

sor. This sensor can also yield an accurate crankshaft position measurement. Nevertheless, an on-board version is not available today.

9.4 INFERRED TORQUE MEASUREMENT

Indirect measurements of torque-related parameters can be made with a view to inferring torque from the measurements. Typically, such measurements require considerable real-time computation in the control microcomputer, along with precision measurement of the instantaneous crank angle position. Much work is in progress in a variety of locations to make these methods into practical instantaneous torque control signals.

9.4.1 Instantaneous Cylinder Pressure Sensors

Engine development engineers have long used piezoelectric crystal cylinder pressure sensors in the laboratory to make engine power and heat release measurements and as an aid to development. The best of these sensors use doped quartz single crystals. They are accurate and reasonably robust, but expensive and unforgiving if overranged or subjected to excessive temperatures. Much work continues on development of a mass-producible on-board cylinder pressure sensor.⁹ One of the Japanese car manufacturers is reported to have a top-of-the-line passenger car model, available only in Japan, with engine control using piezoceramic cylinder pressure sensors.

The signals from cylinder pressure sensors need considerable real-time data processing to produce inferred "torque" signals. In one method, the noise always present is filtered, the pressure signal is multiplied by an instantaneous shaft angle term, and integrated over the angle range representative of the power stroke of the cylinder. From this a measure of torque contribution from that cylinder is obtained. The best digital signal processing (DSP) chips available in the early 1990s are barely able to keep up with cylinder events in such a process. Nevertheless, we can be confident that if the proper sensors are available in the late 90s, the microcomputer chip performance required will be available and cost effective too.

9.4.2 Digital Period Analysis (DPA)

When an engine is run at low speed and heavy load, the instantaneous angular velocity of its output shaft on the engine side of the flywheel varies at the fundamental frequency of the cylinders, since the compression stroke of each cylinder abstracts torque and the power stroke adds a larger amount. The signal-to-noise ratio of the measurement of instantaneous angular velocity (or rather of its reciprocal, instantaneous period) degrades with increasing engine speed and lighter load, but is a useful way to infer torque-like measures of engine performance.

Figure 9.4 shows an idealized plot of instantaneous crankshaft period against crank angle under constant speed, lean conditions. The instantaneous period wave is seen to be a variation about the mean period value. This waveform can actually be measured using a precision, multitoothed crankshaft position sensor. For reasons which will be explained later, the instantaneous angular velocity lags the torque inputs producing it. As a result, the period wave appears to lead the torque or cylinder pressure variations.

Timing Control by DPA. The general case of the variation in crankshaft velocity in a four-cylinder engine can be described by:

$$T_N = AL P_N(\theta) \sin \theta = AL P_{(N+3)}(\theta) \sin \theta + T_F(\theta) + T_L + I\ddot{\theta} \quad (9.1)$$

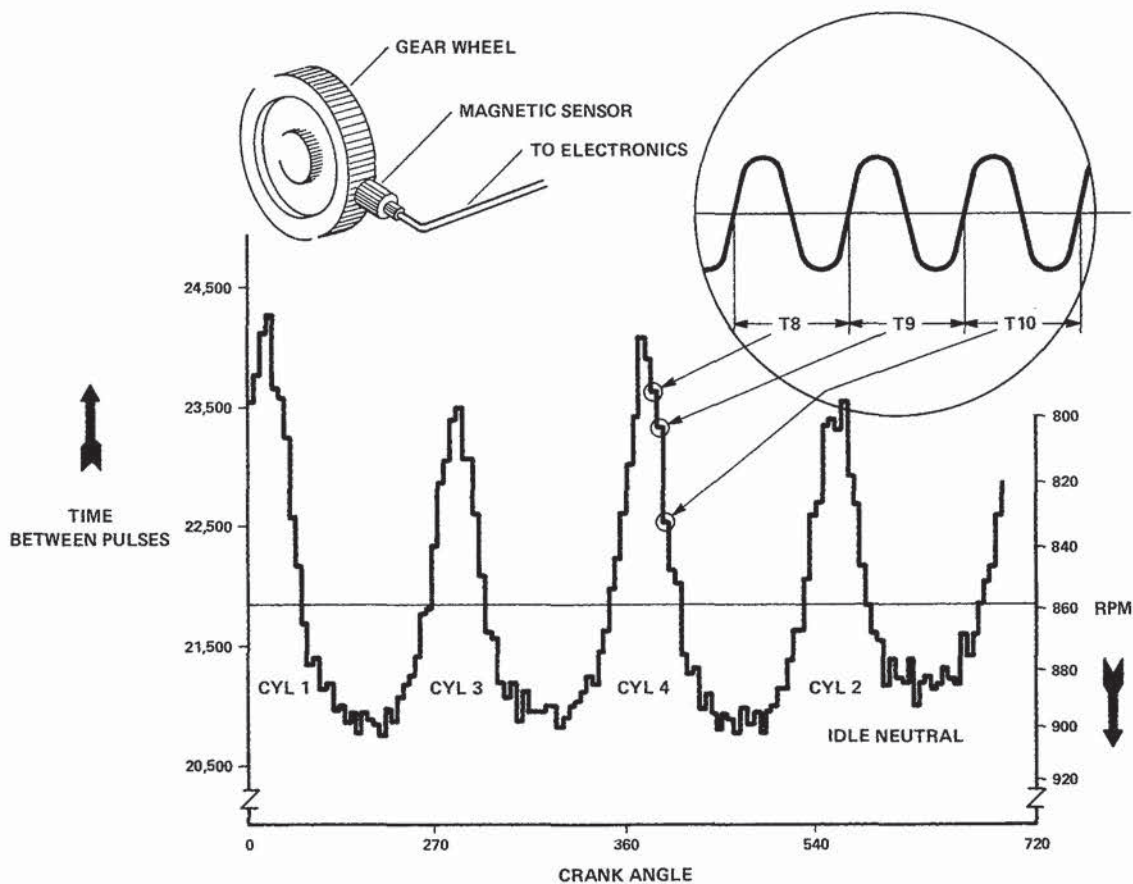


FIGURE 9.4 Digital period input.

where

- T_N = instantaneous torque due to burning gases in cylinder N at angle θ
- A = area of piston
- L = maximum effective crank lever arm
- $P_N(\theta)$ = pressure in cylinder N (a function of crank angle and many other variables)
- $P_{(N+3)}(\theta)$ = pressure in third cylinder to fire after N which is in its compression stroke when cylinder N is in its power stroke
- $T_F(\theta)$ = so-called "fixed load" torque due to friction, accessories, etc., and is generally a function of $d\theta/dt$
- T_L = torque delivered to the load
- I = inertia of the engine, drivetrain, and vehicle reaction through the wheels
- $\ddot{\theta}$ = instantaneous angular acceleration of the crankshaft

In order for Eq. (9.1) to remain valid, as T_N varies with angle θ due to the variations of $P_N(\theta)$ and the $\sin \theta$ term, some term in the right-hand side of the equation must vary correspondingly. In fact, the major effect is upon $\ddot{\theta}$, the angular acceleration, which varies both in magnitude and sign; being positive when P_N is large and θ is near $\pi/2$, and negative when P_N is small and θ is near 0 and π . If Eq. (9.1) is integrated as a function of θ from $\theta = 0$ to $\theta = \pi$ and

then the summation is extended to angles larger than π by adding in the contributions of cylinders $N + 1$ and $N + 3$, the term in $I\dot{\theta}$ becomes an average angular velocity over a complete engine cycle.

One important consequence of the preceding analysis is that, upon integration of the equation, the $\sin \theta$ term becomes $\cos \theta$ —that is, the angular velocity wave lags the torque impulses causing it by $\pi/2$. Another consequence is that the amplitude of the period wave reflects the net contribution of the cylinders—if the load increases, and $P_N(\theta)$ increases to keep average angular velocity constant, the amplitude of the period wave must increase. The $I\dot{\theta}$ term has become an $I\omega$, it is the reciprocal of this term which was plotted in Fig. 9.4.

