle Drive Angle Sensor signals (1 & 2), if the Throttle Drive Angle Sensor signals (1 & 2) indicate a time greater than the time limit, then the DTC will set.

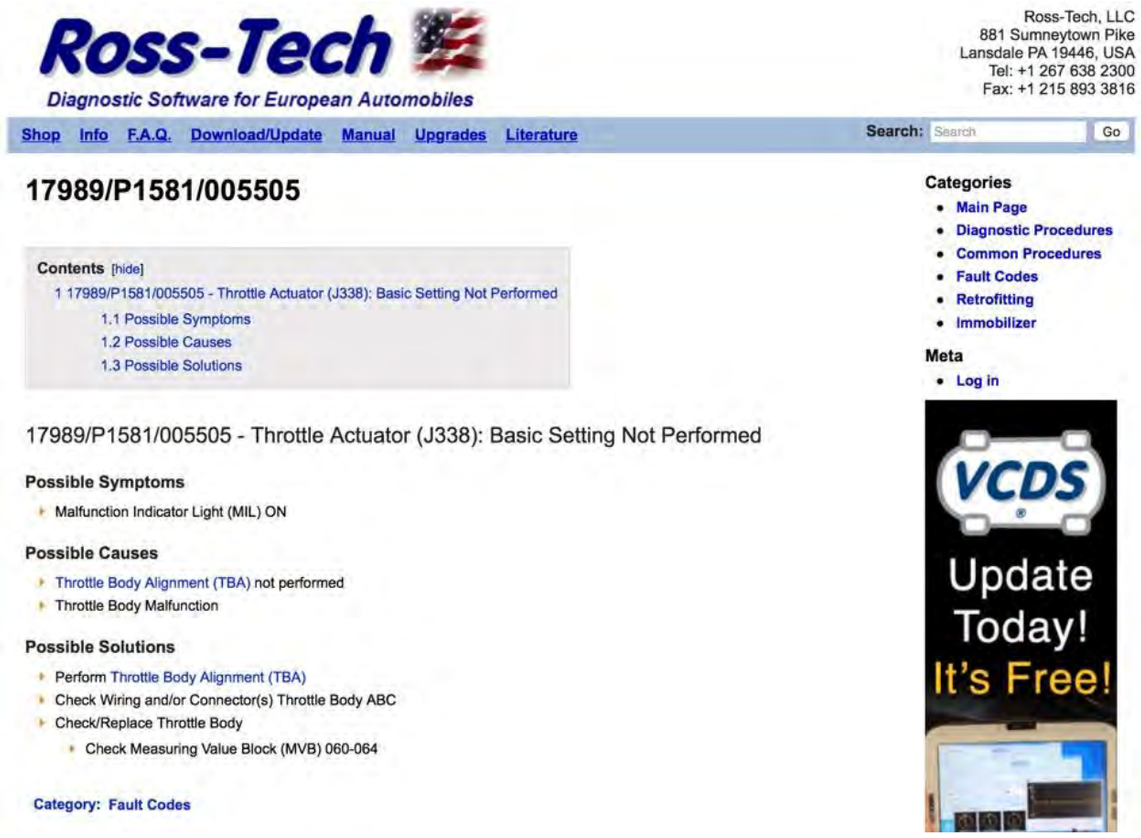
On information and belief, the ECM hardware and software perform the step of "reducing said control effort when said control effort exceeds a threshold for a period."

Figure 31



DTC / Description	Monitor Strategy Description	Malfunction Criteria and Threshold Value	Secondary Parameters with Enable Conditions	Monitoring Time Length	MIL Illumination	Component Diagnostic Procedure
	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 ⇒ 3.6.32 Throttle Valve Control Module GX3 , Checking", page 893 .
	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: • Engine shut-off-time > 5.0 s • ECT 5.0 – 115° C • IAT 5.0 – 143° C	• 0.3 s • Multiple		
P0641 Sensor Reference Voltage "A" Circuit/ Open	Engine Control Module (ECM): Sensor Reference Circuit A Short Circuit	• Signal voltage < 4.8; > 5.2 V		• 0.5 s • Continuous	• 2 DCY	– If a related sensor voltage code is also set, refer to that code for diagnosis. If no other related codes set, replace the Engine Control Module - J623- . Refer to appropriate repair manual.

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http://wiki.ross-tech.com/wiki/index.php/17989/P1581/005505

For example, as shown above, the positioning device, Throttle Valve Control Module J338, is commanded by Engine Control Module (ECM) J623, to change to a commanded position (upper position or lower position) comprising at least one of the commands to the positioning device to open to a hold open mode (upper position) and one of the commands to the positioning device to close to a hold close mode (mechanical stop low).

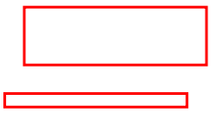
On information and belief, the ECM hardware and software perform the step of "commanding the positioning device to at least one of a hold open mode or a hold close mode."

Figure 32

40. Claim 11 of the '804 patent recites a system for controlling a positioning device of an internal combustion engine to prevent overheat conditions, the system comprising: an electric motor for actuating the positioning device with a control effort; a control effort detector coupled to said electric motor and intended to detect said control effort; and a controller coupled to said electric motor and said control effort detector, said controller including control logic

operative to command the positioning device to change to a commanded position, detect a control effort required to change to said commanded position, determine whether said control effort exceeds a threshold for a predetermined time period, and reduce said control effort when said control effort exceeds said threshold for said predetermined time period; wherein said controller further includes control logic operative to command the positioning device to close to said commanded position in a hold close mode.

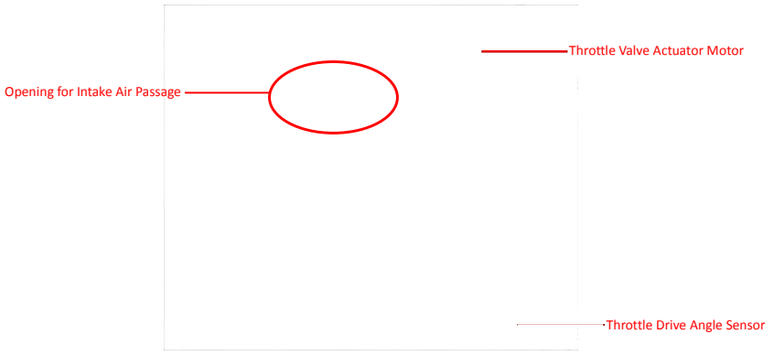
41. On information and belief, the ’804 patent Accused Instrumentalities infringe claim 11 of the ’804 patent. The ’804 patent Accused Instrumentalities comprise a system for controlling a positioning device of an internal combustion engine to prevent overheat conditions (*Figure 33*), the system comprising: an electric motor for actuating the positioning device with a control effort (*Figure 34*); a control effort detector coupled to said electric motor and intended to detect said control effort (*Figure 35*); and a controller coupled to said electric motor and said control effort detector, said controller including control logic operative to command the positioning device to change to a commanded position, detect a control effort required to change to said commanded position, determine whether said control effort exceeds a threshold for a predetermined time period, and reduce said control effort when said control effort exceeds said threshold for said predetermined time period (*Figure 36*); wherein said controller further includes control logic operative to command the positioning device to close to said commanded position in a hold close mode (*Figures 36-37*).



2.3 Electronic Throttle Control (ETC) System

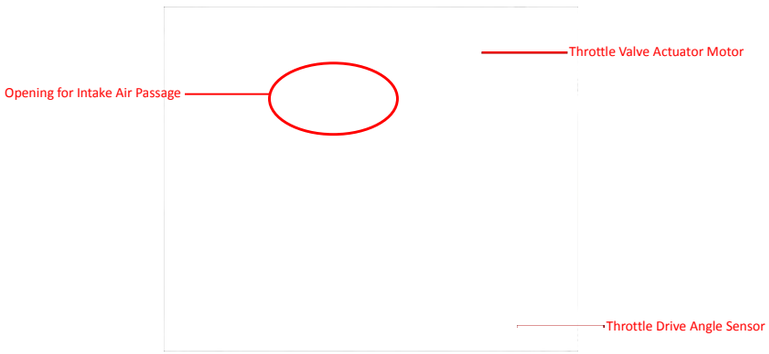
The electronic throttle control (ETC) system consists of the accelerator-pedal module, the engine control module (ECM), and the electronic throttle body. The electronic throttle body mainly consists of the throttle valve, the electric throttle-valve drive element, and the throttle-valve position sensor (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.

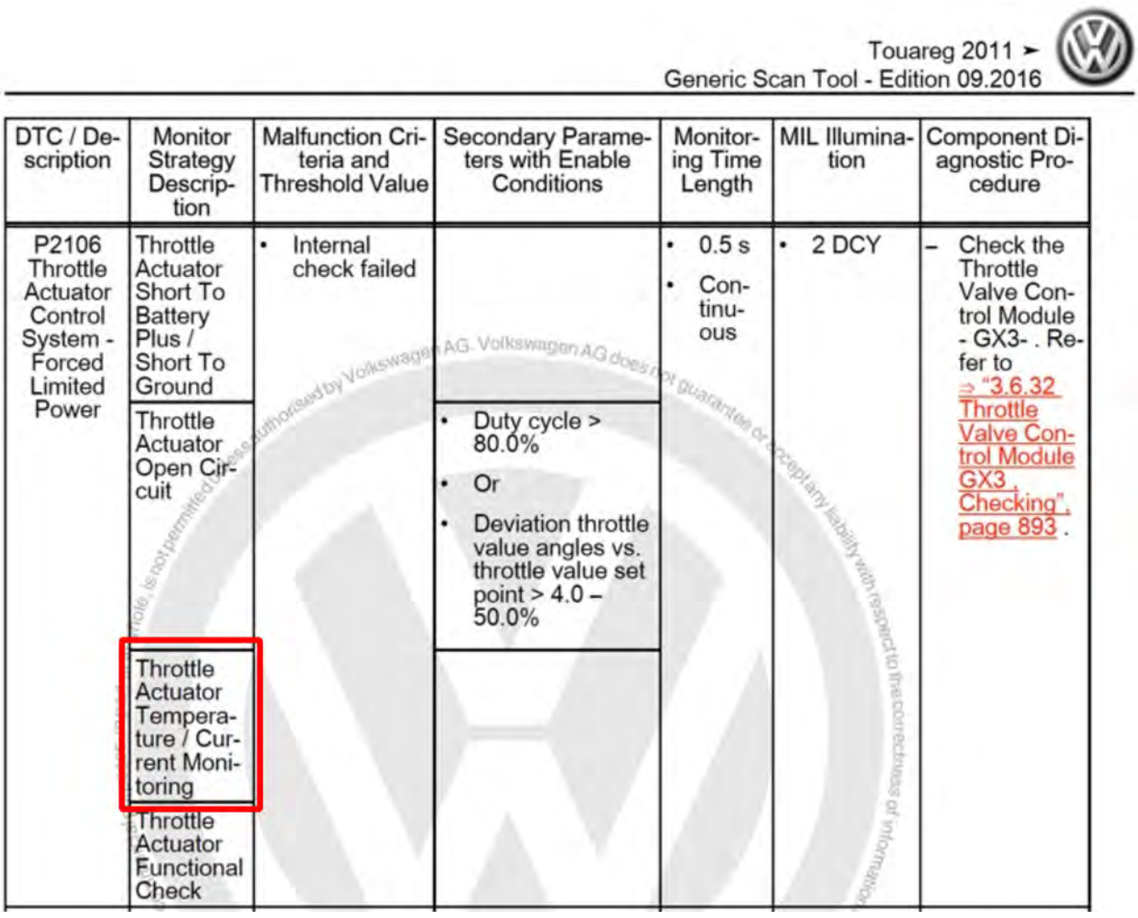
The driver command is detected by a redundant sensor system in the accelerator-pedal module, and the signal is sent to the engine control module. The engine control module then determines the required throttle-valve position by performing calculations from data measured by sensors such as accelerator 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.



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), which comprises a system for controlling a positioning device of an internal combustion engine to prevent overheat condition.

Figure 33





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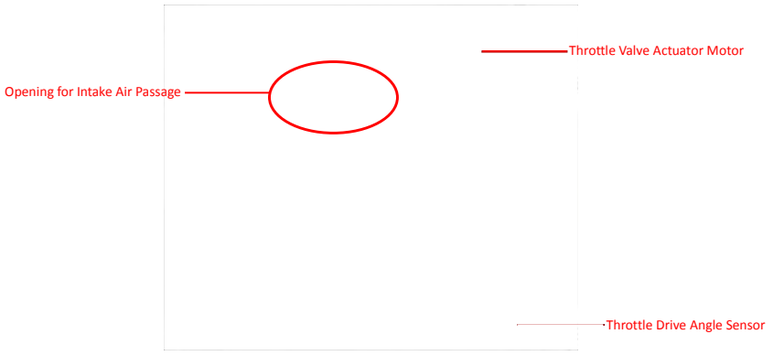
DTC / Description	Monitor Strategy Description	Malfunction Criteria and Threshold Value	Secondary Parameters with Enable Conditions	Monitoring Time Length	MIL Illumination	Component Diagnostic Procedure
P2106 Throttle Actuator Control System - Forced Limited Power	Throttle Actuator Short To Battery Plus / Short To Ground	• Internal check failed		• 0.5 s • Continuous	• 2 DCY	– Check the Throttle Valve Control Module - GX3- . Refer to ⇒ "3.6.32 Throttle Valve Control Module GX3 , Checking", page 893 .
	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					

For example, as shown above, a positioning device, the Throttle Valve Control Module J338 of an internal combustion engine (VW 3.2L & 3.6L), is actuated via a Throttle Valve Actuator Motor with control effort indicated by the amount of current required to actuate the motor.

Figure 34

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 ⇒ "3.6.32 Throttle Valve Control Module GX3 , Checking", page 893 .
	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					

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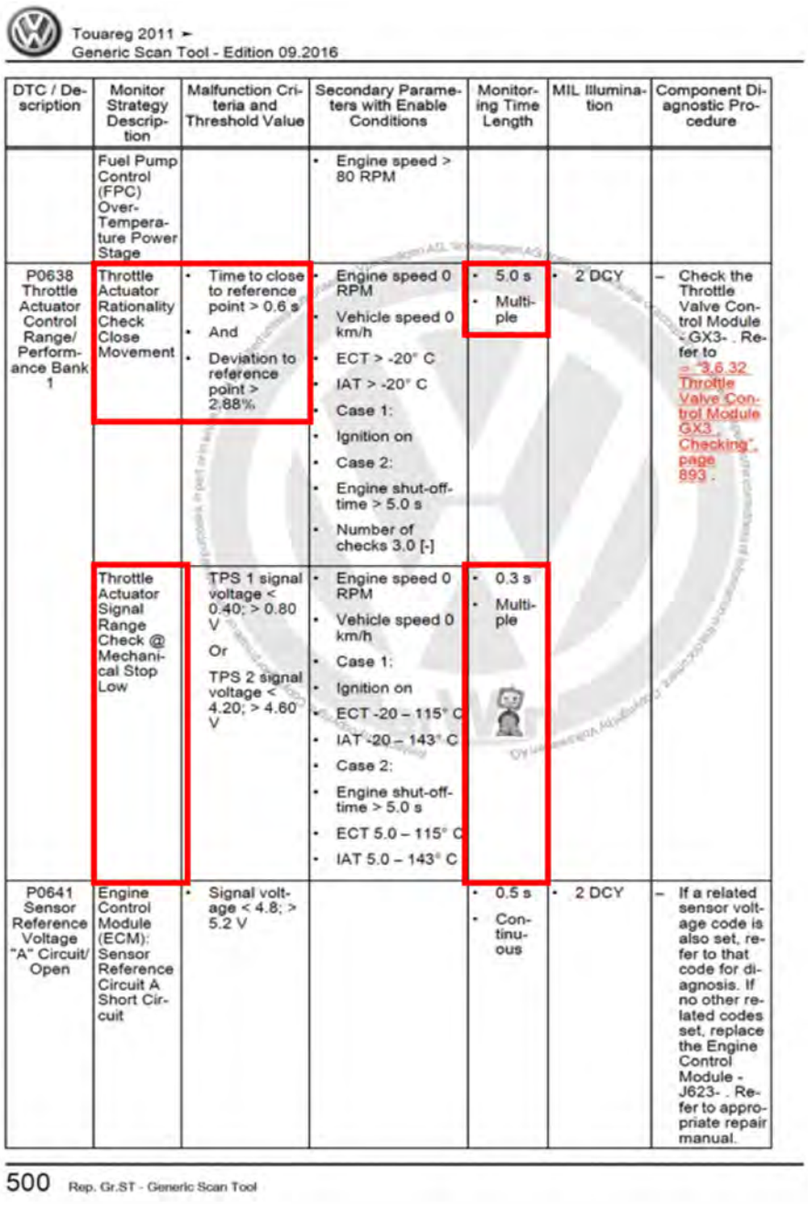


For example, as shown above, a control effort detector in the Engine Control Module (ECM) J623 is coupled to the Throttle Valve Actuator Motor and utilizes a diagnostic strategy (DTC P2106) to detect control effort indicated by the amount of current required to actuate the motor.