When a spark plug fires or fuel is injected into a diesel cylinder, the pressure in the cylinder takes a finite length of time to build—first, because of a delay to get the fire started and then because of the finite and relatively constant flame propagation time, and second, because the temperature rise which causes pressure to rise, peaks only shortly before combustion is completed. Thereafter, pressure falls as the piston displaces under the pressure of the gases. Mean best torque (MBT) will be achieved from that cylinder when the pressure pulse, convolved with $\sin \theta$ yields a maximum upon integration. As described previously, researchers at Stanford University have found analytically and confirmed experimentally that this condition prevails for a fairly wide range of engine conditions when the centroid of the pressure pulse occurs at 15 degrees past top dead center (TDC). Because of the delays described previously, ignition must occur early enough to position the pressure peak near this value. It is this “anticipation” in spark plug firing that is termed *ignition advance*. The reason why advance angle has to be larger at higher speeds is now obvious: the flame propagation delay time covers more degrees of crank angle when the engine is running faster.

Further experiments by the Stanford researchers and others confirmed the suspicion that the period wave is a strong function of the crank angle, and that the angle associated with the centroid of the pressure wave is a unique function of the phase of the fundamental component of the period wave measured with respect to a crankshaft angle index point, say top dead center of cylinder no. 1. The period wave is measured with a sensor which is a precision version of a crankshaft position sensor.¹⁰ It produces a fast, sharp pulse for every small and equal angle increment—say one degree—through which the shaft turns. Pulses from a high-frequency quartz crystal clock are counted to measure each period. The crankshaft angle index is available from the crankshaft position sensor. In principle, the period wave could be Fourier analyzed into the Fourier integral coefficients A_n and B_n by computing the Fourier integrals, and the phase of the fundamental (first harmonic) is then $\arctan B_1/A_1$. To perform this computation in real time is a bit much to ask of today’s microcomputer (but not tomorrow’s!) and various shortcuts are utilized to achieve an approximate result. Remembering that the period wave appears to lead the torque impulses that cause it by $\pi/2$, the spark timing can now be varied so as to place the centroid of the pressure wave, on the average, at or very near the 15-degree-after-TDC point.

It is instructive to consider what performance is required of the DPA and crankshaft position sensors to achieve a given signal-to-noise ratio. The repeatability of the crankshaft angle marked by the sensor is a function of the diameter of the sensing disc. For the various magnetic sensors, a repeatability better than ± 0.5 degree can be achieved with a 10-cm-diameter disc. In the DPA sensor, the concern is for the period-to-period jitter. It is obviously worse for smaller angle increments both because the angle jitter is a larger part of the period, and also because the period-counting roundoff error is larger for any given clock frequency. At the same time, the more periods measured per revolution, the more fidelity the period wave will have for its high-frequency components. The period-to-period jitter of the magnetic sensor in this example is about ± 0.5 degree. This is satisfactory for 24 periods per revolution but marginal for 60 periods; a typical period wave amplitude is only ± 3 percent of the average period. On the other hand, even 60 periods per revolution is marginal for ignition or injection timing control.

The granularity due to counting roundoff also needs to be considered. Today’s low-cost LSI circuits can count reliably at 20 MHz, so that is a practical clock frequency. If a four-cylin-

der engine is running at 1800 rev/min (30 Hz), the associated period wave will have a fundamental of 60 Hz. If the DPA sensor has one degree angle indices, referred to the crankshaft, each period will have about 2000 counts from the clock. Therefore, the period counting round-off noise will be ± 1 part per 2000. Referred to a nominal ± 3 percent amplitude period wave, this jitter amounts to ± 2 percent of the peak value of the period wave (not of the period itself), not counting any smoothing.

For the fundamental of the period wave, the phase of which is used for DPA timing control, a good deal of smoothing can be realized, so that for a "clean" engine, estimation of the correct angle to \pm one crankshaft degree is feasible.

Figure 9.5 shows an actual period wave measured using an electromagnetic DPA sensor with one-degree increments and a 10-MHz clock. Both the jitter described previously and a fixed pattern noise can be discerned in the signal. The latter effect is due to slight imperfections in the tooth spacing of the precision gear used as the sensing disc. Such systematic errors can be eliminated in the microcomputer, but they are troublesome and consume integration time. The better solution is to design a precision DPA sensor which minimizes fixed pattern noise.

DPA Used for Diagnostics. During the 1980s, one of the heavy duty diesel engine manufacturers introduced an off-board diagnostic instrument capable of doing DPA on the engine with the clutch disengaged and using snap acceleration and deceleration to load the engine

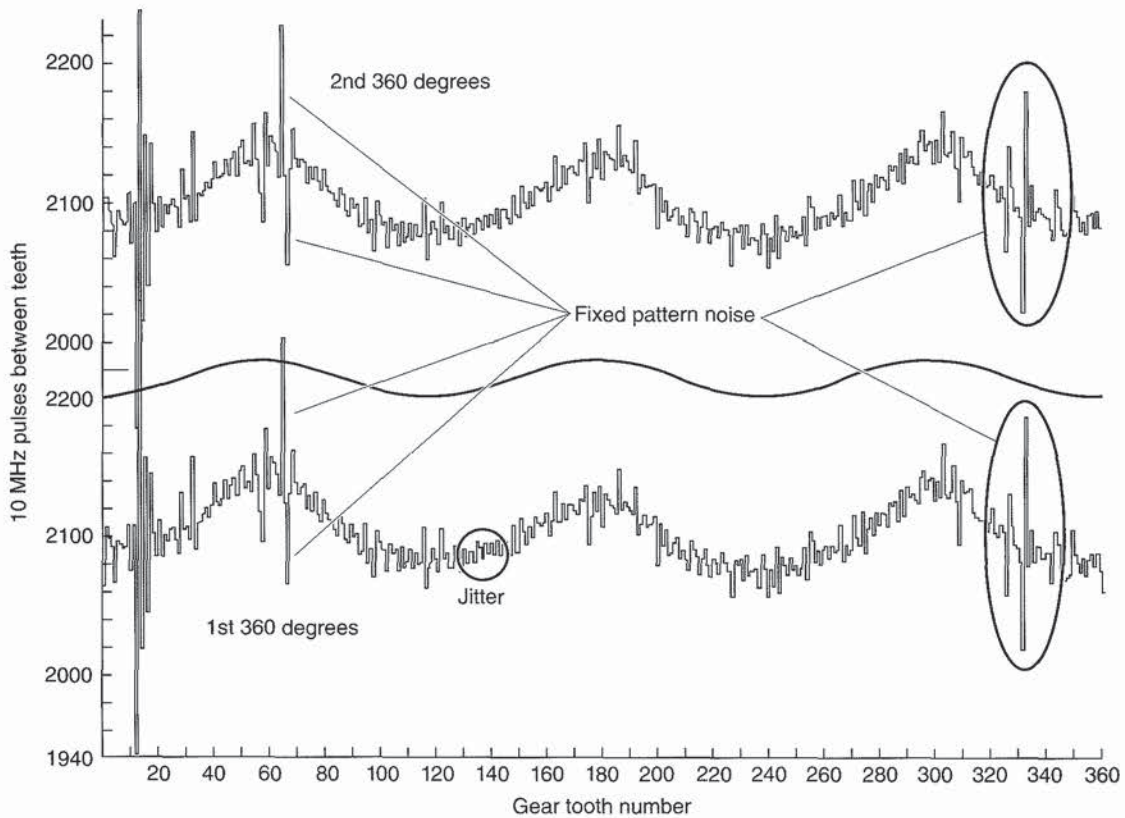


FIGURE 9.5 Actual period wave data from engine crankshaft; unsmoothed data. (Courtesy of The Bendix Corp., Diesel Operation)

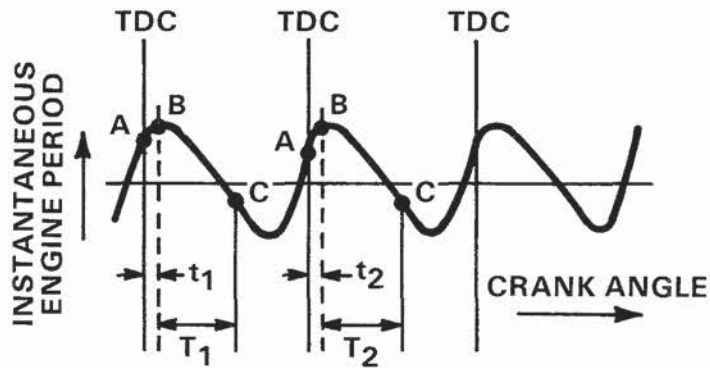
inertially. This instrument used the very imperfect engine ring gear as the DPA target but solved the fixed pattern noise problem in a very elegant way.¹¹ The position sensor is actually a dual sensor, with the two magnetic circuits disposed tangential to the ring gear and closer together than one tooth pitch. A particular tooth is sensed by the first magnetic circuit and then by the second before the next tooth is sensed by the first circuit. Virtually all of the fixed pattern noise is eliminated.

What would be achieved in an on-board DPA system would be real-time, nearly ideal closed-loop control of spark timing. As with most controls for spark-ignited engines, there are some trims required to make the system work. Flame front propagation is in fact a complex process which has a substantial jitter in the time of propagation, so it is necessary to average the computation of the phase angle over a number of cylinder pulses in order to obtain a good phase estimator. Under transient conditions, the shape of the pressure pulse may change enough so that the angle for mean best torque (MBT) shifts slightly. These factors can also be incorporated in the control. A similar method could be used for compression-ignition engines; in fact, the period wave has a more reproducible signature than for a spark-ignited engine.

It is useful at this point to emphasize again that these principles hold under any conditions, but that the control works well only in the lean regime. As the air/fuel ratio nears stoichiometry, the amplitude of the period wave becomes quite small. Because the method of measuring the instantaneous period—counting clock pulses over a finite angle increment—is a differencing method, the signal-to-noise ratio (S/N) is always a problem, since a differencing process always yields a poorer S/N than that of the original function. Hence, the DPA technique yields poorer results the nearer the engine is to stoichiometry and the higher the engine speed.

Referring to Fig. 9.6, if a figure of merit is formed

$$R = \left| \frac{T_2 - T_1}{t_1 + t_2} \right| \tag{9.2}$$



$$\text{ROUGHNESS } \alpha F \left(\left| \frac{T_1 - T_2}{t_1 + t_2} \right| \right)$$

FIGURE 9.6 Digital roughness control.

we have a measure of the “roughness” of the engine useful for lean limit control or misfire detection. This is one example of many such optimizing algorithms which may be derived from DPA

9.5 SUMMARY

One can conclude from this chapter that torque measurement, whether direct or inferred, is a useful parameter for engine evaluation off-board, but that the proper sensors and computer analysis equipment for on-board control are not yet available. Yet the number of facilities working to advance this art, the resources being added, and the sporadic reports of progress are such that one can predict with some confidence that a breakthrough is imminent. Just what kind of control will first appear, and what kind or kinds will ultimately be successful, is not yet clear.

GLOSSARY

Algorithm A set of software instructions causing a digital computer to go through a prescribed routine. Because embedded computer engine controls have become so common, algorithm has become essentially synonymous with control law for automotive engineers.

Compression leveling A (theoretical) type of engine control which would cause each piston in each cylinder to compress its air charge to the same maximum pressure.

Dynamometer A machine to absorb power in a controlled manner, especially from an engine under test.

Hooke's law A relationship for an ideal elastic member which says that the displacement is proportional to the force.

Interdigitated An arrangement of two multiple-finger structures such that each pair of fingers from one structure has a finger from the other interposed.

Pulse sequential A type of fuel control for gasoline spark-ignited engines in which the fuel for each cylinder is injected into the air manifold near the intake valve for that cylinder just as it opens.

Robust Able to survive and operate properly in a severe environment.

Stoichiometric Pertaining to a combustion process in which the oxidizing agent (oxygen) and the reducing agent (fuel) are in balance such that, were the reaction to go to completion, there would be neither oxygen nor fuel left over, and all the reaction products such as carbon monoxide would be oxidized to their highest state—carbon dioxide.

Torsional Hooke's law A relationship for an ideal elastic shaft which says that the angle through which the shaft twists is proportional to the torque.

Torque The moment tending to make the output shaft of an engine turn. Torque can be expressed as a force acting perpendicular to a lever arm at a distance from the center of rotation. Its units are Newton-meters (pound force-feet).

Unit injector A type of fuel control for diesel engines which has fuel metered into a piston-barrel injector for injection into a specific cylinder at a specific time. Each engine cylinder has its own cam-driven injector, which operates something like a hypodermic syringe.

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For biographical information on William G. Wolber, see Chap. 8.

CHAPTER 10

ACTUATORS

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10.1 PREFACE

10.1.1 Introductory Remarks

Numerous open- and closed-loop control systems find application in modern production vehicles, where they provide improved operating characteristics together with enhanced safety, comfort, and environmental compatibility.

The actuators respond to position commands from the electronic control unit to regulate energy, mass, and volume flows.

10.1.2 Actuators: Basic Design and Operating Principles

Conventional final-control elements (standard and spool valves, etc.) have been familiar for some time. A provision for electronic control is required for actuator applications in modern vehicles. The actuator consists of a transformer to convert the input signal from the control unit into (usually) mechanical output quantities, and the conventional final-control element which it governs. (See Fig. 10.1.)

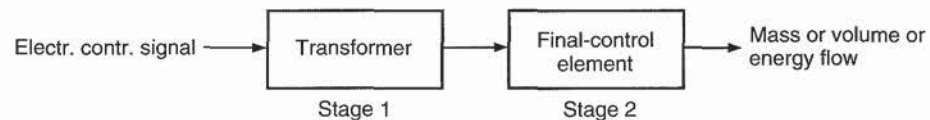


FIGURE 10.1 Basic actuator elements.

Either the control unit or the actuator itself will feature an integral electronic output amplifier. The energy conversion principles (stage 1) determine the classification of the actuators. Electromechanical actuators will also be discussed in the following pages.

10.1

10.2 TYPES OF ELECTROMECHANICAL ACTUATORS

10.2.1 Magnetic Actuators

dc Solenoids

Actuator Principles. In order to operate, actuators depend on the forces found at the interfaces in a coil-generated magnetic field when current passes through it. The solenoid actuation force F_m is calculated as

$$F_m = \frac{A B^2}{2 \mu_0} \tag{10.1}$$

where A = pole face area
 B = magnetic induction
 μ_0 = permeability constant ($\mu_0 = 4 \pi 10^{-7}$ Vs/Am)

On the flat-armature solenoid illustrated in Fig. 10.2a, the total solenoid force is $2 F_m$. Equation (10.1) can also be applied to versions equipped with a permanent magnet (Fig. 10.2b). A particular solenoid force is specified for each technical application. The pole face area, the magnetic circuit, and the coil are then determined for this force.

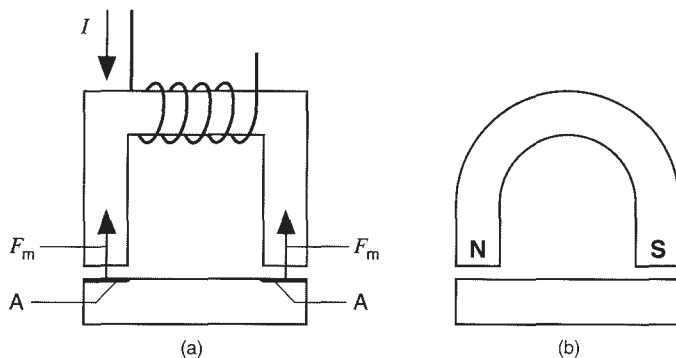


FIGURE 10.2 Flat-armature solenoid featuring field excitation (a) via coil; (b) via permanent magnet.