Figure 35

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 ⇒ "3.6.32 Throttle Valve Control Module GX3 , Checking", page 893 .
	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					

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DTC / Description	Monitor Strategy Description	Malfunction Criteria and Threshold Value	Secondary Parameters with Enable Conditions	Monitoring Time Length	MIL Illumination	Component Diagnostic Procedure
	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 = "3.6.32 Throttle Valve Control Module GX3 Checking", page 893 .
	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: • Engine shut-off-time > 5.0 s • ECT 5.0 – 115° C • IAT 5.0 – 143° C	• 0.3 s • Multiple		
P0641 Sensor Reference Voltage "A" Circuit/ Open	Engine Control Module (ECM): Sensor Reference Circuit A Short Circuit	• Signal voltage < 4.8; > 5.2 V		• 0.5 s • Continuous	• 2 DCY	– If a related sensor voltage code is also set, refer to that code for diagnosis. If no other related codes set, replace the Engine Control Module - J623- . Refer to appropriate repair manual.

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For example, as shown above, a control effort detector in the Engine Control Module (ECM) J623 is coupled to the Throttle Valve Actuator Motor and includes software-implemented control logic operative to command the positioning device to change to a commanded position (P0638), detect a control effort required to change to said commanded position (P2106), determine whether said control effort exceeds a threshold (Throttle Actuator Temperature/Current Monitoring), continuously monitor which continuously monitors the Throttle Actuator Control System, for a predetermined time period (Time to close to reference point > 0.6 s), and reduce said control effort when said control effort exceeds said threshold for said predetermined time period.

On information and belief, the ECM hardware and software "reduce[s] said control effort when said control effort exceeds said threshold for said predetermined time period."

Figure 36



For example, as shown above (and in Figure 36), the Engine Control Module (ECM) J623 is a controller with control logic to command the positioning device, the Throttle Valve Control Module J338, to close to said commanded position in a hold close mode (P0638).

Figure 37

Based upon the totality of the foregoing evidence, and based further upon information and belief, the '804 patent Accused Instrumentalities practice 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.

COUNT VI – INFRINGEMENT OF U.S. PATENT NO. 6,347,680

42. The allegations set forth in the foregoing paragraphs 1 through 41 are incorporated into this Sixth Claim for Relief.

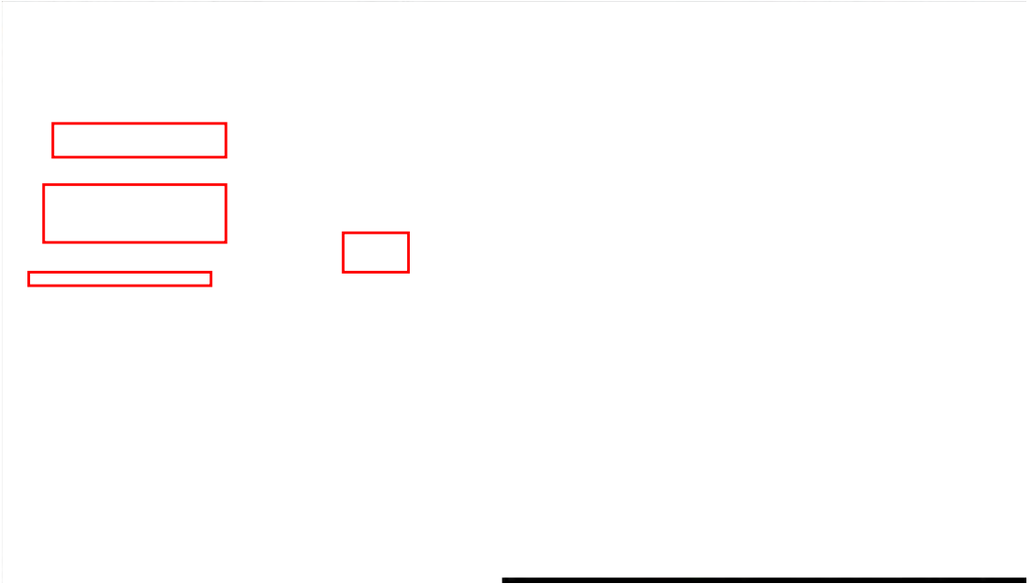
43. On February 19, 2001, U.S. Patent No. 6,347,680 ("the '680 patent"), entitled "Engine Output Controller," was duly and legally issued by the United States Patent and Trademark Office. A true and correct copy of the '680 patent is attached as Exhibit 6.

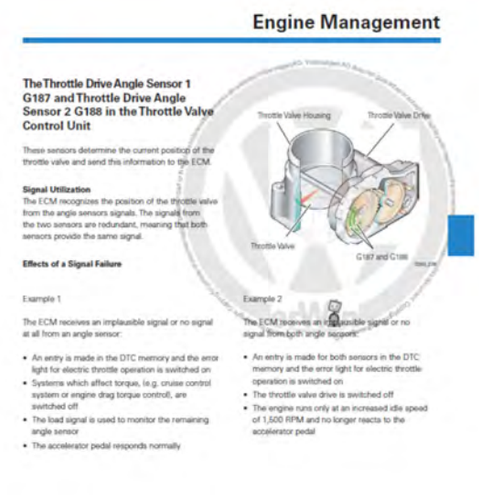
44. Plaintiff is the assignee and owner of the right, title and interest in and to the '680 patent, including the right to assert all causes of action arising under said patents and the right to any remedies for infringement of them.

45. Upon information and belief, Defendants have directly infringed at least claim of the '680 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 "'680 patent Accused Instrumentalities").

46. In particular, claim 1 of the '680 patent recites an engine output control method for a vehicle having a drive by wire engine system responsive to a desired engine speed signal, the method comprising the steps of: generating a driver demanded engine speed value corresponding to an operator input; generating a speed control system engine speed value corresponding to a predetermined speed value to permit vehicle operation at a constant speed by a speed control system; arbitrating between said driver demanded engine speed value and said speed control system engine speed value to derive a first desired engine speed value; limiting said first desired engine speed value by a vehicle speed limit value, engine speed limit value, and transmission speed limit value to generate a second desired engine speed value; and controlling said engine output as a function of said second desired engine speed value and an actual engine speed value.

47. On information and belief, the ’680 patent Accused Instrumentalities infringe at least claim 1 of the ’680 patent. The ’680 patent Accused Instrumentalities practice an engine output control method for a vehicle having a drive by wire engine system responsive to a desired engine speed signal (*Figure 38*), the method comprising the steps of: generating a driver demanded engine speed value corresponding to an operator input (*Figure 39*); generating a speed control system engine speed value corresponding to a predetermined speed value to permit vehicle operation at a constant speed by a speed control system (*Figure 40*); arbitrating between said driver demanded engine speed value and said speed control system engine speed value to derive a first desired engine speed value (*Figure 4*1); limiting said first desired engine speed value by a vehicle speed limit value, engine speed limit value, and transmission speed limit value to generate a second desired engine speed value (*Figure 42*); and controlling said engine output as a function of said second desired engine speed value and an actual engine speed value (*Figures 38-42*).





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

Throttle Valve Housing

Throttle Valve Drive

Throttle Valve

G187 and G188

Example 2

The ECM receives an implausible signal or no signal from both angle sensors:

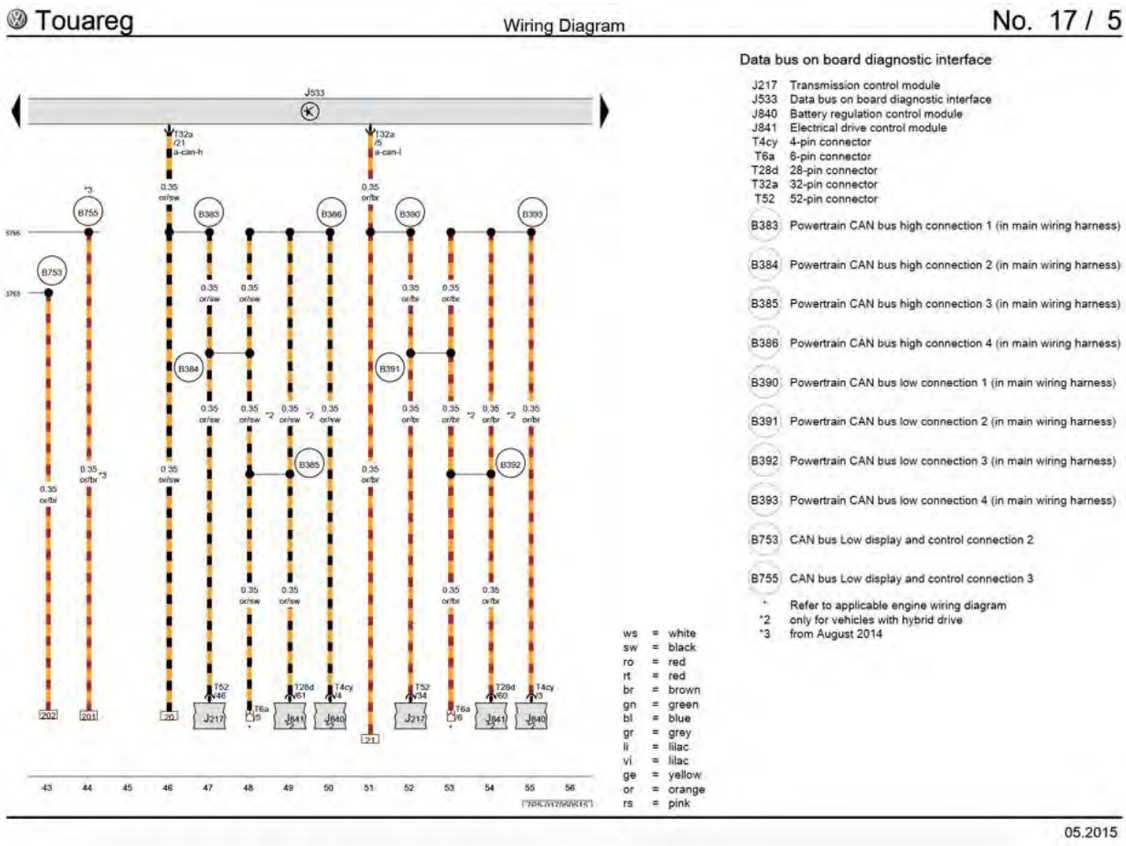
- An entry is made for both sensors in the DTC memory and the error light for electric throttle operation is switched on
- The throttle valve drive is switched off
- The engine runs only at an increased idle speed of 1,500 RPM and no longer reacts to the accelerator pedal

The CAN data bus and the ECM (J623), TCM (J217), ABS System (J104) (controllers) practice an engine output control method.

3.6.32 Vehicle Speed Signal, Checking

General Description

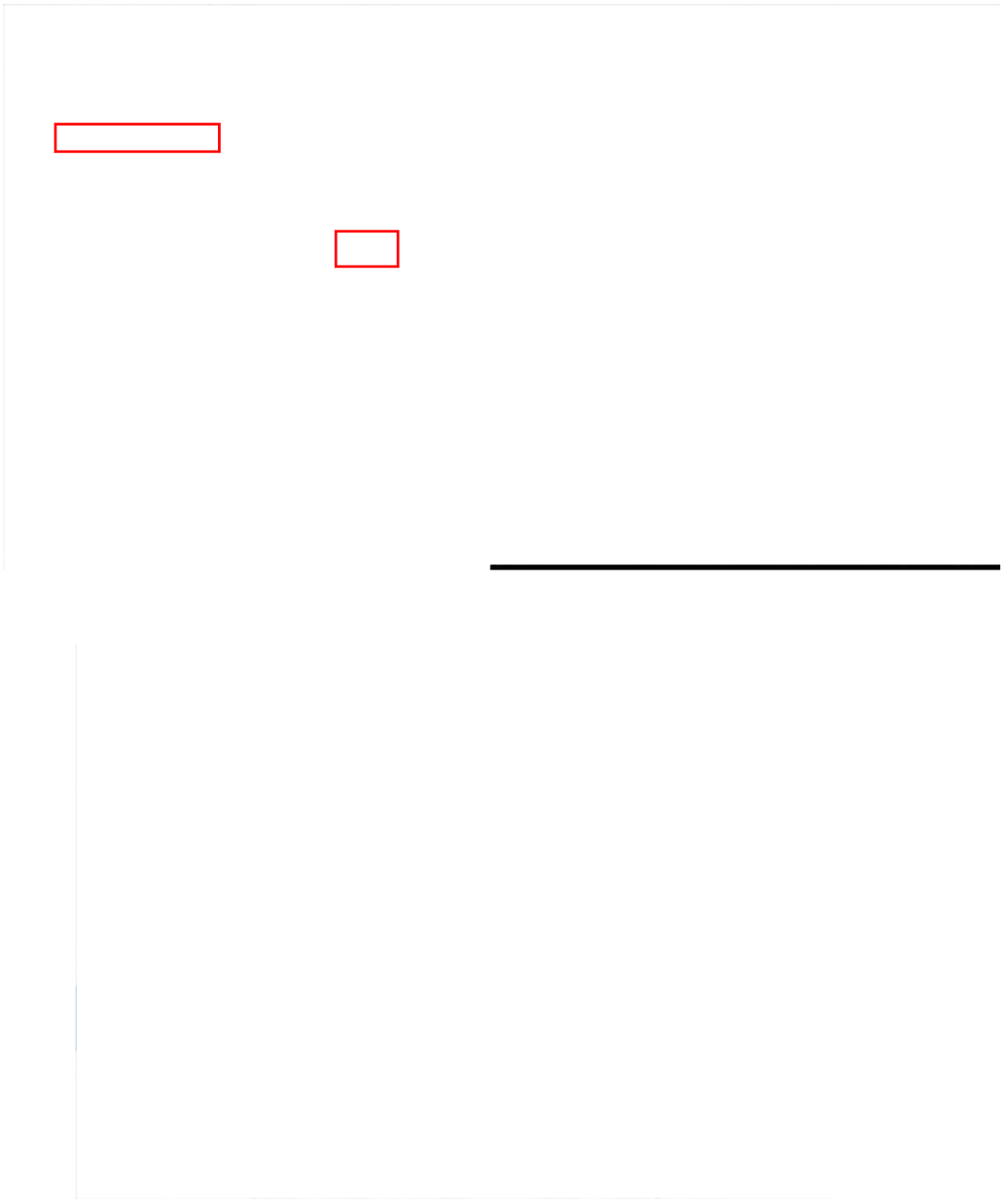
The Vehicle Speed Signal or VSS measures Transmission / Transaxle output or Wheel Speed from the ABS System. The signal is broadcasted over the CAN Bus. The Engine Control Module - J623- uses this information to modify engine functions such as ignition timing, A/F ratio, transmission shift points, and to initiate diagnostic routines.

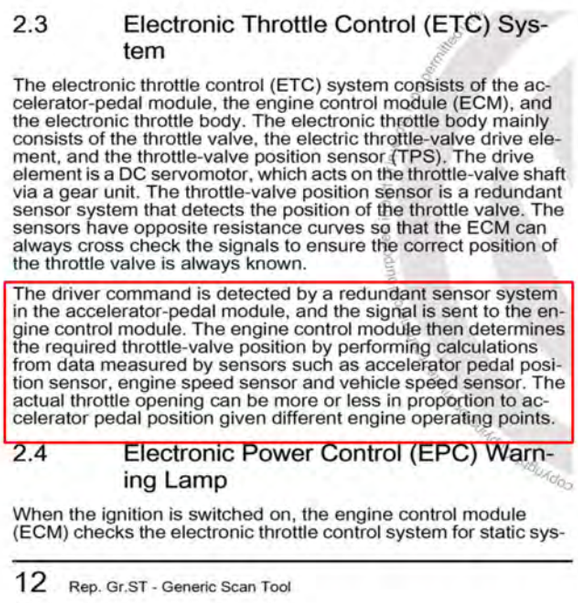


The ’680 patent Accused Instrumentalities comprise a CAN (Controller Area Network) which allows microcontrollers like the Engine Control Module (ECM) J623, Transmission Control Module (TCM), and Antilock Brake System/Electronic Stability Control (ABS/ESC) to communicate with each other.