Determining Magnetic Circuit and Coil Specifications. The magnetic circuit consists of the working gap (between the armature and the base) and the ferrous regions. Permeability in iron is approximately three orders of magnitude greater than in air. For this reason, the iron regions conduct the field. If the effects of leakage flux are discounted, the absence of magnetic charge, $\oint B \cdot dA = 0$, means that the magnetic flux Φ_m remains constant for all cross sections A in the magnetic circuit:

$$\Phi_m = \iint_{A_1} B \cdot dA_1 = \iint_{A_2} B \cdot dA_2 = \iint_{A_i} B \cdot dA_i = \text{const.} \tag{10.2}$$

If the magnetic induction is assumed to be homogeneous for all cross sections A_i , then Eq. (10.2) can be simplified to:

$$\Phi_m = B_1 A_1 = B_2 A_2 = B_i A_i = \text{const.} \tag{10.3}$$

The induction lines run at a 90° angle to the surfaces A_i . Equation (10.3) defines the magnetic induction in each section of the magnetic circuit (Fig. 10.3). If, as an example, Index 1 is assigned to the gap section, then B_1 and A_1 are derived with the assistance of Eq. (10.1), and one can proceed to calculate B_i for the other sections.

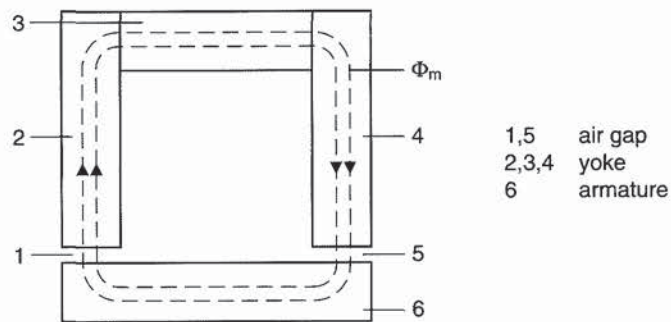


FIGURE 10.3 Magnetic circuit divided into individual sections.

The magnitude of the magnetic field strength H_i is determined by the material properties (permeability μ_{ri}) of the section in question. Field strength H_i :

$$B_i = \mu_0 \mu_{ri} H_i \tag{10.4}$$

In air, $\mu_r = 1$. In ferromagnetic materials, μ_r does not remain constant. Rather, it varies as a function of the magnetic field strength H (see Fig. 10.4). The relationship between B and H is defined by the B - H -curve.

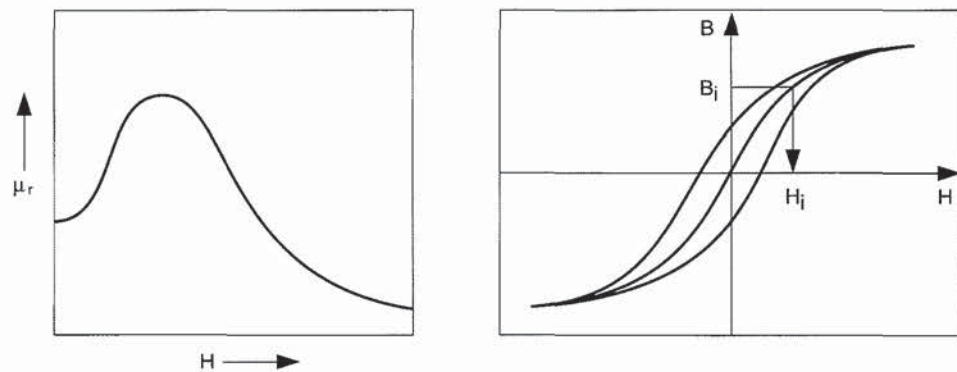


FIGURE 10.4 Progression of permeability and B - H curve.

Using the magnetic voltage $V_{mi} = \int H_i ds$ for the individual section, it is possible to calculate the peripheral magnetic voltage as the sum of the individual magnetic voltages V_{mi} . According to Ampere's law,

$$\Theta = \int H ds \tag{10.5}$$

this magnetic peripheral voltage is equal to the magnetomotive force Θ . It defines the *total current* of the coil, $\Theta = I w$. (I = current, w = number of windings.)

Because the preceding calculation fails to consider leakage flux, the results must frequently be treated as approximations only. It is possible to increase the precision of the calculations by portraying the magnetic circuit as a general network (with gaps and iron regions as reluctance elements) instead of as a series circuit. The results will then reflect the effects of a large proportion of the leakage flux. Maximum precision is achieved with numeric field calculations, which provide numerical solution of Maxwell's equations.

After magnetomotive force Θ has been determined, the field coil must be dimensioned to produce the required magnetic field. The formulas contained in Fig. 10.5 can be employed to determine the field coil's specifications. For a graphic interpretation, see Fig. 10.6.

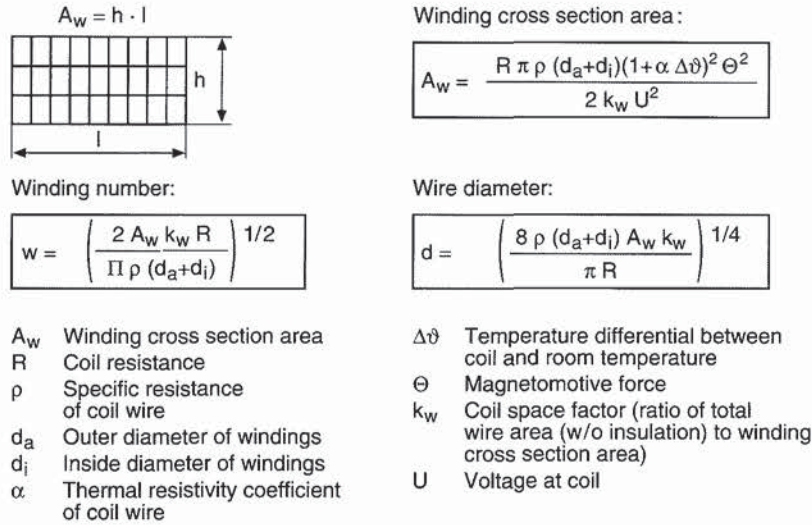


FIGURE 10.5 Determining coil data for specified coil resistance and voltage levels.

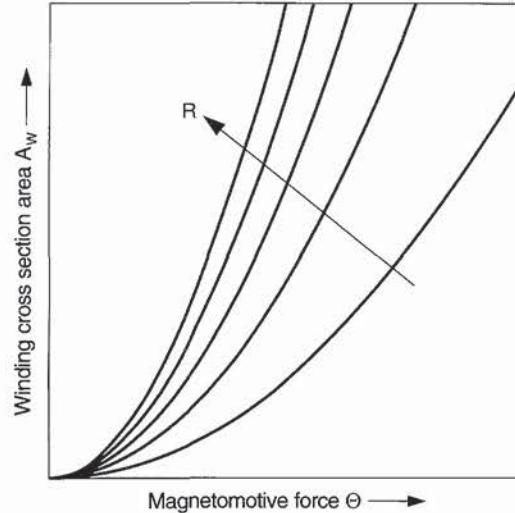


FIGURE 10.6 Area of winding A_w as function of magnetomotive force Θ (parameter coil resistance).

To minimize the size of the solenoid assembly, the magnetic circuit and the coil must be dimensioned to produce the smallest overall size. The formulas for coil dimensions (Fig. 10.7) can be used to minimize the volume of pot-shaped solenoids.

$$\frac{l}{d} \approx 1.5 \quad \frac{h}{d} \approx 0.4 \dots 0.5$$

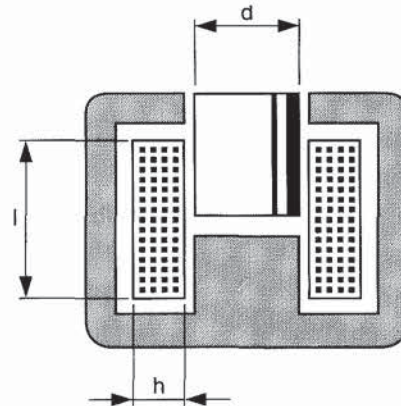


FIGURE 10.7 Selecting coil dimensions for pot-shaped solenoids.

In general, the solenoid is iteratively optimized by changing geometry in those critical areas within the magnetic circuit requiring a high magnetic voltage V_{mi} . The magnetomotive force Θ is then recalculated for the modified magnetic circuit. Figure 10.8 shows the optimization of solenoid diameter D for a particular armature diameter d .

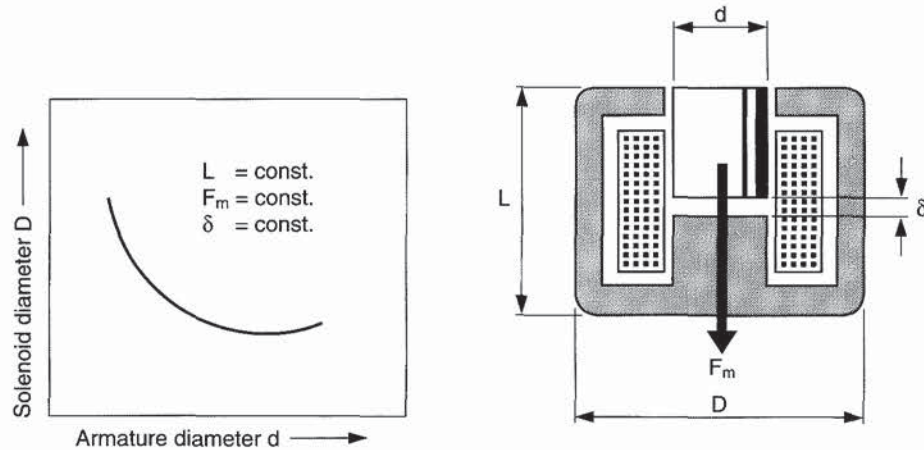


FIGURE 10.8 Relationship between solenoid and armature diameters.

Magnetic Force Curve. When the unit is intended for use in an actuator, the relationship between magnetic force and stroke will be required. With a flat armature and base, and without including the iron regions, Ampere's law [Eq. (10.5)] and Eq. (10.4) provide the following:

$$\Theta = H_{\delta} \delta = \frac{B_{\delta} \delta}{\mu_0} \tag{10.6}$$

where δ = working gap

Together with the force relationship, Eq. (10.1), the following result is obtained:

$$F_m = \frac{\Theta^2 \mu_0 A_1}{2 \delta^2}, \text{ i.e., } F_m \sim \frac{1}{\delta^2} \quad (10.7)$$

The substantial drop in magnetic force will be undesirable in many applications. Modifications to the curve for magnetic force versus stroke represent an alternative to increases in solenoid dimensions. This expedient can be effected through control of the current in the coil or by means of design modifications to the armature and base (see Fig. 10.9).

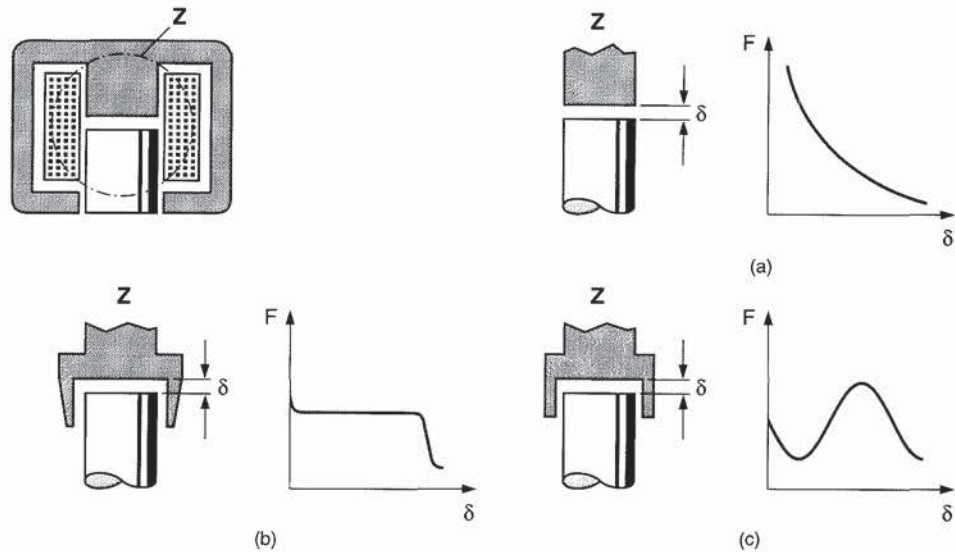


FIGURE 10.9 Design modifications and force curve.

The areas below the force-travel curves, a measure of the work performed, are always the same.

$$\int_0^{\infty} F_m(\delta) d\delta = \text{const.} \quad (10.8)$$

with $I = \text{const.}$

Configuration c can be employed together with a spring to produce a proportional solenoid in which armature travel can be regulated as a function of current. This type of system is sensitive to interference from extraneous factors such as mechanical friction, and hydraulic and pneumatic forces. Thus, final-control systems for high-precision applications must also incorporate a position sensor and a controller (Fig. 10.10).

Dynamic Response. To show the dynamic response pattern more clearly, Fig. 10.11 provides a schematic illustration of the progression over time of three parameters: voltage u at the excitation coil, excitation current i , and armature position s .

The dynamic response pattern can be calculated using computer programs that apply Maxwell's equations (field propagation with eddy currents, self-induction) in conjunction with the motion equation.

Approximation formulas can be employed to derive rapid estimates (eddy currents and magnetic resistance in the iron regions are not taken into account):

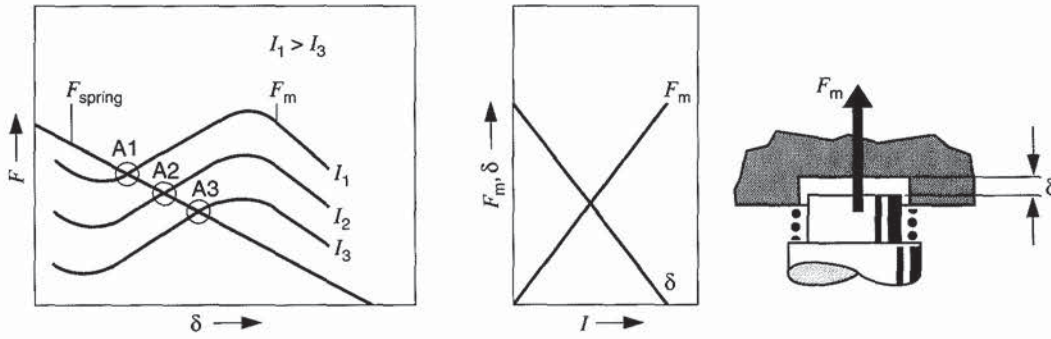


FIGURE 10.10 Operating points of a proportional solenoid.