For example, as shown above, the drive by wire system comprises the Accelerator Pedal Position Sensor 2 G185, Throttle Valve Control Module J338, and other components, and is controlled by the ECM J623.

Figure 38





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.

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 sys-

12 Rep. Gr.ST - Generic Scan Tool

The ’680 patent Accused Instrumentalities comprise an ECM (J623), which generates a driver demanded engine speed value corresponding to operator input from the Accelerator Pedal Position Sensor 2 (G185).

Figure 39



2015 Volkswagen Touareg (7P5) V6-3.6L (CGRA)
Vehicle » Cruise Control » Description and Operation » Adaptive Cruise Control

ADAPTIVE CRUISE CONTROL

General Information

General Description

Adaptive Cruise Control (ACC) is a cruise control system with distance regulation that influences driving behavior with both active acceleration and deceleration.

The 2010 Touareg has an improved ACC system. The ACC with Front Assist is also known as "Stop and Go". In addition to the current ACC features, the vehicle will resume driving 2 seconds after it has stopped.

Using ACC, any desired speed between 0 km/h and 210 km/h (130.48 mph) can be maintained. In addition, ACC maintains a pre-set time distance to the vehicle ahead.

With active brake intervention, the vehicle can brake to a stop. System-specified thresholds are set and driver intervention is prompted with optical and acoustic warnings when necessary.

The driver assistance system is activated using the front button in the turn signal lever and a selection display in the instrument cluster display. ACC is operated using the multifunction steering wheel buttons or, on vehicles without multifunction steering wheel, using the front rocker switch in the windshield wiper lever. While driving, important information is shown in the instrument cluster display.

Malfunction Recognition And Malfunction Indicator

Distance Regulation Control Module (J428) is equipped with On Board Diagnostics (OBD) which assists troubleshooting.

The "Guided Fault Finding" function is to be used for troubleshooting of one of the systems described as in chapter "Vehicle Diagnosis, Testing and Information System".

Start the ACC when first using the or replacing the Distance Regulation Control Module (J428). Refer to (Automatic Distance Regulation, Initializing | See: Testing and Inspection/Automatic Distance Regulation, Initializing.

Automatic Distance Regulation, Adapting

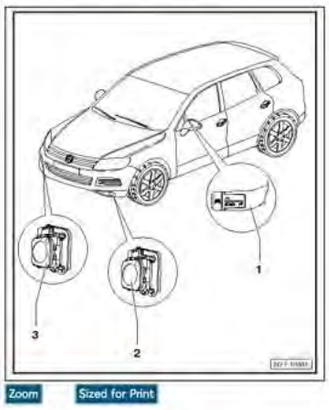
- Distance Regulation Control Module (J428)
- Distance Regulation Control Module 2 (J850)
- Adaptive Cruise Control Button (E337) inside the turn signal switch
- image Processing Control Module (J851). Refer to [Image Processing Control Module (J851) | See: Accessories and Optional Equipment/Collision Avoidance Module/Description and Operation/Image Processing Control Module (J851)
- Depending on equipment, for adjusting ACC, the multifunction steering wheel buttons or
- The front rocker switch on the windshield wiper lever

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2015 Volkswagen Touareg (7P5) V6-3.6L (CGRA)
Vehicle » Cruise Control » Service and Repair

SERVICE AND REPAIR

Overview - Adaptive Cruise Control (ACC)



Zoom Sized for Print

1 - Adaptive Cruise Control Button (E357)

The Adaptive Cruise Control Button (E357) is a component in the turn signal switch on the steering column.

Turn signal switch on steering column, removing and installing. Refer to [Steering Column Switch Module] See: Accessories and Optional Equipment\Steering Mounted Controls Communication Module\Description and Operation:

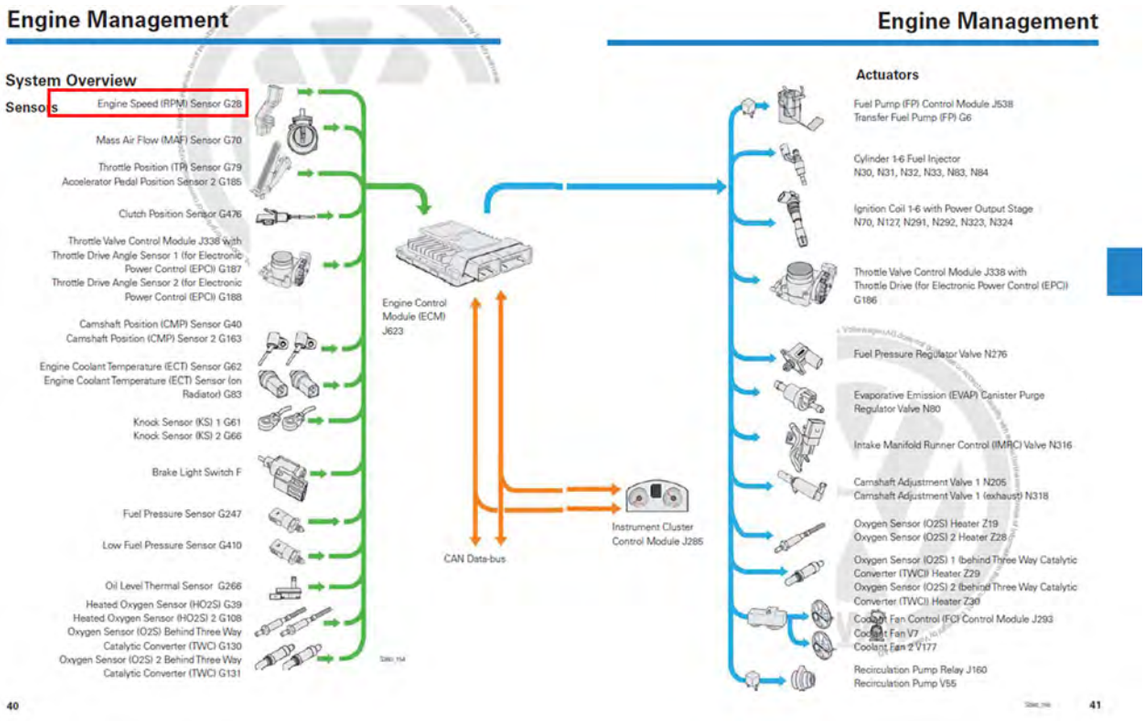
2 - Distance Regulation Control Module 2 (J850)

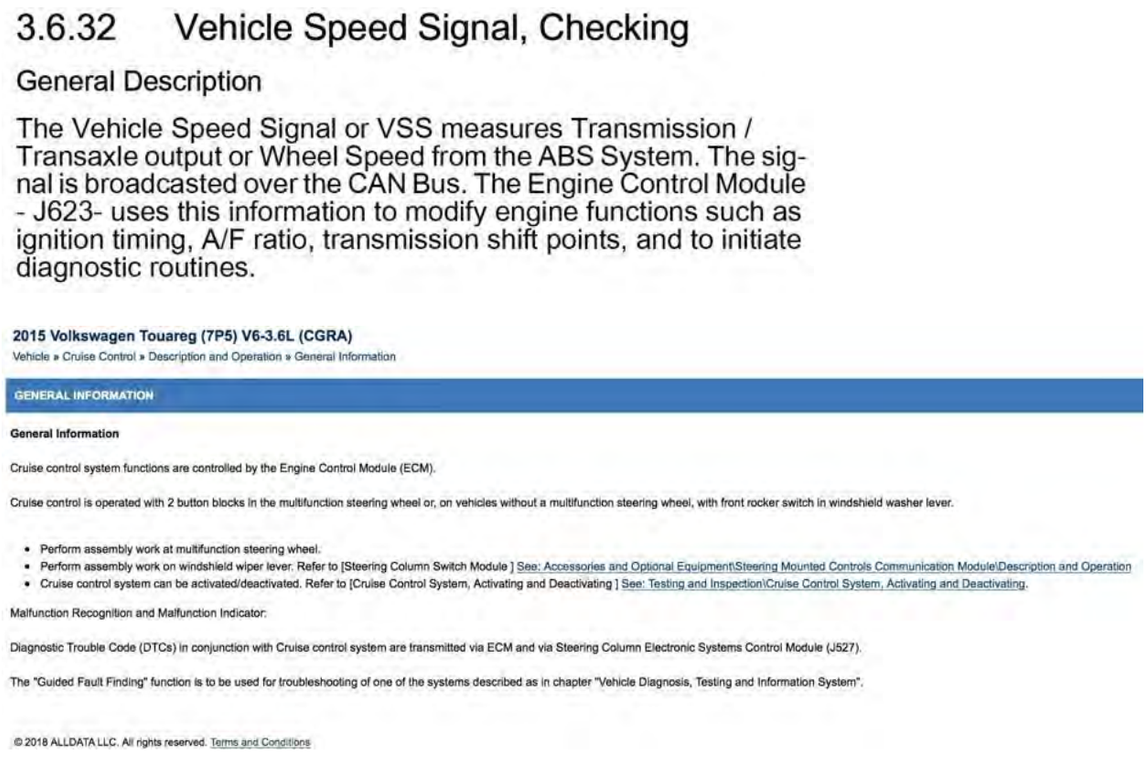
- Contains Adaptive Cruise Control Sensor 2
- Removing and installing. Refer to [Distance Regulation Control Module (J428), Removing and Installing] See: Cruise Control Module\Description and Operation\Distance Regulation Control Module (J428), Removing and Installing

3 - Distance Regulation Control Module (J428)

- Contains Adaptive Cruise Control Sensor (G550)
- Removing and installing. Refer to [Distance Regulation Control Module (J428)] See: Cruise Control Module\Description and Operation

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3.6.32 Vehicle Speed Signal, Checking

General Description

The Vehicle Speed Signal or VSS measures Transmission / Transaxle output or Wheel Speed from the ABS System. The signal is broadcasted over the CAN Bus. The Engine Control Module - J623- uses this information to modify engine functions such as ignition timing, A/F ratio, transmission shift points, and to initiate diagnostic routines.

2015 Volkswagen Touareg (7P5) V6-3.6L (CGRA)

Vehicle » Cruise Control » Description and Operation » General Information

GENERAL INFORMATION

General Information

Cruise control system functions are controlled by the Engine Control Module (ECM).

Cruise control is operated with 2 button blocks in the multifunction steering wheel or, on vehicles without a multifunction steering wheel, with front rocker switch in windshield washer lever.

- Perform assembly work at multifunction steering wheel.
- Perform assembly work on windshield wiper lever. Refer to [Steering Column Switch Module] See: Accessories and Optional Equipment\Steering Mounted Controls Communication Module\Description and Operation
- Cruise control system can be activated/deactivated. Refer to [Cruise Control System, Activating and Deactivating] See: Testing and Inspection\Cruise Control System, Activating and Deactivating.

Malfunction Recognition and Malfunction Indicator:

Diagnostic Trouble Code (DTCs) in conjunction with Cruise control system are transmitted via ECM and via Steering Column Electronic Systems Control Module (J527).

The "Guided Fault Finding" function is to be used for troubleshooting of one of the systems described as in chapter "Vehicle Diagnosis, Testing and Information System".

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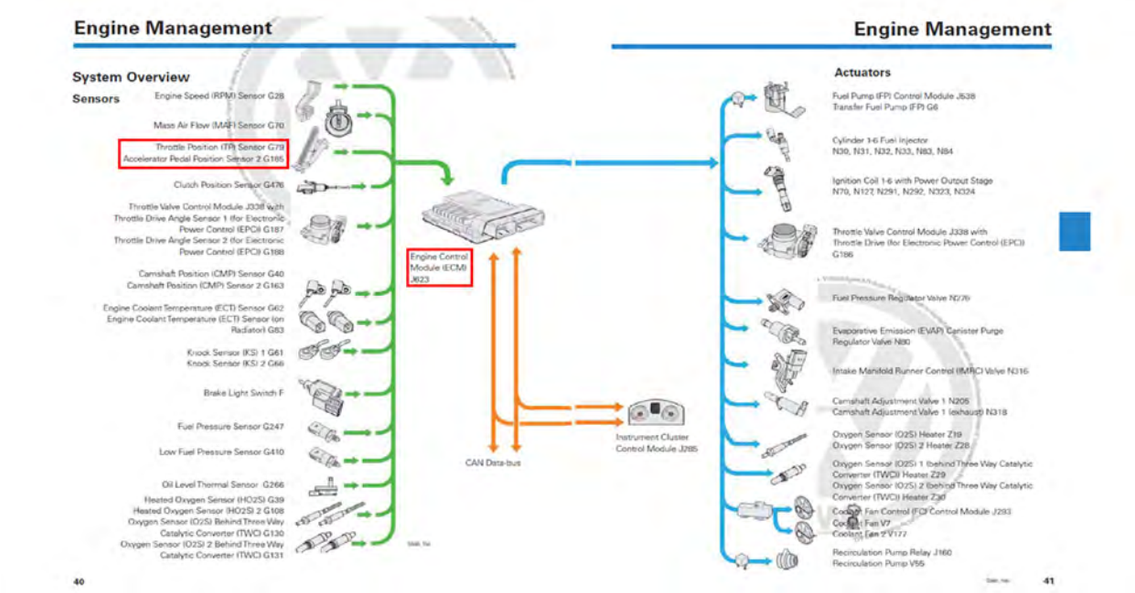
For example, as shown above, the adaptive cruise control (ACC) is a cruise control system with speed regulation that influences driving behavior with both active acceleration and deceleration. Upon information and belief, using ACC, any desired speed between 0 km/hr and 210 km/hr can be maintained. System-specified thresholds are set during operation of the ACC; the ECM (J623) generates an engine speed value to maintain vehicle operation at a constant speed based on the predetermined speed value from the set/coast switch of the cruise control system.

Figure 40

2.5 Engine Control Module (ECM)

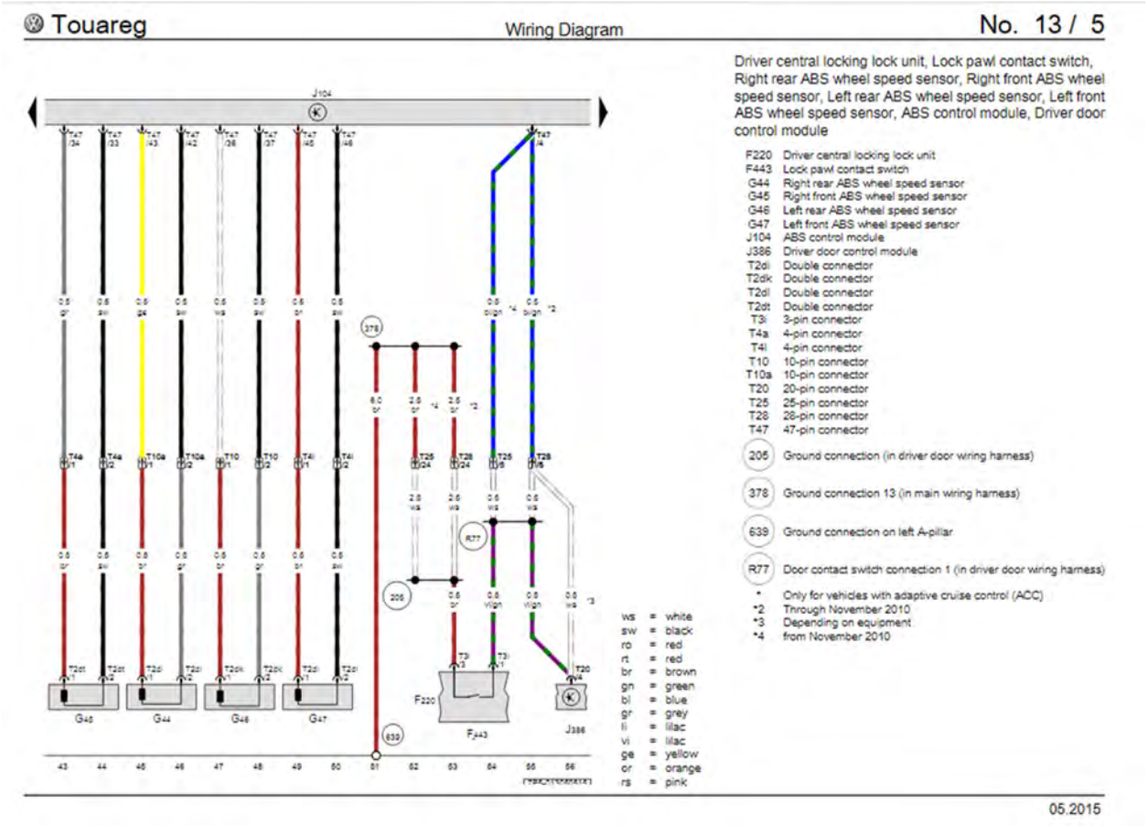
The Engine Control Module (ECM) is a generic term for any embedded system that controls one or more of the electrical systems or subsystems in a vehicle. It controls a series of actuators on an internal combustion engine to ensure that driver commands (e.g. to accelerate) are translated into appropriate engine performance. It reads values from a multitude of sensors, interprets the data, and adjusts the engine actuators accordingly. The ECM also interacts with the transmission control module (TCM), ABS/traction/stability control module and other vehicle function related control systems.