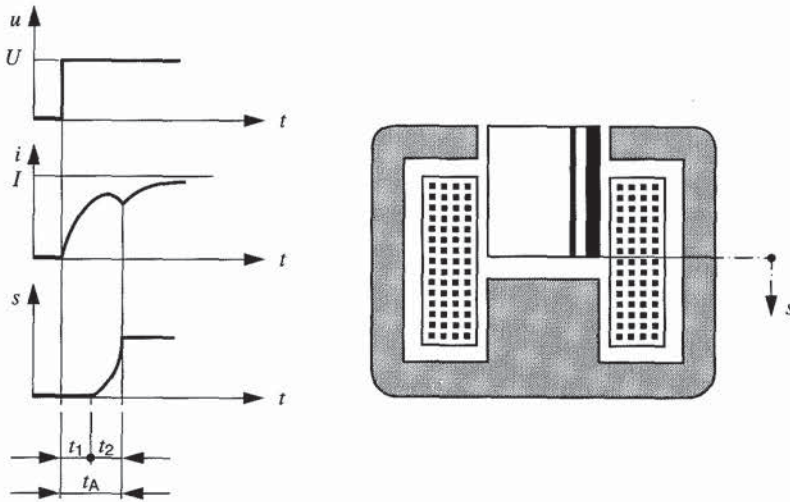


FIGURE 10.11 Progression of voltage, current, and armature travel.

$$t_1 \approx \frac{L_o}{R} \ln \frac{1}{1 - \frac{R}{U} \left(\frac{2 F_{mech} \delta_o}{L_o} \right)^{1/2}} \tag{10.9a}$$

$$t_2 \approx \left(\frac{3 \delta_o m}{U \left(\frac{F_{mech}}{2 \delta_o L_o} \right)^{1/2} - R \frac{F_{mech}}{L_o}} \right)^{1/3} \tag{10.9b}$$

where L_o = initial inductance
 R = coil resistance
 U = voltage at solenoid
 δ_o = gap with armature lowered
 F_{mech} = armature counterforce (treated as constant)
 and t_1, t_2 , see Fig. 10.11

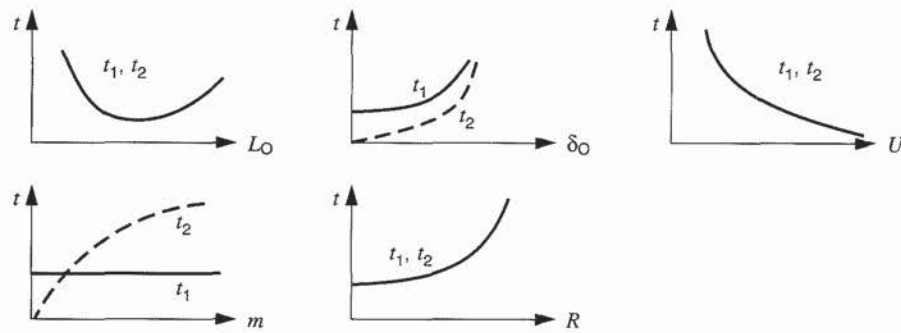

FIGURE 10.12 Relationships of t_1 and t_2 .

Figure 10.12 provides an overview of the relationships between t_1 and t_2 and the parameters.

The eddy currents must also be considered in calculations dealing with electromagnets intended for operation at high speeds or switching frequencies. When the excitation current is applied suddenly, the progress over time for the magnetic force is

$$F_m(t) = F_{m0} (1 - e^{-t/\tau})^2 \quad \text{for field generation}$$

and

$$F_m(t) = F_{m0} e^{-2t/\tau} \quad \text{for field dissipation}$$

with

$$\tau = \frac{\mu_0 l_{Fe} ab}{\pi^2 \rho \delta (a/b + b/a)} \quad \text{for rectangular cross sections}$$

with

$$\tau = \frac{\mu_0 l_{Fe} d^2}{4 (2.405)^2 \rho \delta} \quad \text{for circular cross sections}$$

where F_{m0} = static solenoid force according to Eq. (10.1)

t = time

l_{Fe} = length of iron core in which eddy currents occur

a/b = height/width of iron core (rectangular cross section)

d = diameter of iron core (circular cross section)

ρ = specific resistance

δ = working gap

Lamination to inhibit eddy currents in dc solenoids is not a standard procedure; its application is restricted to extreme cases.

Figures 10.6 and 10.12 illustrate the fact that at a given voltage, small coil resistances will furnish a small coil and short activation times. However, these benefits are accompanied by a simultaneous increase in the power loss $P_v = U^2/R$. The coil is thus designed to operate at the maximum permissible temperature.

Torque Motors. The torque motor consists of a stator and an armature—both made of soft magnetic material—and a permanent magnet. The pivoting armature can be equipped with either one or two coils.

Figure 10.13a shows only the magnetic flux generated by the permanent magnet. The armature is resting at the center position. The magnitude of the magnetic induction is the same at all

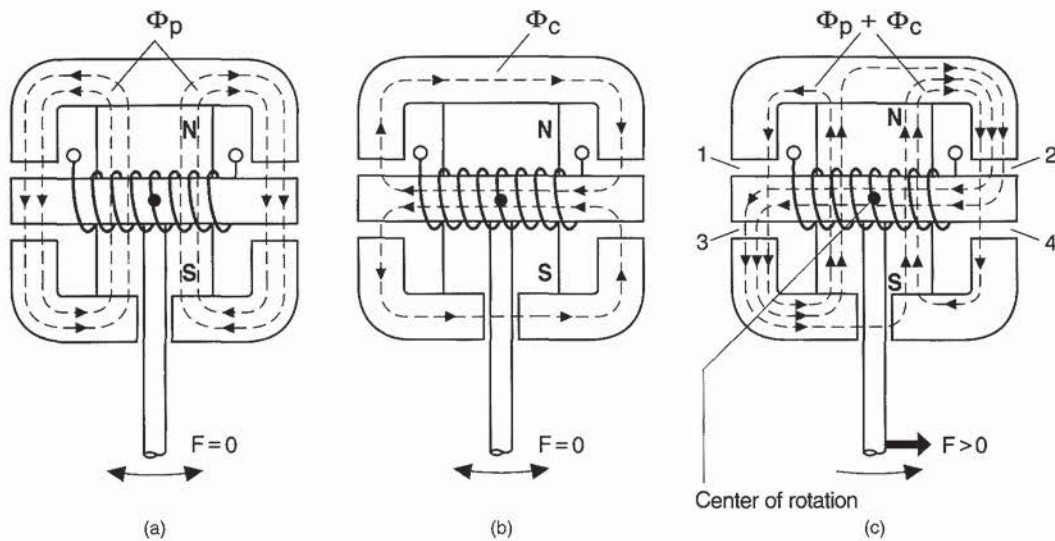


FIGURE 10.13 Design and operation of the torque motor.

gaps. Because equal amounts of force are generated at the armature ends, the forces acting on it exercise a mutual canceling effect.

Figure 10.13b illustrates only that magnetic flux which is generated at the coil. Figure 10.13c shows the cumulative pattern for the fluxes from *a* and *b*, with increased flow at gaps 2 and 3 ($\Phi_p/2 + \Phi_c/2$) accompanied by reductions at gaps 1 and 4 ($\Phi_p/2 - \Phi_c/2$). Using Eq. (10.1), the torque in the center position is

$$M = F_m r = \frac{r A B_p}{2 s} w I, \text{ i.e., } M \sim I \quad (10.10)$$

where r = armature radius

A = pole face area

B_p = magnetic induction in gap generated by permanent magnet

s = length of gap

w = number of coil windings

I = current.

Torque motors are used for applications in which substantial forces are required over small operating angles. They react more rapidly than electromagnets. In hydraulic and pneumatic applications, torque motors deliver good performance as drive units for flapper and nozzle systems.