ECM controlled systems and functions (performance and emission related) will be introduced in the following chapters. These include the OBD system, controller area network (CAN), throttle control module, fuel supply, ignition, variable valve timing, exhaust-gas recirculation, secondary air injection, exhaust system, and EVAP system.



Upon information and belief, the ECM (J623) receives signals from sensors. Accelerator Pedal Position Sensor 2 (G185), which determine the driver demanded engine speed value. The speed control system engine speed value is determined by the ECM based upon the set speed of the cruise control. The engine management system (a drive by wire system) arbitrates between the driver demanded engine speed value and said speed control system engine speed value to derive a first desired engine speed value.

Figure 41



Upon information and belief, the first desired engine speed value limited by an engine speed limit value determined by the ECM based on various monitored conditions (e.g. road conditions; driving conditions).


2015 Volkswagen Touareg (7P5) V6-3.6L (CGRA)
Vehicle » Cruise Control » Description and Operation » Adaptive Cruise Control

ADAPTIVE CRUISE CONTROL

General Information

General Description

Adaptive Cruise Control (ACC) is a cruise control system with distance regulation that influences driving behavior with both active acceleration and deceleration

The 2010 Touareg has an improved ACC system. The ACC with Front Assist is also known as "Stop and Go". In addition to the current ACC features, the vehicle will resume driving 2 seconds after it has stopped.

Using ACC, any desired speed between 0 km/h and 210 km/h (130.48 mph) can be maintained. In addition, ACC maintains a pre-set time distance to the vehicle ahead.

With active brake intervention, the vehicle can brake to a stop. System-specified thresholds are set and driver intervention is prompted with optical and acoustic warnings when necessary.

The driver assistance system is activated using the front button in the turn signal level and a selection display in the instrument cluster display. ACC is operated using the multifunction steering wheel buttons or, on vehicles without multifunction steering wheel, using the front rocker switch in the windshield wiper lever. While driving, important information is shown in the instrument cluster display.

Malfunction Recognition And Malfunction Indicator

Distance Regulation Control Module (J428) is equipped with On Board Diagnostics (OBD) which assists troubleshooting.

The "Guided Fault Finding" function is to be used for troubleshooting of one of the systems described as in chapter "Vehicle Diagnosis, Testing and Information System".

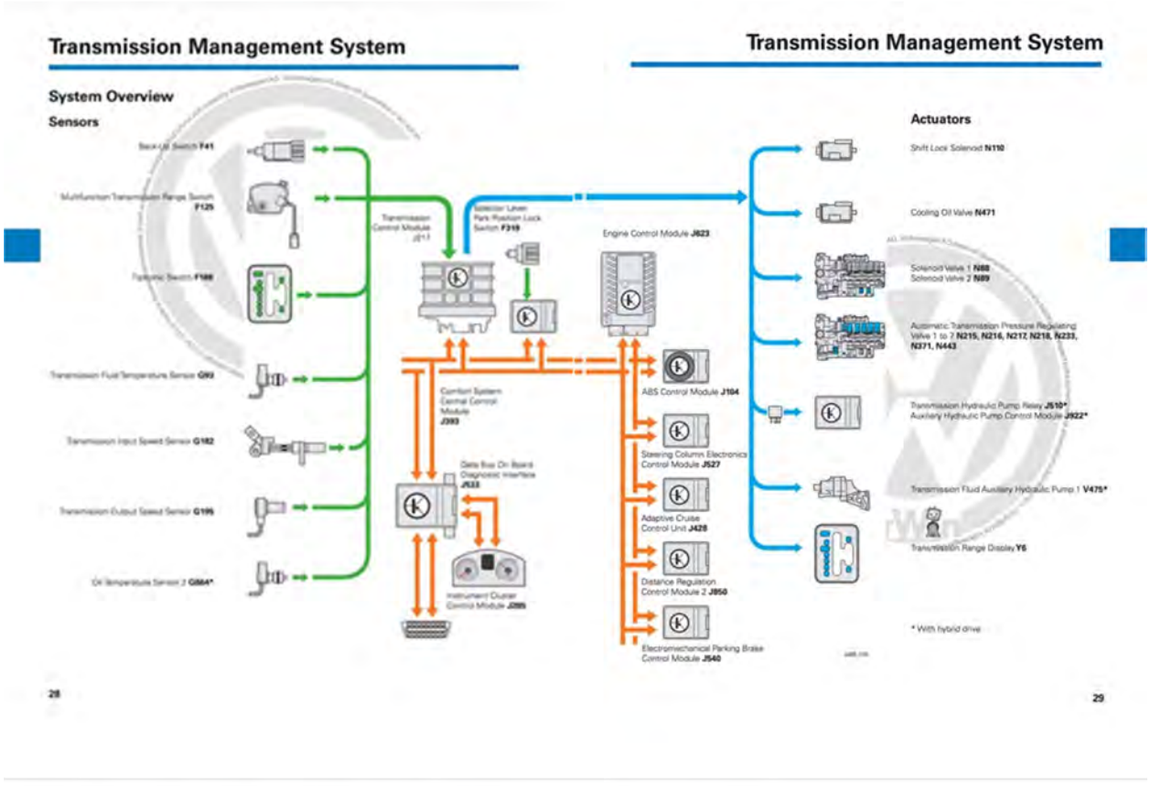
Start the ACC when first using the or replacing the Distance Regulation Control Module (J428). Refer to [Automatic Distance Regulation, Initializing] See: Testing and Inspection/Automatic Distance Regulation, Initializing

Automatic Distance Regulation, Adapting

- Distance Regulation Control Module (J428)
- Distance Regulation Control Module 2 (J860)
- Adaptive Cruise Control Button (E537) inside the turn signal switch
- Image Processing Control Module (J851). Refer to [Image Processing Control Module (J851)] See: Accessories and Optional Equipment/Collision Avoidance Module/Description and Operation/Image Processing Control Module (J851)
- Depending on equipment, for adjusting ACC, the multifunction steering wheel buttons or
- The front rocker switch on the windshield wiper lever

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Upon information and belief, the first desired engine speed value is further limited by a transmission speed limit value based on transmission torque capacity limits which is monitored by the Transmission Control Module (J217).



Transmission Management System

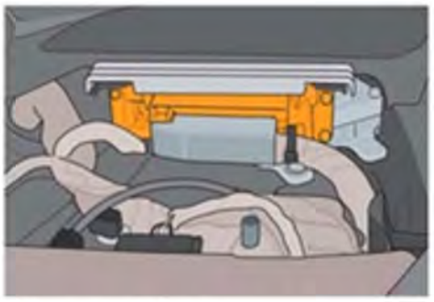
The Transmission Control Module J217

The Transmission Control Module J217 is located under the right front seat. It is connected to the gateway via the powertrain CAN - bus.

J217 receives information from the sensors inside of the transmission and actuates the solenoid valves in the valve body.

If equipped with the Transmission Fluid Auxiliary Hydraulic Pump 1 V475, the Oil Temperature Sensor 2 G664 transmits the operating temperature of the pump.

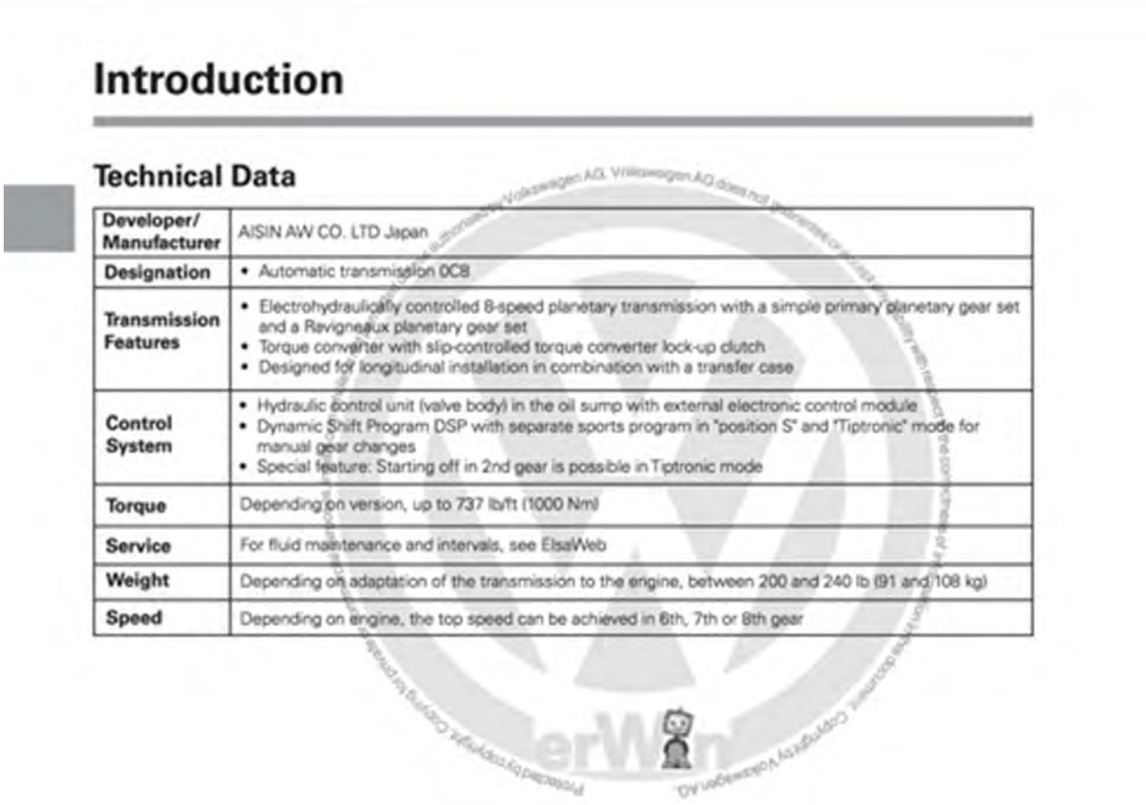
The dynamic shift program is also integrated into J217. It selects gear changes based on the operating status (aerodynamic drag and rolling resistance and driving style).



J217 under the right front seat

Upon information and belief, the first desired engine speed value is limited by a vehicle speed limit value, engine speed limit value, and transmission speed limit value to generate a second

desired engine speed value which is generated when a lower engine speed value is desired due to various system capacities or limits as shown above (e.g. transmission torque capacity below).



Introduction

Technical Data

Developer/ Manufacturer	AISIN AW CO. LTD Japan
Designation	• Automatic transmission 0C8
Transmission Features	• Electrohydraulically controlled 8-speed planetary transmission with a simple primary planetary gear set and a Ravigneaux planetary gear set • Torque converter with slip-controlled torque converter lock-up clutch • Designed for longitudinal installation in combination with a transfer case
Control System	• Hydraulic control unit (valve body) in the oil sump with external electronic control module • Dynamic Shift Program DSP with separate sports program in "position S" and "Tiptronic" mode for manual gear changes • Special feature: Starting off in 2nd gear is possible in Tiptronic mode
Torque	Depending on version, up to 737 lbft (1000 Nm)
Service	For fluid maintenance and intervals, see ElsaWeb
Weight	Depending on adaptation of the transmission to the engine, between 200 and 240 lb (91 and 108 kg)
Speed	Depending on engine, the top speed can be achieved in 6th, 7th or 8th gear

As stated above, the first desired engine speed value is determined via the ECM (J623).

Upon information and belief, the first desired engine speed value is limited by a vehicle speed limit value which is generated from the ABS control module (J104) based on conditions such as wheel slippage from the wheel speed sensors (J44-47) communicated via the CAN data-bus (shown above).

For example, as shown above the CAN Data bus and ECM (J623) control the drive by wire system by calculating engine output as a function of said second desired engine speed value and an actual speed value. Necessarily, the second desired speed value must be reconciled with the actual engine speed value, thereby controlling the commanded throttle position and resultant engine output.

Figure 42

Based upon the totality of the foregoing evidence, and based further upon information and belief, the ’680 patent Accused Instrumentalities practice “an engine output control method for a vehicle having a drive by wire engine system responsive to a desired engine speed signal, the method comprising the steps of: generating a driver demanded engine speed value corresponding to an operator input; generating a speed control system engine speed value corresponding to a

predetermined speed value to permit vehicle operation at a constant speed by a speed control system; arbitrating between said driver demanded engine speed value and said speed control system engine speed value to derive a first desired engine speed value; limiting said first desired engine speed value by a vehicle speed limit value, engine speed limit value, and transmission speed limit value to generate a second desired engine speed value; and controlling said engine output as a function of said second desired engine speed value and an actual engine speed value."

COUNT VII – INFRINGEMENT OF U.S. PATENT NO. 6,561,166

48. The allegations set forth in the foregoing paragraphs 1 through 47 are incorporated into this Seventh Claim for Relief.

49. On May 13, 2003, U.S. Patent No. 6,561,166 ("the '166 patent"), entitled "Purge Fuel Canister Measurement Method and System," was duly and legally issued by the United States Patent and Trademark Office. A true and correct copy of the '166 patent is attached as Exhibit 7.

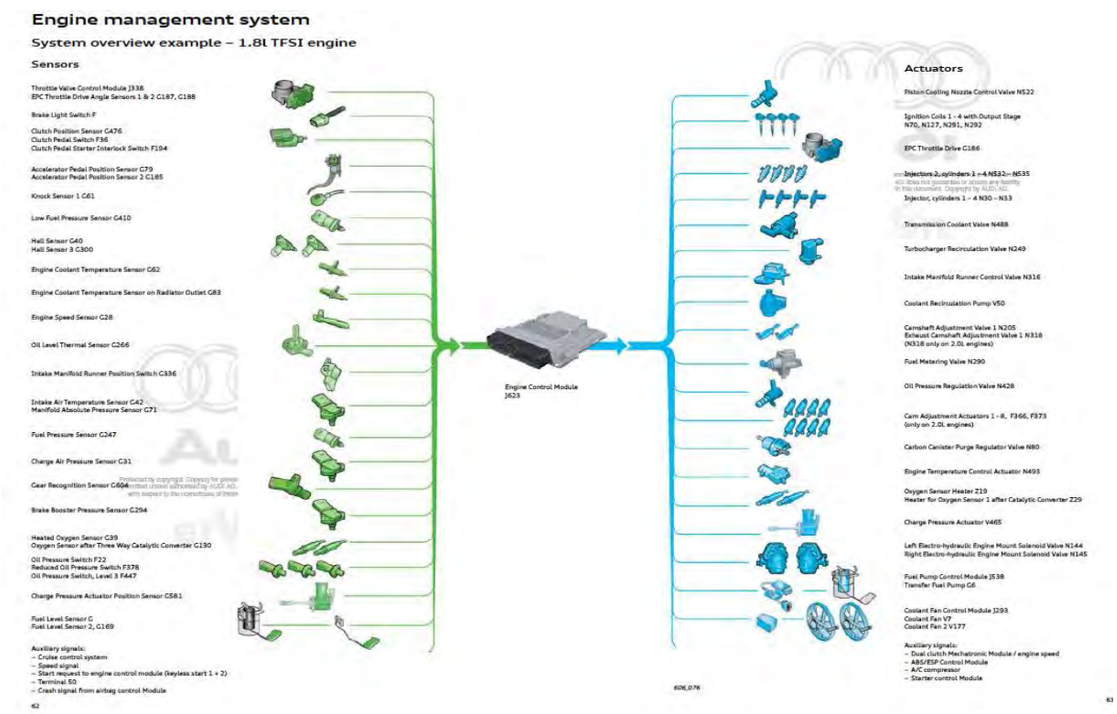
50. Plaintiff is the assignee and owner of the right, title and interest in and to the '166 patent, including the right to assert all causes of action arising under said patents and the right to any remedies for infringement of them.

51. Upon information and belief, Defendants have directly infringed at least claim1 of the '166 patent by making, using, selling, importing and/or providing and causing to be used the 2012-2018 Tiguan, 2012-2018 Audi A3, 2012-2018 Audi A4, 2012-2018 Audi A5, 2012-2018 Audi A6, 2016-2018 Audi TT, 2015-2018 Audi S3, 2015-2018 VW Golf, 2012-2018 VW Golf GTI, 2015-2018 VW Golf R, 2015-2018 Golf Sportwagon, 2013-2018 Jetta GLI, 2014-2018 VW Jetta Sedan, 2014-2018 VW Passat, 2012-2017 WV CC, 2012-2018 VW Beetle, 2018 VW Atlas, 2015- 2018 Audi Q3, 2012-2018 Audi Q5, and 2017-2018 Porsche Macan with the EA888 engines (the "'166 patent Accused Instrumentalities").

52. In particular, claim 1 of the '166 patent recites a method of controlling a direct injection spark ignited internal combustion engine that is capable of operating in a stratified mode where fuel is injected during a compression stroke of the engine and a homogeneous mode

where fuels is injected during an intake stroke of the engine, the internal combustion engine having a catalytic converter and an NOx trap, comprising: measuring a first temperature of an NOx trap that is in contact with an exhaust gas exhausted from a combustion chamber while the engine is operating in the stratified mode; enabling evaporated fuel vapors to enter the combustion chamber at a flow rate while the engine is operating in the stratified mode; measuring a second temperature of the NOx trap while the engine is operating in the stratified mode; and adjusting the flow rate of the evaporated fuel vapors as a function of the second temperature when the second temperature is within a lower temperature threshold and an upper temperature threshold.

53. On information and belief, the ’166 patent Accused Instrumentalities infringe at least claim 1 of the ’166 patent. The ’166 patent Accused Instrumentalities practice a method of controlling a direct injection spark ignited internal combustion engine (*Figure 43*) that is capable of operating in a stratified mode (*Figure 44*) where fuel is injected during a compression stroke of the engine (*Figure 45*) and a homogeneous mode where fuels is injected during an intake stroke of the engine, the internal combustion engine having a catalytic converter (*Figure 46*) and an NOx trap (*Figure 47*), comprising: measuring a first temperature of an NOx trap that is in contact with an exhaust gas exhausted from a combustion chamber while the engine is operating in the stratified mode (*Figures 48*); enabling evaporated fuel vapors to enter the combustion chamber at a flow rate while the engine is operating in the stratified mode (*Figure 49*); measuring a second temperature of the NOx trap while the engine is operating in the stratified mode (*Figure 50*); and adjusting the flow rate of the evaporated fuel vapors as a function of the second temperature when the second temperature is within a lower temperature threshold and an upper temperature threshold (*Figure 51*).



As shown above, the Engine Management System including the Engine Control Module (ECM; J623) controls the Audi 1.8L and 2.0L Third Generation EA888 Engines (direct injection spark ignited internal combustion engine). The '166 patent Accused Instrumentalities comprise the Audi 1.8L and 2.0L Third Generation EA888 Engines.

Figure 43

Direct Injection

Injectors in directly injected (DI) engines are mounted on the cylinder head and fuel is injected directly into the engine's combustion chamber. In order to overcome the pressure in the combustion chamber during compression and power stroke, injectors often operate at a primary pressure as high as 3000 psi. At such extreme pressure level, no single fuel pump can supply the required pressure directly from the fuel tank to the injectors. Instead, a low-pressure and a high-pressure system are employed. The low-pressure system principally utilizes the same fuel systems and components for multiport injected engines. The high-pressure system consists of a high-pressure fuel pump driven directly by the camshaft, a fuel rail (high-pressure accumulator), a high-pressure sensor and, depending on the system, a pressure-control valve or a pressure limiter. The injectors are operated by the ECM to send a precise amount of fuel from the high-pressure rail directly into the combustion chamber.

The distinctive difference between direct injection and other injection methods is that direct injection offers the flexibility regarding when in the combustion cycle the fuel is added and how. MPI systems can only add fuel during induction; A DI system can add fuel whenever it needs to. For example, fuel can be added during induction to create a homogeneous charge then added again after ignition to enhance power delivery under full load conditions.

VW/Audi Fuel Stratified Injection (FSI)

The goal of a stratified-charge operation is to form an ignitable mixture near the spark plug at the instant of ignition. This means that, instead of supplying the corresponding stoichiometric fuel quantity to the amount of air in the combustion chamber, the fuel interacts only with a portion of the air before it is conveyed to the spark plug. The rest of the fresh air surrounds the stratified charge allowing an ultra-lean condition with air-fuel ratio exceeding 50:1 in some instances. As less fuel is used to "burn" more air, stratified injection helps to further reduce fuel consumption when the engine is operating in low-load conditions (e.g. highway cruising). This is created by designing the combustion chamber so that a "swirling" effect of the air-fuel charge is caused.

2.9 Ignition and Timing

Ignition

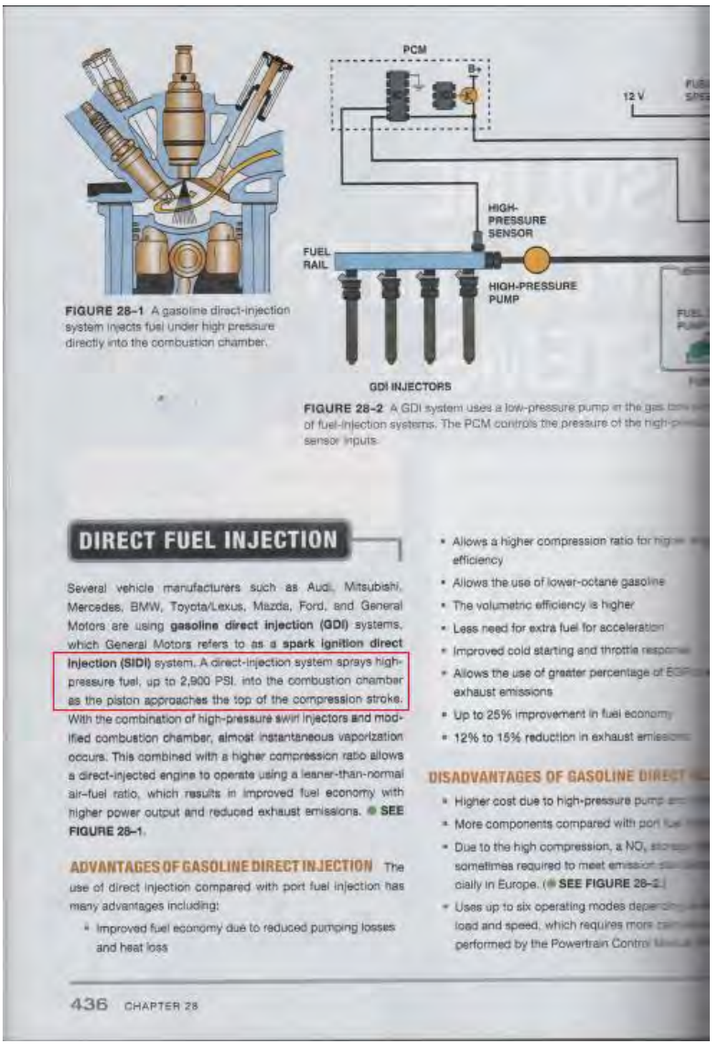
A spark ignition (SI) engine requires a spark to initiate combustion in the combustion chamber. Voltage is supplied to the spark plug where the electricity will arc across a gap at a voltage as high as 100 kilovolts. The ECM determines the precise moment to fire each spark plug using ignition logic which is pre-programmed into the ECM as a function of engine speed and load. An optimally calibrated ignition system ensures consistent and reliable ignition under all conditions. Knock or misfire as a result of incorrect ignition can lead to destruction of engine components or damage of the catalytic converter.

Timing

Shifts in the moment of ignition (ignition timing) can result in increased emissions, decreased performance and fuel economy. Whereas more spark advance improves power and fuel economy, it also raises HC and NOx emissions. Excessive spark advance can cause engine knock which is potentially destructive to engines. If the ECM detects knock from a signal sent by a knock sensor, it will delay (retard) the timing of the spark. Excessive spark retard lowers power output and produces high exhaust temperatures, which can also harm the engine. Carefully designed ignition logic provides optimum timing that best balances performance, fuel economy and emissions.

As shown above, the 1.8L and 2.0L TFSI engines are capable of operating in the stratified mode.

Figure 44



James D Halderman, *Automotive Engine Performance* 436 (5 ed. 2017)

For example, as suggested by the image above, the ’166 patent Accused Instrumentalities inject fuel during the compression stroke as is common in a Gasoline Direct Injection (GDI) systems. The Audi 1.8L & 2.0L engines are a GDI engine.

Figure 45

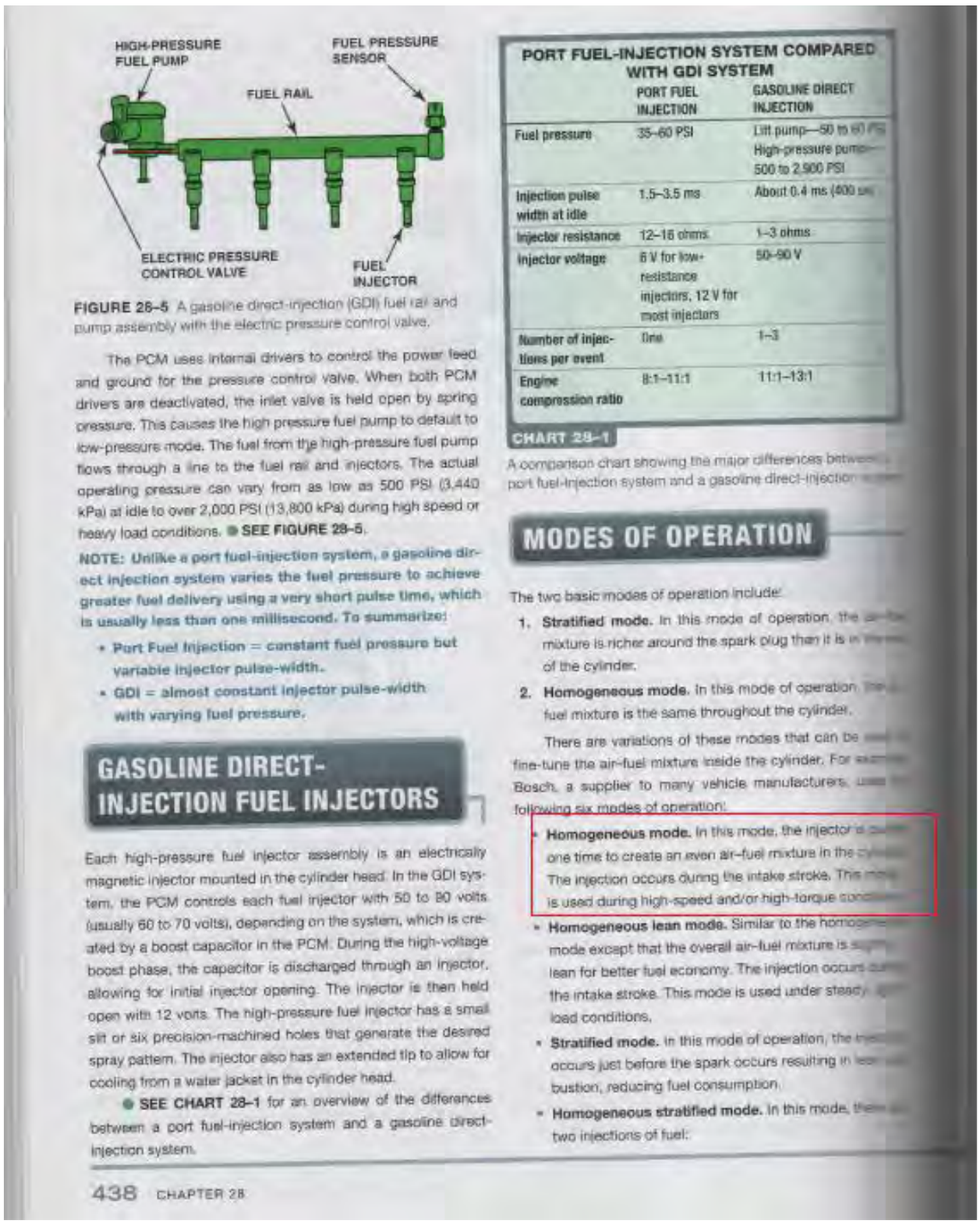


FIGURE 28–5 A gasoline direct-injection (GDI) fuel rail and pump assembly with the electric pressure control valve.

The PCM uses internal drivers to control the power feed and ground for the pressure control valve. When both PCM drivers are deactivated, the inlet valve is held open by spring pressure. This causes the high pressure fuel pump to default to low-pressure mode. The fuel from the high-pressure fuel pump flows through a line to the fuel rail and injectors. The actual operating pressure can vary from as low as 500 PSI (3,440 kPa) at idle to over 2,000 PSI (13,800 kPa) during high speed or heavy load conditions. ● **SEE FIGURE 28–5.**

NOTE: Unlike a port fuel-injection system, a gasoline direct injection system varies the fuel pressure to achieve greater fuel delivery using a very short pulse time, which is usually less than one millisecond. To summarize:

- **Port Fuel Injection = constant fuel pressure but variable injector pulse-width.**
- **GDI = almost constant injector pulse-width with varying fuel pressure.**

GASOLINE DIRECT-INJECTION FUEL INJECTORS

Each high-pressure fuel injector assembly is an electrically magnetic injector mounted in the cylinder head. In the GDI system, the PCM controls each fuel injector with 50 to 80 volts (usually 60 to 70 volts), depending on the system, which is created by a boost capacitor in the PCM. During the high-voltage boost phase, the capacitor is discharged through an injector, allowing for initial injector opening. The injector is then held open with 12 volts. The high-pressure fuel injector has a small slit or six precision-machined holes that generate the desired spray pattern. The injector also has an extended tip to allow for cooling from a water jacket in the cylinder head.

● **SEE CHART 28–1** for an overview of the differences between a port fuel-injection system and a gasoline direct-injection system.

PORT FUEL-INJECTION SYSTEM COMPARED WITH GDI SYSTEM

	PORT FUEL INJECTION	GASOLINE DIRECT INJECTION
Fuel pressure	35–60 PSI	Lift pump—50 to 60 PSI High-pressure pump—500 to 2,900 PSI
Injection pulse width at idle	1.5–3.5 ms	About 0.4 ms (400 µs)
Injector resistance	12–16 ohms	1–3 ohms
Injector voltage	6 V for low-resistance injectors, 12 V for most injectors	50–90 V
Number of injections per event	One	1–3
Engine compression ratio	8:1–11:1	11:1–13:1

CHART 28–1

A comparison chart showing the major differences between a port fuel-injection system and a gasoline direct-injection system.

MODES OF OPERATION

The two basic modes of operation include:

1. **Stratified mode.** In this mode of operation, the air-fuel mixture is richer around the spark plug than it is in the rest of the cylinder.
2. **Homogeneous mode.** In this mode of operation, the air-fuel mixture is the same throughout the cylinder.

There are variations of these modes that can be used to fine-tune the air-fuel mixture inside the cylinder. For example, Bosch, a supplier to many vehicle manufacturers, uses the following six modes of operation:

- **Homogeneous mode.** In this mode, the injector sprays one time to create an even air–fuel mixture in the cylinder. The injection occurs during the intake stroke. This mode is used during high-speed and/or high-torque conditions.
- **Homogeneous lean mode.** Similar to the homogeneous mode except that the overall air-fuel mixture is slightly lean for better fuel economy. The injection occurs during the intake stroke. This mode is used under steady-state load conditions.
- **Stratified mode.** In this mode of operation, the injection occurs just before the spark occurs resulting in lean combustion, reducing fuel consumption.
- **Homogeneous stratified mode.** In this mode, there are two injections of fuel:

James D Halderman, *Automotive Engine Performance* 438 (5 ed. 2017)

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,581,565
Page 7581



S3, TT 2015 ➢
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Direct Injection

Injectors in directly injected (DI) engines are mounted on the cylinder head and fuel is injected directly into the engine's combustion chamber. In order to overcome the pressure in the combustion chamber during compression and power stroke, injectors often operate at a primary pressure as high as 3000 psi. At such extreme pressure level, no single fuel pump can supply the required pressure directly from the fuel tank to the injectors. Instead, a low-pressure and a high-pressure system are employed. The low-pressure system principally utilizes the same fuel systems and components for multiport injected engines. The high-pressure system consists of a high-pressure fuel pump driven directly by the camshaft, a fuel rail (high-pressure accumulator), a high-pressure sensor and, depending on the system, a pressure-control valve or a pressure limiter. The injectors are operated by the ECM to send a precise amount of fuel from the high-pressure rail directly into the combustion chamber.