Electromagnetic Step Motors. Electromagnetic step motors are drive elements in which a special design operates in conjunction with pulse-shaped control signals to carry out rotary or linear stepped movements. Thus, one complete rotation of the motor shaft will be composed of a precisely defined number of increments, step angles ϕ_0 . The magnitude of these angles is determined by the phase number q , the pole pair number p , and by the number of teeth z in the step motor. The step motor is thus capable of transforming digital control signals directly into discontinuous rotary motion. In principle, the step motor is essentially a combination of dc solenoids. The calculations employed for dc solenoids are thus also suitable for application with electromagnetic step motors. Depending upon the configuration of the magnetic circuit, a distinction is made between three types of step motors: the variable-reluctance step motor (neutral magnetic circuit), heteropolar units (polarized magnetic circuit), and hybrid devices.

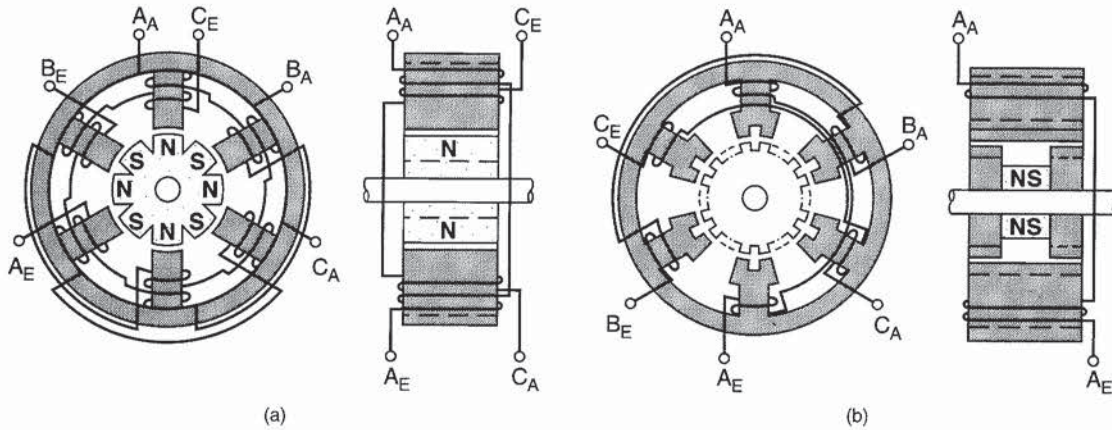


FIGURE 10.14 (a) Heteropolar step motor and (b) hybrid step motor.

Due to its positive operating characteristics (holding force available in power-off state, improved cushioning, lower control power requirement for a given volume), the polarized step motor has come to be the most widely applied (see Fig. 10.14).

Drive systems featuring electromagnetic step motors combine the following characteristics:

- Field forces induce controllable, incremental movements (minimal wear).
- Precisely graduated movements can be generated using an open-loop control circuit (without position monitors or feedback signals).
- High torque remains available at low angular velocities and in single-step operation.
- Brushless motor design makes it possible to create drive systems which combine reliability with long service life.

The operating characteristics of the rotational step motor can be described with the aid of a stationary torque-angle ($M-\phi$) curve. A reasonable approximation can be obtained using sinus-shaped curves with a phase displacement reflecting the switching states of the phase windings (A, B, C) (Fig. 10.15a). Assuming that external torque inputs can be excluded, the

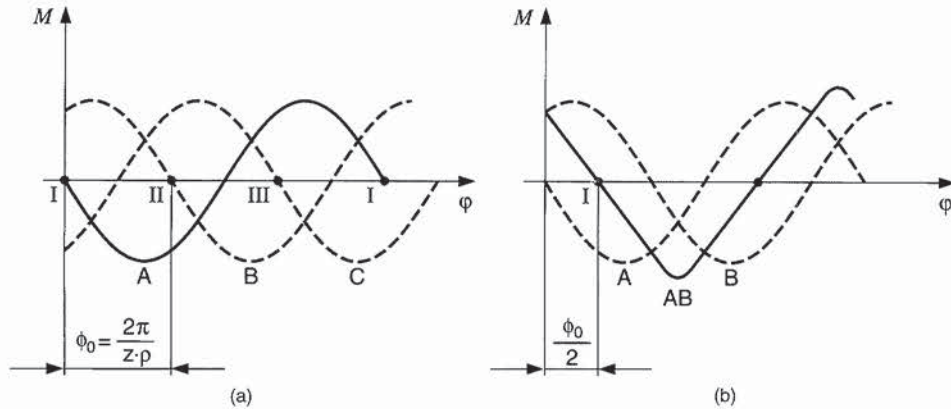


FIGURE 10.15 (a) Stationary torque-angle characteristics and (b) step-halved.

armature's stable position will be found where the backslope of the curve intersects the abscissa ($I, \Sigma M = 0, dM/d\phi < 0$). Phase B, C, etc., can then be activated to perpetuate rotation. The periodicity of the stable positions I, II, III is the step angle ϕ_0 .

If phase A is followed by simultaneous excitation of A and B with current pulses of the same amplitude, the result is a summing pattern corresponding to Fig. 10.15b. The geometric step angle ϕ_0 can then be halved. Alternatively, simultaneous excitation with current pulses of different amplitudes (current control) can be used to subdivide ϕ_0 to almost any degree desired (microstep operation). However, the use of this strategy to enhance the step motor's positioning precision is not possible due to manufacturing tolerances. When step motors are used in drive systems which rely upon open-loop control methods, avoiding stepping errors becomes an important priority (synchronous response).

For critical applications, dynamic simulation of the step drive system's dynamic response pattern is recommended. Here, a good approximation is derived by portraying the step motor using a transfer function of a second-order system. Dynamic response can also be evaluated using the torque-step frequency pattern (M - f pattern) for potential step-error-free operation in a start-stop frequency range, Fig. 10.16a, and an operating frequency range, Fig. 10.16b.

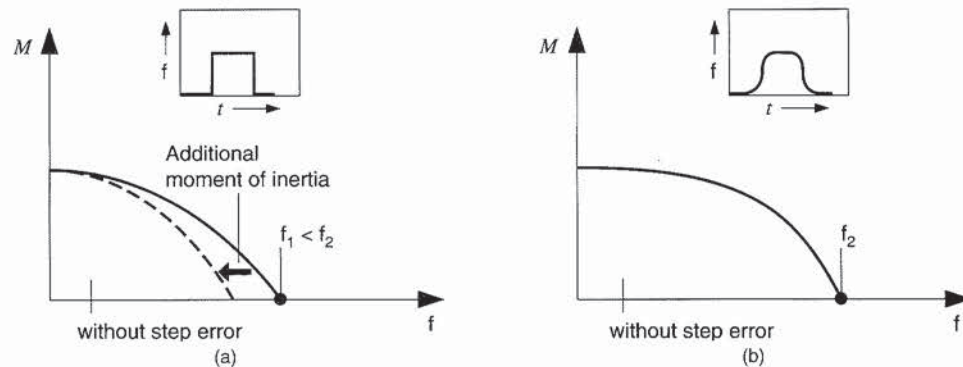


FIGURE 10.16 Torque-step frequency characteristic.

The range in which step error does not occur contracts in response to additional inertial torques or mobile masses. Impressed current induces an upward shift in the potential frequency range which is larger than that derived from impressed voltage. This demonstrates that the step motor's response pattern is strongly influenced by the electronic control strategy. The stepping frequency controls the angular velocity, the pulse distribution ($A \rightarrow B$ or $A \rightarrow C$, see Fig. 10.15) determines the direction of rotation, and the number of pulses governs the pivot angle.

Step motors are only suitable for use as direct-drive elements (the motor's armature operates directly against the actuated unit, no gear drive) in those applications where the influence of load fluctuations and interference factors remains limited, as stepping errors can otherwise occur. For this reason, digital linear actuators featuring integrated rotary step motors and threaded spindles are becoming increasingly popular as linear-motion generators in high-demand applications. When operated within a closed-loop control system, step motors can provide improvements in dynamics, positioning precision, and sturdiness. However, the cost advantages associated with open-loop operation are forfeited.