The distinctive difference between direct injection and other injection methods is that direct injection offers the flexibility regarding when in the combustion cycle the fuel is added and how. MPI systems can only add fuel during induction; A DI system can add fuel whenever it needs to. For example, fuel can be added during induction to create a homogeneous charge then added again after ignition to enhance power delivery under full load conditions.

VW/Audi Fuel Stratified Injection (FSI)

The goal of a stratified-charge operation is to form an ignitable mixture near the spark plug at the instant of ignition. This means that, instead of supplying the corresponding stoichiometric fuel quantity to the amount of air in the combustion chamber, the fuel interacts only with a portion of the air before it is conveyed to the spark plug. The rest of the fresh air surrounds the stratified charge allowing an ultra-lean condition with air-fuel ratio exceeding 50:1 in some instances. As less fuel is used to "burn" more air, stratified injection helps to further reduce fuel consumption when the engine is operating in low-load conditions (e.g. highway cruising). This is created by designing the combustion chamber so that a "swirling" effect of the air-fuel charge is caused.

2.9 Ignition and Timing

Ignition

A spark ignition (SI) engine requires a spark to initiate combustion in the combustion chamber. Voltage is supplied to the spark plug where the electricity will arc across a gap at a voltage as high as 100 kilovolts. The ECM determines the precise moment to fire each spark plug using ignition logic which is pre-programmed into the ECM as a function of engine speed and load. An optimally calibrated ignition system ensures consistent and reliable ignition under all conditions. Knock or misfire as a result of incorrect ignition can lead to destruction of engine components or damage of the catalytic converter.

Timing

Shifts in the moment of ignition (ignition timing) can result in increased emissions, decreased performance and fuel economy. Whereas more spark advance improves power and fuel economy, it also raises HC and NOx emissions. Excessive spark advance can cause engine knock which is potentially destructive to engines. If the ECM detects knock from a signal sent by a knock sensor, it will delay (retard) the timing of the spark. Excessive spark retard lowers power output and produces high exhaust temperatures, which can also harm the engine. Carefully designed ignition logic provides optimum timing that best balances performance, fuel economy and emissions.

10 Rep. Gr. ST - Generic Scan Tool

For example, a homogeneous mode may be used during high load operation. As shown above, fuel is injected during an intake stroke of the GDI engine.

Figure 46

the vehicle (often underneath the rear bumper). A passenger-car exhaust system consists of the following; exhaust manifold, exhaust treatment components, sound absorption components and the system of pipes connecting these components.

Exhaust Manifold

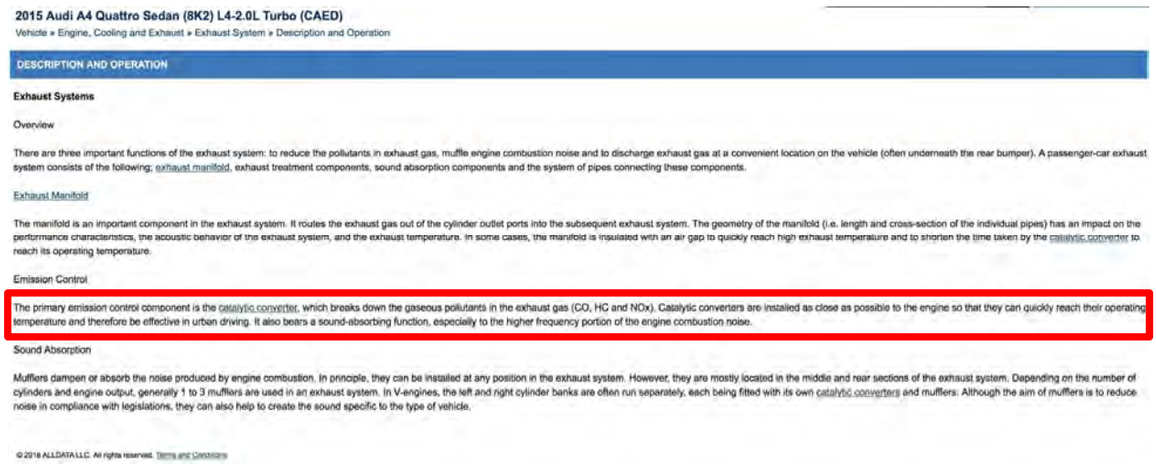
The manifold is an important component in the exhaust system. It routes the exhaust gas out of the cylinder outlet ports into the subsequent exhaust system. The geometry of the manifold (i.e. length and cross-section of the individual pipes) has an impact on the performance characteristics, the acoustic behavior of the exhaust system, and the exhaust temperature. In some cases, the manifold is insulated with an air gap to quickly reach high exhaust temperature and to shorten the time taken by the catalytic converter to reach its operating temperature.

Emission Control

The primary emission control component is the catalytic converter, which breaks down the gaseous pollutants in the exhaust gas (CO, HC and NOx). Catalytic converters are installed as close as possible to the engine so that they can quickly reach their operating temperature and therefore be effective in urban driving. It also bears a sound-absorbing function, especially to the higher frequency portion of the engine combustion noise.

Sound Absorption

Mufflers dampen or absorb the noise produced by engine combustion. In principle, they can be installed at any position in the exhaust system. However, they are mostly located in the middle and rear sections of the exhaust system. Depending on the number of cylinders and engine output, generally 1 to 3 mufflers are used in an exhaust system. In V-engines, the left and right cylinder banks are often run separately, each being fitted with its own catalytic converters and mufflers. Although the aim of mufflers is to reduce noise in compliance with legislations, they can also help to create the sound specific to the type of vehicle.



2015 Audi A4 Quattro Sedan (8K2) L4-2.0L Turbo (CAED)

Vehicle » Engine, Cooling and Exhaust » Exhaust System » Description and Operation

DESCRIPTION AND OPERATION

Exhaust Systems

Overview

There are three important functions of the exhaust system: to reduce the pollutants in exhaust gas, muffle engine combustion noise and to discharge exhaust gas at a convenient location on the vehicle (often underneath the rear bumper). A passenger-car exhaust system consists of the following; exhaust manifold, exhaust treatment components, sound absorption components and the system of pipes connecting these components.

Exhaust Manifold

The manifold is an important component in the exhaust system. It routes the exhaust gas out of the cylinder outlet ports into the subsequent exhaust system. The geometry of the manifold (i.e. length and cross-section of the individual pipes) has an impact on the performance characteristics, the acoustic behavior of the exhaust system, and the exhaust temperature. In some cases, the manifold is insulated with an air gap to quickly reach high exhaust temperature and to shorten the time taken by the catalytic converter to reach its operating temperature.

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The ’166 patent Accused Instrumentalities comprise a NO_x trap.

As shown above, there is a catalytic converter in the engine exhaust after treatment system.

Figure 47

DTC / Description	Monitor Strategy Description	Malfunction Criteria and Threshold Value	Secondary Parameters with Enable Conditions	Monitoring Time Length	MIL Illum.	Component Diagnostic Procedure
P0136 O2 Sensor Circuit	Oxygen Sensors rear response check	• gradient sensor voltage < 600.00 [mV/s]	general conditions: • forced close the gap stimulation not active • internal resistance O2S rear < 700.00 [Ohm] • close the gap stimulation request active • vehicle speed >= 6 [mph] • catalyst overheating protection not active • turbine overheating protection not active • O2S rear ready • O2S front ready • ECT @ cylinder head > 60 [°C] • modeled catalyst temperature 470...780 [°C] • difference between dynamic and stationary catalyst temperature -306...304 [°C] • modeled catalyst temperature once after engine start > 550 [°C] • integrated MAF, catalyst temp. conditions fulfilled >= 0.0 [g] • modeled EGT @ O2S rear <= 900 [°C] • MAF per cylinder 30.00...200.00 [kg/h] • MAF per cylinder per stroke, lower range >= 89.99 [mg/stk]	• 60-70 [s] • once / DCY	• 1 DCY	– Check the Oxygen Sensor After Three Way Catalytic Converter - G130- . Refer to ⇒ "3.6.27 Oxygen Sensor 1 After Catalytic Converter GX7 , Checking", page 1004

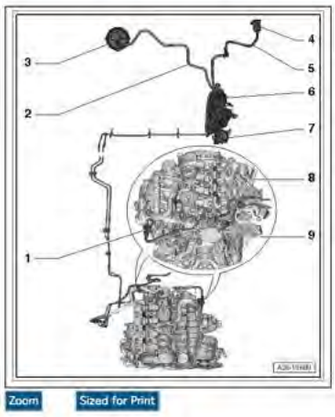
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Figure 48

2015 Audi A4 Quattro Sedan (8K2) L4-2.0L Turbo (CAED)
Vehicle » Powertrain Management » Emission Control Systems » Evaporative Emissions System » Diagrams » Connection Diagram - EVAP System, with Tank Leak Diagnosis System, Vehicles with 4-Cylinder Engine

CONNECTION DIAGRAM - EVAP SYSTEM, WITH TANK LEAK DIAGNOSIS SYSTEM, VEHICLES WITH 4-CYLINDER ENGINE

Connection Diagram - EVAP System, with Tank Leak Diagnosis System, Vehicles with 4-Cylinder Engine



Zoom Sized for Print

1 EVAP Canister Purge Regulator Valve 1 (N80)

2 Breather Line

- From the fuel tank locking flange to the EVAP canister
- Clipped into brackets under the vehicle underbody

3 Fuel Tank **Locking Flange**

4 Air Filter

- For the Leak Detection Pump (V144)

5 Connecting Line

- From the Leak Detection Pump (V144) to the air filter
- Clipped into brackets under the vehicle underbody

6 Evaporative Emission (EVAP) Canister

- Installed location: under the luggage compartment floor
- Removing and installing. Refer to => [EVAP Canister, Removing and Installing] See: Evaporative Emission Control Canister\Service and Repair\EVAP Canister, Removing and Installing\EVAP Canister, Removing and Installing.

7 Leak Detection Pump **(V144)**

- From MY 2013 replaced with Fuel Tank Leak Detection Control Module (J909) with integrated Fuel Tank Pressure Sensor (G400)
- Installed location: on the EVAP canister under the bottom of the luggage compartment
- Check in Guided Fault Finding mode using the Vehicle Diagnostic Tester.
- Removing and installing. Refer to => [Leak Detection Pump, Removing and Installing] See: Leak Detection Pump\Service and Repair.

8 Breather Line

- From EVAP canister to EVAP Canister Purge Regulator Valve 1 (N80)
- Clipped into brackets under the vehicle underbody

9 Vacuum Line

- From the engine to the Leak Detection Pump (V144).
- Clipped into brackets under the vehicle underbody

As shown above, the NOx trap (catalyst) is in contact with an exhaust gas exhausted from a combustion chamber. The ’166 patent Accused Instrumentalities both measured and model catalyst temperature.

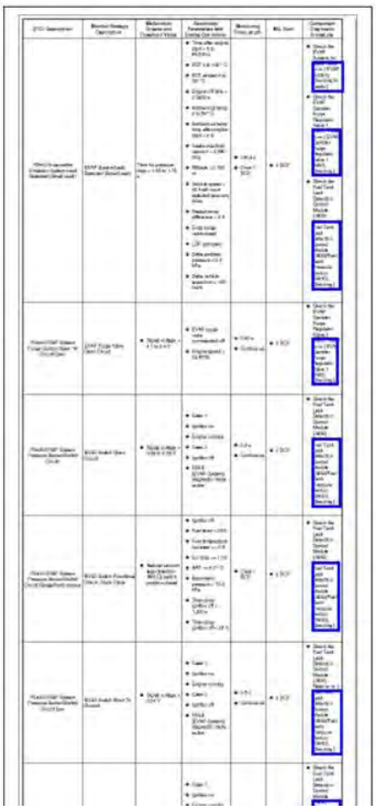
The ’166 patent Accused Instrumentalities comprise a method of controlling a direct injection spark ignited internal combustion engine enabling evaporated fuel vapors to enter the combustion chamber at a flow rate while the engine is operating in the stratified mode.

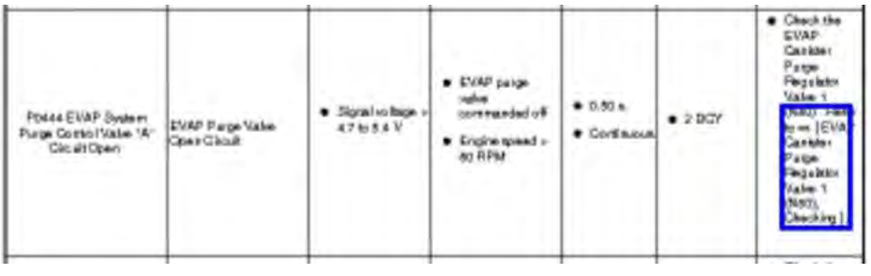
2015 Audi A4 Quattro Sedan (8K2) L4-2.0L Turbo (CAED)

Vehicle » A L L Diagnostic Trouble Codes (DTC) » Testing and Inspection » P Code Charts » P0444 » Engine Control Module 2015 MY

ENGINE CONTROL MODULE 2015 MY

Engine Control Module 2015 MY



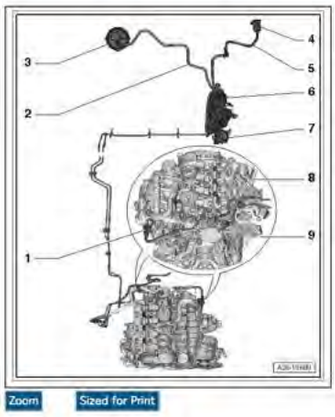


For example, as shown above, the duty cycle is between 0% and 90%.

2015 Audi A4 Quattro Sedan (8K2) L4-2.0L Turbo (CAED)
Vehicle » Powertrain Management » Emission Control Systems » Evaporative Emissions System » Diagrams » Connection Diagram - EVAP System, with Tank Leak Diagnosis System, Vehicles with 4-Cylinder Engine

CONNECTION DIAGRAM - EVAP SYSTEM, WITH TANK LEAK DIAGNOSIS SYSTEM, VEHICLES WITH 4-CYLINDER ENGINE

Connection Diagram - EVAP System, with Tank Leak Diagnosis System, Vehicles with 4-Cylinder Engine



Zoom Sized for Print

1 EVAP Canister Purge Regulator Valve 1 (N80)

2 Breather Line

- From the fuel tank locking flange to the EVAP canister
- Clipped into brackets under the vehicle underbody

3 Fuel Tank **Locking Flange**

4 Air Filter

- For the Leak Detection Pump (V144)

5 Connecting Line

- From the Leak Detection Pump (V144) to the air filter
- Clipped into brackets under the vehicle underbody

6 Evaporative Emission (EVAP) Canister

- Installed location: under the luggage compartment floor
- Removing and installing. Refer to => [EVAP Canister, Removing and Installing] See: Evaporative Emission Control Canister\Service and Repair\EVAP Canister, Removing and Installing\EVAP Canister, Removing and Installing.

7 Leak Detection Pump **(V144)**

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- Check in Guided Fault Finding mode using the Vehicle Diagnostic Tester.
- Removing and installing. Refer to => [Leak Detection Pump, Removing and Installing] See: Leak Detection Pump\Service and Repair.

8 Breather Line

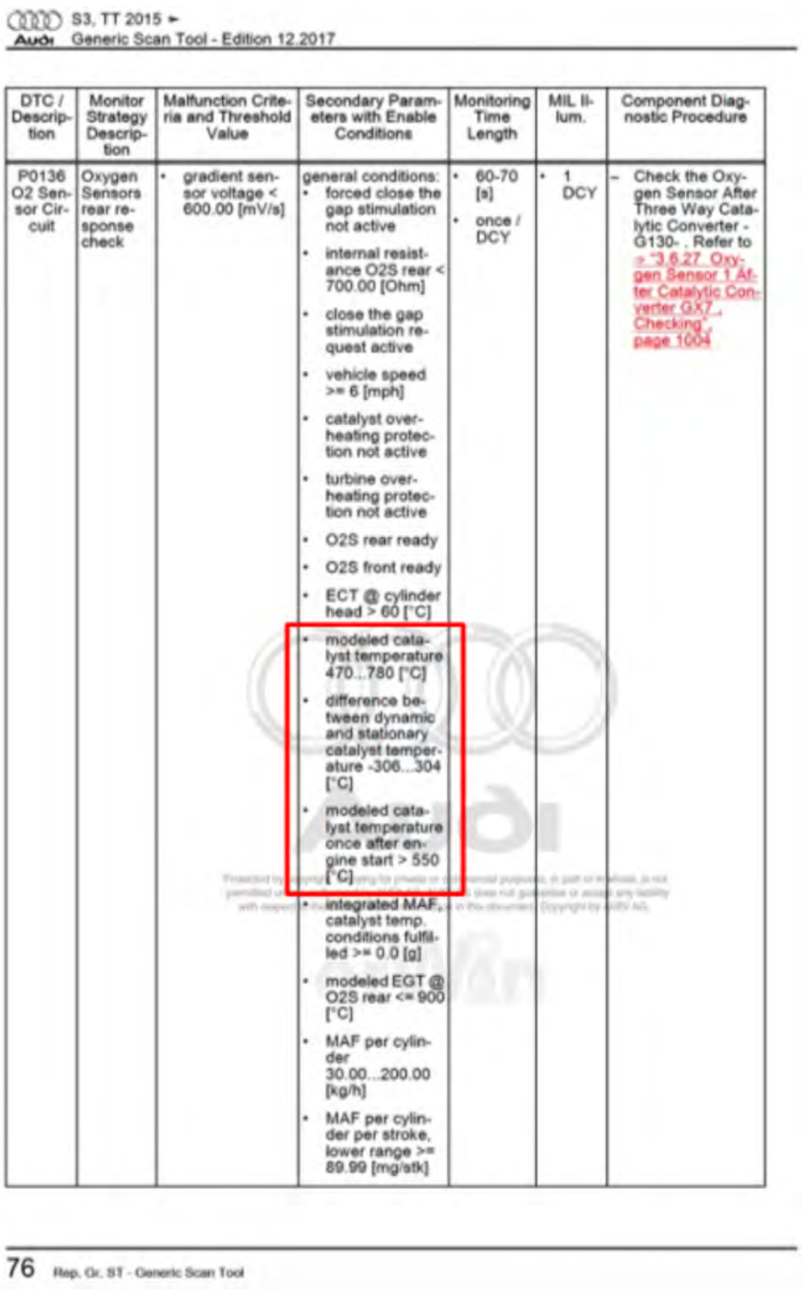
- From EVAP canister to EVAP Canister Purge Regulator Valve 1 (N80)
- Clipped into brackets under the vehicle underbody

9 Vacuum Line

- From the engine to the Leak Detection Pump (V144).
- Clipped into brackets under the vehicle underbody

The ’166 patent Accused Instrumentalities comprise a charcoal canister (Evaporative Emissions EVAP Canister) which contains evaporative fuel content.

Figure 49



S3, TT 2015 ►
Audi Generic Scan Tool - Edition 12.2017

DTC / Description	Monitor Strategy Description	Malfunction Criteria and Threshold Value	Secondary Parameters with Enable Conditions	Monitoring Time Length	MIL Illum.	Component Diagnostic Procedure
P0136 O2 Sensor Circuit	Oxygen Sensors rear response check	• gradient sensor voltage < 600.00 [mV/s]	general conditions: • forced close the gap stimulation not active • internal resistance O2S rear < 700.00 [Ohm] • close the gap stimulation request active • vehicle speed >= 6 [mph] • catalyst overheating protection not active • turbine overheating protection not active • O2S rear ready • O2S front ready • ECT @ cylinder head > 60 [°C] • modeled catalyst temperature 470...780 [°C] • difference between dynamic and stationary catalyst temperature -306...304 [°C] • modeled catalyst temperature once after engine start > 550 [°C] • integrated MAF, catalyst temp. conditions fulfilled >= 0.0 [g] • modeled EGT @ O2S rear <= 900 [°C] • MAF per cylinder 30.00...200.00 [kg/h] • MAF per cylinder per stroke, lower range >= 89.99 [mg/stk]	• 60-70 [s] • once / DCY	• 1 DCY	– Check the Oxygen Sensor After Three Way Catalytic Converter - G130- . Refer to ⇒ "3.6.27 Oxygen Sensor 1 After Catalytic Converter GX7 , Checking", page 1004

76 Rep. Gr. 97 - Generic Scan Tool

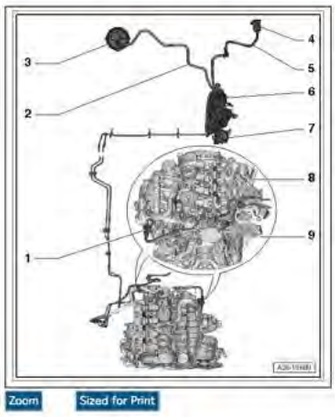
As shown above, the ’166 patent Accused Instrumentalities comprise a method of modeling catalyst temperature.

Figure 50

2015 Audi A4 Quattro Sedan (8K2) L4-2.0L Turbo (CAED)
Vehicle » Powertrain Management » Emission Control Systems » Evaporative Emissions System » Diagrams » Connection Diagram - EVAP System, with Tank Leak Diagnosis System, Vehicles with 4-Cylinder Engine

CONNECTION DIAGRAM - EVAP SYSTEM, WITH TANK LEAK DIAGNOSIS SYSTEM, VEHICLES WITH 4-CYLINDER ENGINE

Connection Diagram - EVAP System, with Tank Leak Diagnosis System, Vehicles with 4-Cylinder Engine



Zoom Sized for Print

1 EVAP Canister Purge Regulator Valve 1 (N80)
2 Breather Line
- From the fuel tank locking flange to the EVAP canister
- Clipped into brackets under the vehicle underbody

3 Fuel Tank **Locking Flange**
4 Air Filter
- For the Leak Detection Pump (V144)

5 Connecting Line
- From the Leak Detection Pump (V144) to the air filter
- Clipped into brackets under the vehicle underbody

6 Evaporative Emission (EVAP) Canister
- Installed location: under the luggage compartment floor
- Removing and installing. Refer to => [EVAP Canister, Removing and Installing] See: Evaporative Emission Control Canister\Service and Repair\EVAP Canister, Removing and Installing\EVAP Canister, Removing and Installing.

7 Leak Detection Pump **(V144)**
- From MY 2013 replaced with Fuel Tank Leak Detection Control Module (J909) with integrated Fuel Tank Pressure Sensor (G400)
- Installed location: on the EVAP canister under the bottom of the luggage compartment
- Check in Guided Fault Finding mode using the Vehicle Diagnostic Tester.
- Removing and installing. Refer to => [Leak Detection Pump, Removing and Installing] See: Leak Detection Pump\Service and Repair.

8 Breather Line
- From EVAP canister to EVAP Canister Purge Regulator Valve 1 (N80)
- Clipped into brackets under the vehicle underbody

9 Vacuum Line
- From the engine to the Leak Detection Pump (V144).
- Clipped into brackets under the vehicle underbody

Upon information and belief, the ECM is capable of "adjusting the flow rate of the evaporated fuel vapors as a function of the second temperature when the second temperature is within a lower temperature threshold and an upper temperature threshold."

Figure 51

Based upon the totality of the foregoing evidence, and based further upon information and belief, the '166 patent Accused Instrumentalities practice a "method of controlling a direct injection spark ignited internal combustion engine that is capable of operating in a stratified mode where fuel is injected during a compression stroke of the engine and a homogeneous mode where fuels is injected during an intake stroke of the engine, the internal combustion engine having a catalytic converter and an NOx trap, comprising: measuring a first temperature of an NOx trap that is in contact with an exhaust gas exhausted from a combustion chamber while the engine is operating in the stratified mode; enabling evaporated fuel vapors to enter the combustion

chamber at a flow rate while the engine is operating in the stratified mode; measuring a second temperature of the NOx trap while the engine is operating in the stratified mode; and adjusting the flow rate of the evaporated fuel vapors as a function of the second temperature when the second temperature is within a lower temperature threshold and an upper temperature threshold."

COUNT VIII – INFRINGEMENT OF U.S. PATENT NO. 6,988,031

54. The allegations set forth in the foregoing paragraphs 1 through 53 are incorporated into this Eighth Claim for Relief.

55. On January 17, 2006 U.S. Patent No. 6,988,031 ("the '031 patent"), entitled "System and Method for Determining Engine Stop Position," was duly and legally issued by the United States Patent and Trademark Office. A true and correct copy of the '031 patent is attached as Exhibit 8.

56. Plaintiff is the assignee and owner of the right, title and interest in and to the '031 patent, including the right to assert all causes of action arising under said patents and the right to any remedies for infringement of them.

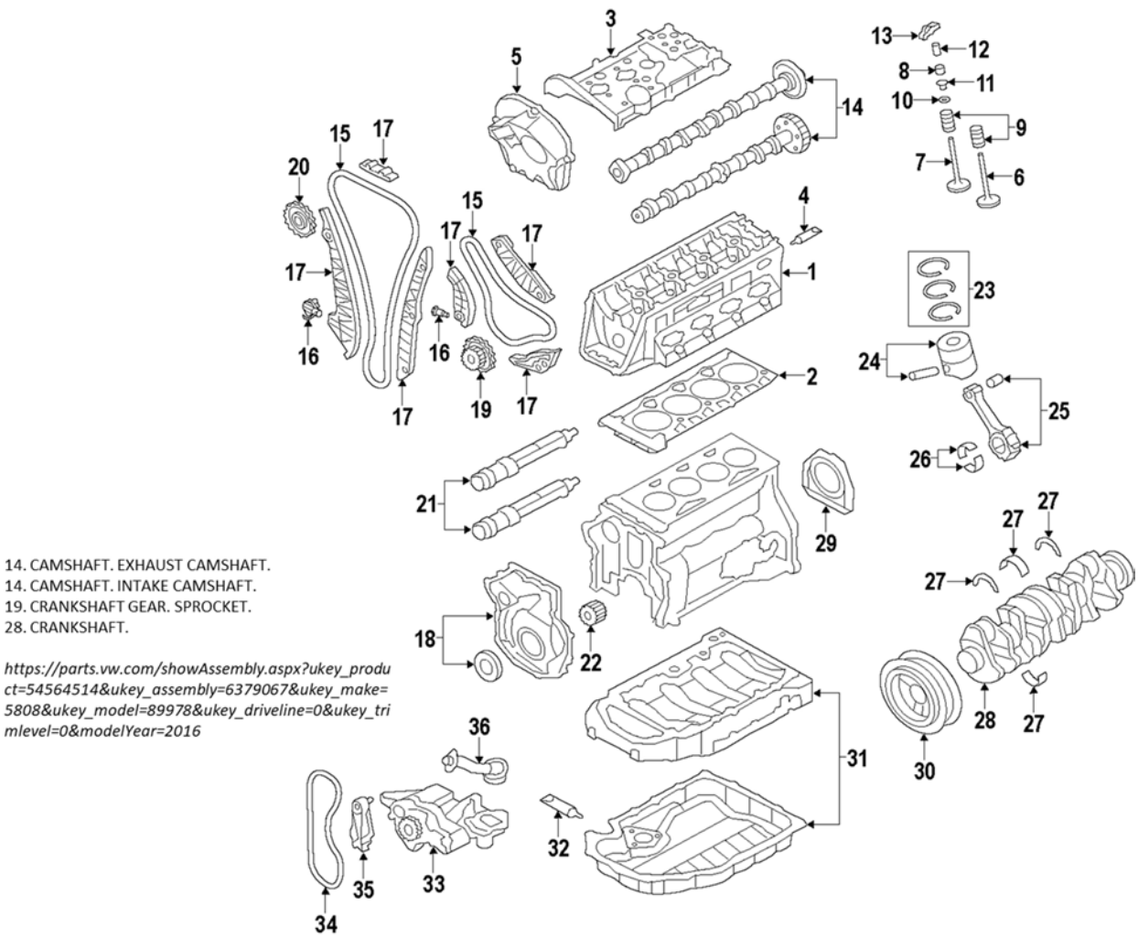
57. Upon information and belief, Defendants have directly infringed at least claim 1 of the '031 patent by making, using, selling, importing and/or providing and causing to be used the 2015-2018 Jetta (1.4L) or other vehicles having incorporated the DTI engine (the "'031 patent Accused Instrumentalities").

58. Upon information and belief, the '031 patent Accused Instrumentalities incorporate the Theta II Engine which comprises a system for determining a stop position of an engine.

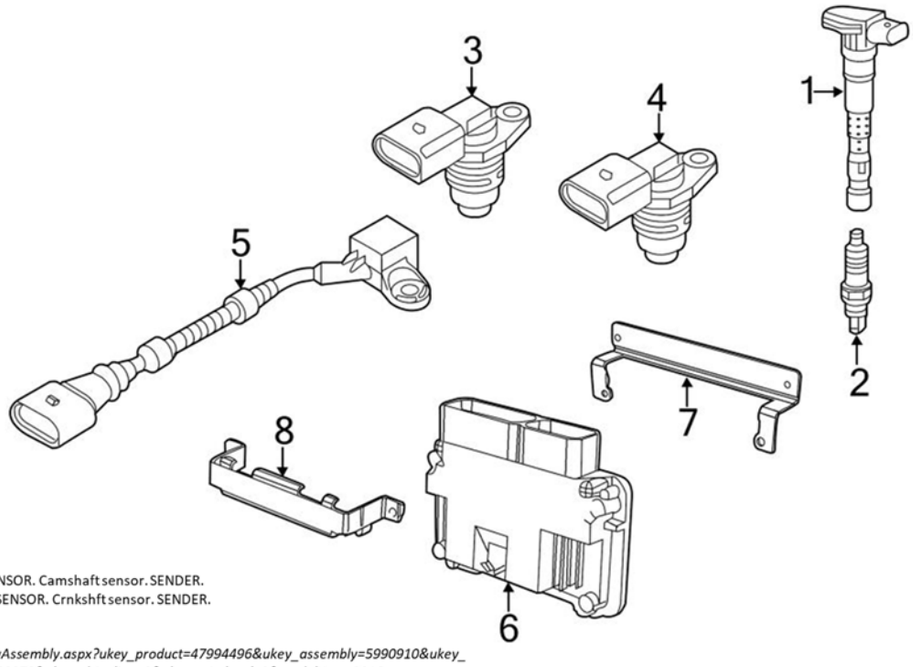
59. In particular, claim 1 of the '031 patent recites a system for determining a stop position of an engine, the system comprising: a sensor configured to generate a signal corresponding to the angle of the engine; a controller coupled to the sensor and configured to receive the signal; and an air flow control device coupled to the engine to control air intake, the

controller being configured to control the air flow control device to lower air pressure in the engine based on an engine shutdown signal.

60. On information and belief, the ’031 patent Accused Instrumentalities infringe claim 1 of the ’031 patent. The ’031 patent Accused Instrumentalities comprise a system for determining a stop position of an engine (*Figure 52*), the system comprising: a sensor configured to generate a signal corresponding to the angle of the engine (*Figure 53*); a controller coupled to the sensor and configured to receive the signal (*Figure 54*); and an air flow control device coupled to the engine to control air intake (*Figure 55*), and upon information and belief the controller being configured to control the air flow control device to lower air pressure in the engine based on an engine shutdown signal (*Figures 52-53*).



The camshaft (14 above) and crankshaft (28 above) control the piston position in an internal combustion engine.

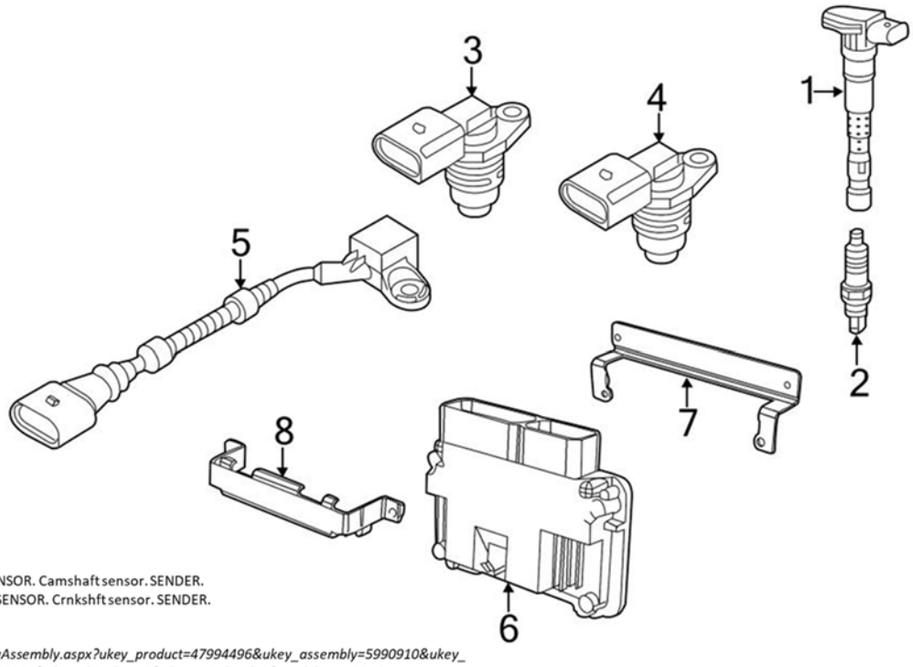


3. CAMSHAFT POSITION SENSOR. Camshaft sensor. SENDER.
4. CRANKSHAFT POSITION SENSOR. Crnkshft sensor. SENDER.
5. Knock sensor. SENSOR.

https://parts.vw.com/showAssembly.aspx?ukey_product=47994496&ukey_assembly=5990910&ukey_make=5808&ukey_model=89978&ukey_driveline=0&ukey_trimlevel=0&modelYear=2016

The camshaft position sensor (3 above) sends a signal to the ECM corresponding with the stop position of an engine.

Figure 52

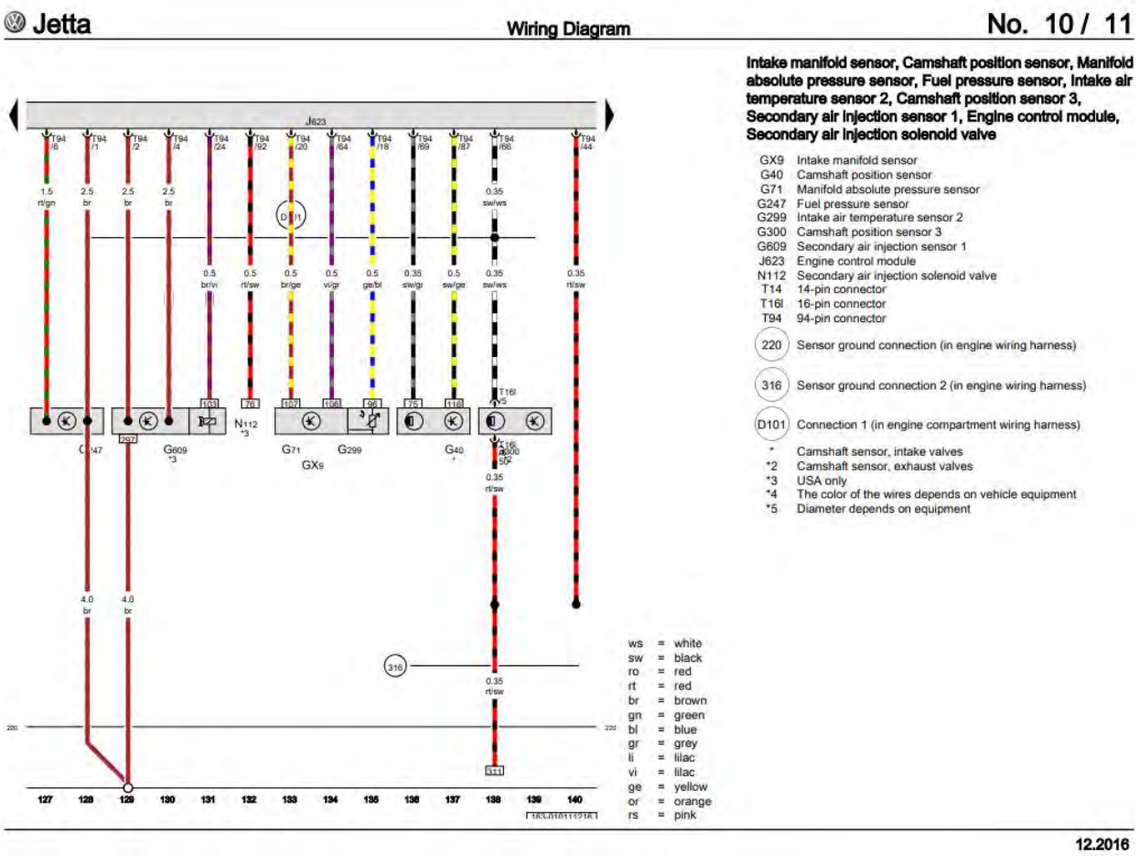


3. CAMSHAFT POSITION SENSOR. Camshaft sensor. SENDER.
4. CRANKSHAFT POSITION SENSOR. Crnkshft sensor. SENDER.
5. Knock sensor. SENSOR.

https://parts.vw.com/showAssembly.aspx?ukey_product=47994496&ukey_assembly=5990910&ukey_make=5808&ukey_model=89978&ukey_driveline=0&ukey_trimlevel=0&modelYear=2016

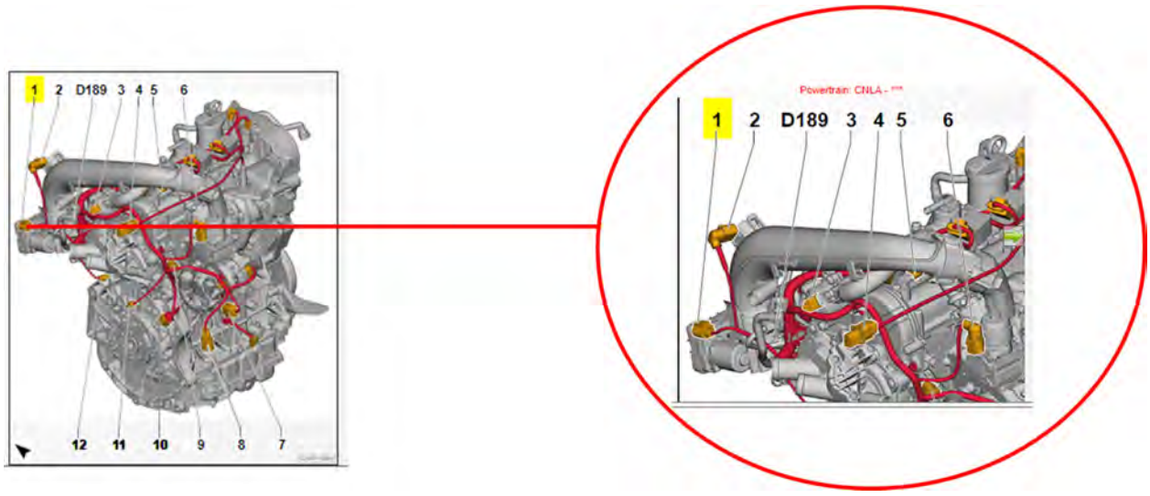
The ’031 patent Accused Instrumentalities comprise a Camshaft Position Sensor (3 above) which generates a signal corresponding to the angle of the engine.

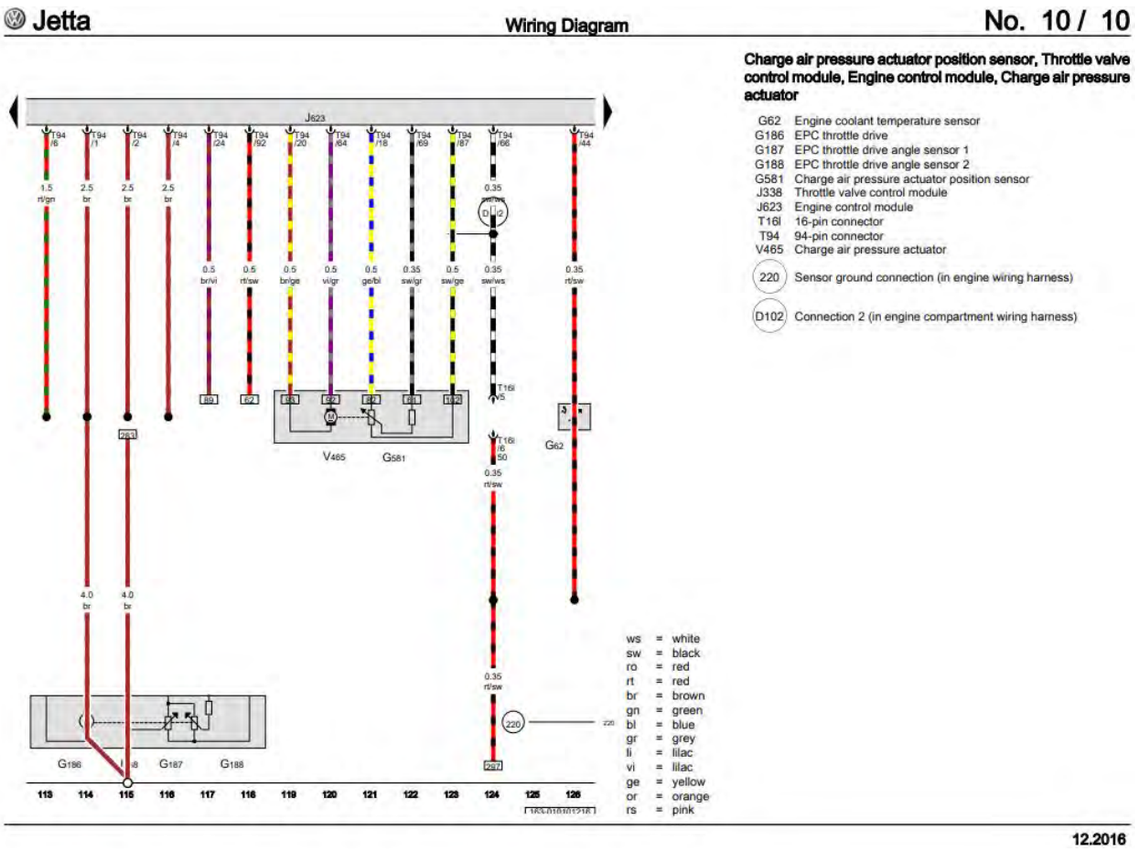
Figure 53



For example, the Engine Control Module (ECM; J623), a controller, is coupled to the Camshaft Position Sensors (G40; G300) and to receive the signals generated by these sensors.

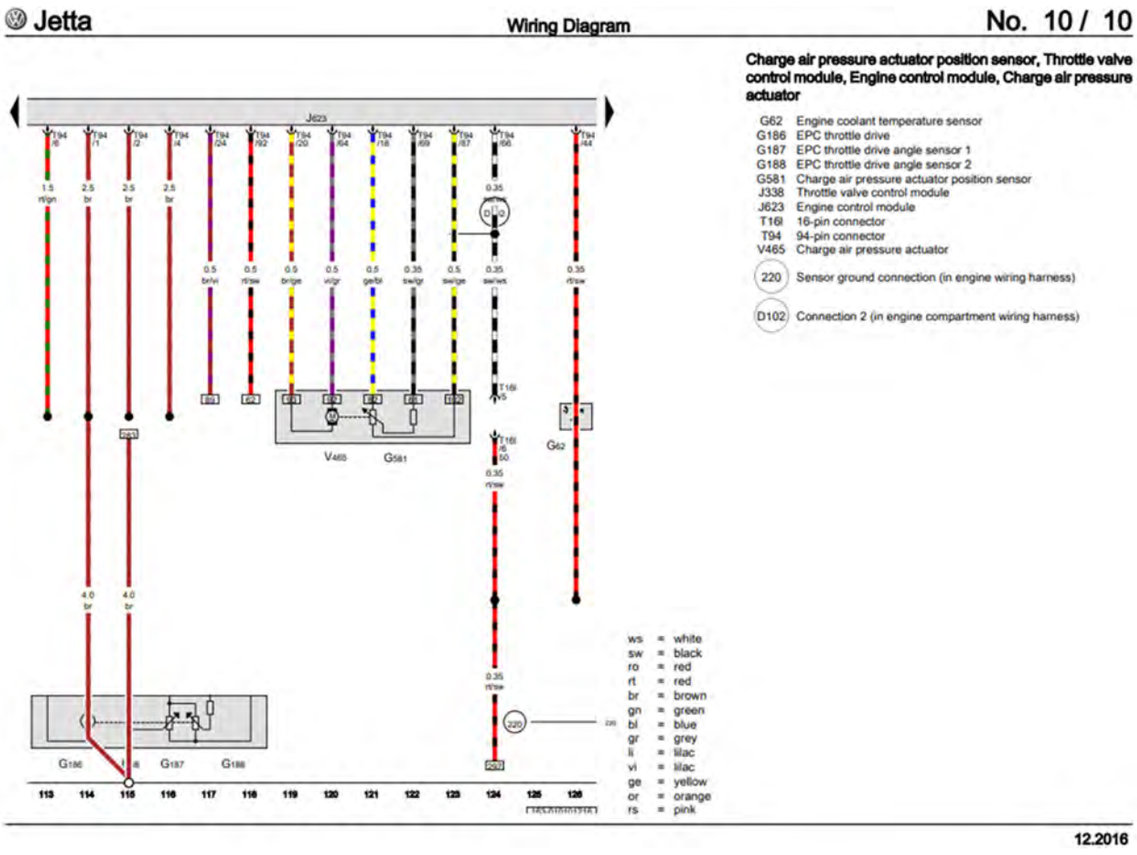
Figure 54





For example, in the images above the throttle valve control module (J338), EPC throttle drive (G186), and EPC throttle drive angle sensor 1 (G187) and 2 (G188) with the ECM (J623) control the air flow and are coupled to the engine to control air intake. The throttle angle sensor has functions for detecting a fully-closed throttle and estimating intake air volume by the amount of throttle opening. Shimatani, K., *Detecting a Fully-Closed Throttle by Manifold Pressure in Fuel Injection System with Idle Speed Control*, SAE Technical Paper 2014-32-0075, 2014, https://doi.org/10.4271/2014-32-0075.

Figure 55



For example, the ECM (J623) is configured to control the air flow control device (throttle valve not shown here) to lower air pressure in the engine based on an engine shutdown signal.

The engine shutdown signal is communicated at the end of a drive cycle. When the engine is shut down, the throttle angle is at 0 degrees, thereby decreasing the air pressure in the engine.

Figure 56

Based upon the totality of the foregoing evidence, and based further upon information and belief, the '031 patent Accused Instrumentalities include "a system for determining a stop position of an engine, the system comprising: a sensor configured to generate a signal corresponding to the angle of the engine; a controller coupled to the sensor and configured to receive the signal; and an air flow control device coupled to the engine to control air intake, the controller being configured to control the air flow control device to lower air pressure in the engine based on an engine shutdown signal."

COUNT IX – INFRINGEMENT OF U.S. PATENT NO. 6,612,287

61. The allegations set forth in the foregoing paragraphs 1 through 60 are incorporated into this Ninth Claim for Relief.

62. On September 2, 2003 U.S. Patent No. 6,612,287 ("the '287 patent"), entitled "Electronic Throttle Position Feedforward System," was duly and legally issued by the United States Patent and Trademark Office. A true and correct copy of the '287 patent is attached as Exhibit 9.

63. Plaintiff is the assignee and owner of the right, title and interest in and to the '287 patent, including the right to assert all causes of action arising under said patents and the right to any remedies for infringement of them.

64. Upon information and belief, Defendants have directly infringed at least claim 1 of the '287 patent by making, using, selling, importing and/or providing and causing to be used the 2012-2018 Tiguan, 2012-2018 Audi A3, 2012-2018 Audi A4, 2012-2018 Audi A5, 2012-2018 Audi A6, 2016-2018 Audi TT, 2015-2018 Audi S3, 2015-2018 VW Golf, 2012-2018 VW Golf GTI, 2015-2018 VW Golf R, 2015-2018 Golf Sportwagon, 2013-2018 Jetta GLI, 2014-2018 VW Jetta Sedan, 2014-2018 VW Passat, 2012-2017 WV CC, 2012-2018 VW Beetle, 2018 VW Atlas, 2015- 2018 Audi Q3, 2012-2018 Audi Q5, and 2017-2018 Porsche Macan with the EA888 engines (the "'281 patent Accused Instrumentalities").

65. In particular, claim 1 of the '287 patent recites a method for controlling a positioning device of an internal combustion engine, the method comprising the steps of: providing an electronic motor for actuating said positioning device with a torque being applied to said motor over the positioning range and said torque changing sign thereby defining a torque reversal point; detecting a commanded position of said positioning device; determining whether said positioning device's command is in the region of said torque reversal point; forming a drive signal for the motor on the basis of said commanded position for said positioning device; and changing said drive signal to abruptly change the motor voltage when said commanded position is in said region of said torque reversal point.

66. On information and belief, the ’281 patent Accused Instrumentalities infringe claim 1 of the ’287 patent. The ’281 patent Accused Instrumentalities practice a method controlling a positioning (*Figure 57*) device of an internal combustion engine (*Figure 57*), the method comprising the steps of: providing an electronic motor (*Figure 57*) for actuating said positioning device with a torque being applied to said motor over the positioning range and said torque changing sign thereby defining a torque reversal point (*Figure 57*); detecting a commanded position of said positioning device (*Figure 57*); determining whether said positioning device's command is in the region of said torque reversal point (*Figure 57*); forming a drive signal for the motor on the basis of said commanded position for said positioning device (*Figure 57*); and changing said drive signal to abruptly change the motor voltage when said commanded position is in said region of said torque reversal point (*Figure 57*).