Moving Coils. The moving coil is an electrodynamic device (force applied to current-saturated conductor in a magnetic field). A spring-mounted coil is located in the ring gap of a magnetic circuit featuring a permanent magnet. When current flows through the coil, a force is exerted against it. The direction of this force is determined by the flow direction of the current itself.

The positioning force can be calculated using

$$F = B_A L_w I, \text{ i.e., } F \sim I \tag{10.11}$$

where B_A = magnetic induction in the gap
 L_w = length of the coil wire
 I = excitation current

As the force is not affected by the travel position, a spring can be included to produce a proportional relationship between travel and current.

The advantages of the moving coil include low hysteresis and good linear response. Low mass acts in combination with low coil inductance to provide excellent dynamic-response characteristics. The main liabilities of this design lie in the low force and limited work per stroke for any given unit dimensions.

dc Motors. dc motors are used to discharge a multiplicity of functions in modern cars (today up to 70 motors per vehicle). These motors are generally permanently excited dc devices, as the magnetic field remains continually available without additional energy consumption. For economic reasons, these units are virtually always equipped with ferrite magnets.

Design and Operation. The dc motor depends for its operation on the forces generated in a conductor within a magnetic field when current is applied.

The permanent-magnet-excited motor consists of

- The magnetic circuit consisting of a permanent magnet for generation and an iron core and a stator frame to conduct the magnetic flux
- Energized coils
- Carbon brushes and commutator, arranged to direct the current to the rotating coil while maintaining the force flow in a single direction

The stationary characteristic can be represented using the following equations (see Fig. 10.17).

$$U_1 = IR + U_i \tag{10.12a}$$

$$U_i = c z \Phi \omega \tag{10.12b}$$

$$M_i = M_v + M = c z \Phi I \tag{10.12c}$$

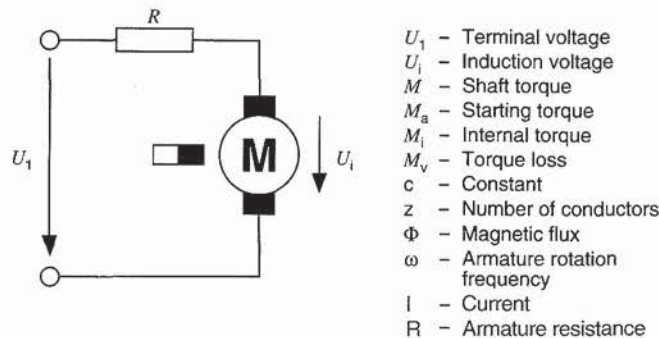


FIGURE 10.17 dc motor, circuit diagram.

After inserting Eqs. (10.12b) and (10.12c) in (10.12a), with

$$\omega_{0i} = \frac{U_1}{c z \Phi} \quad (\text{ideal idle speed}) \quad (10.13a)$$

$$M_a = c z \Phi \frac{U_1}{R} - M_v \quad (\text{stall torque}) \quad (10.13b)$$

one obtains

$$\omega = \omega_{0i} \left(1 - \frac{M + M_v}{M_a + M_v} \right) \quad (10.14)$$

or, with idle speed $\omega_0 = \omega(M=0)$

$$\omega = \omega_0 \left(1 - \frac{M}{M_a} \right) \quad (10.15)$$

The motor draws power P_1 from the dc circuit.

$$P_1 = U_1 I \quad (10.16)$$

or

$$P_1 = \frac{U_1}{c z \Phi} (M_v + M) = \omega_0 \frac{M_v + M_a}{M_a} (M_v + M) \quad (10.17)$$

The output at the shaft is the mechanical power P_2

$$P_2 = M \omega = M \omega_0 \left(1 - \frac{M}{M_a} \right) \quad (10.18)$$

Using Eqs. (10.17) and (10.18), the efficiency η can be calculated as a function of the shaft torque.

$$\eta = \frac{P_2}{P_1} = \frac{M(M - M_a)(M_v + M_a)}{M_a(M_v + M)} \quad (10.19)$$

Maximum efficiency as a function of load is obtained by setting the derivative $d\eta/dM = 0$ with

$$M_{\max} = M_v + [M_v(M_v + M_a)]^{1/2} \quad (10.20)$$

In comparison, the output power derived with Eq. (10.18) reaches a maximum at $M = M_a/2$, and thus at a higher value.

Figure 10.18 shows a performance diagram with speed n , current I , and efficiency η as function of the load torque M . It is not possible to determine speed and current separately.

Equations (10.12a) through (10.20) illustrate the interactions and the factors that affect the motor's performance curve. The influence of the design parameters is shown in Fig. 10.19.

The magnetic flux Φ is determined by the dimensions and intrinsic material characteristics of the magnet, and by the stack length of the armature and the rest of the magnetic circuit. The speed/torque curve responds to increasing magnetic flux Φ by tilting progressively to the horizontal axis; this response pattern is indicative of a more powerful motor (see Fig. 10.19a).

Variations in the number of turns z change the idle speed n_0 at the same starting torque (see Fig. 10.19b); changes in the armature's resistance (produced by selecting a different wire diameter d) affect the stall current, and thus the stall torque, obtained at any given idle speed n_0 (see Fig. 10.19c). The maximum achievable copper content is determined by the winding technique.

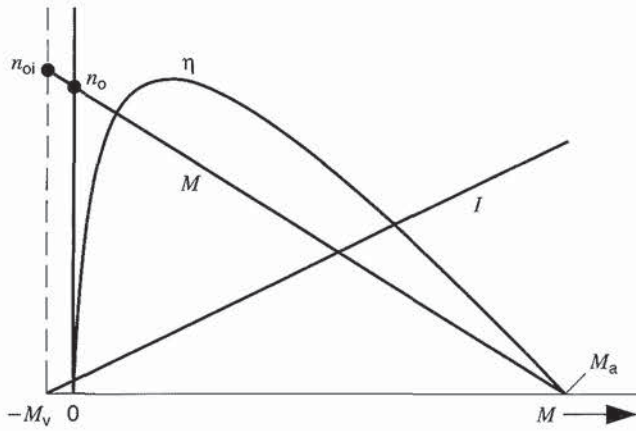


FIGURE 10.18 Motor performance curve.

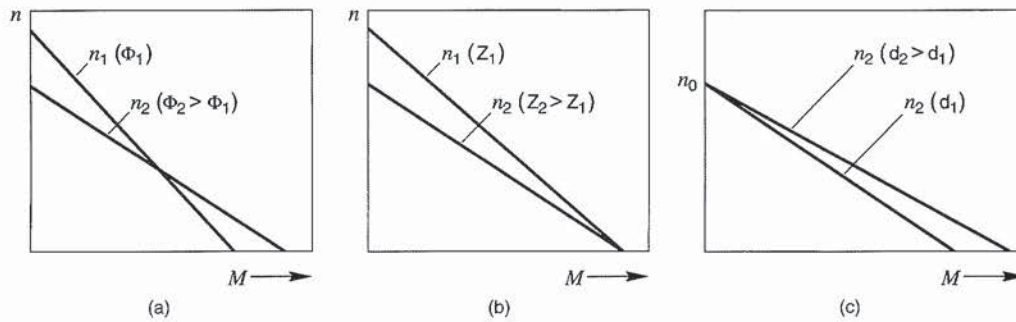


FIGURE 10.19 Effect of design parameters on rotational speed.

Units used in real-world applications display small deviations from the theoretical performance curve as a result of voltage drop at the carbon brushes, the current transfer to the commutator, the armature reaction field produced by the motor's current, and, finally, various rotational and flux losses.

The options for using the electrical parameters to affect the rotating speed are illustrated in Fig. 10.20. Variations in the voltage U (e.g., of the kind produced electronically with a pulse-width modulation) produce a parallel displacement in the speed curve (Fig. 10.20a). Other common options include the installation of a ballast resistor R_v and the inclusion of a third carbon brush. Less common (due to cost) is a design in which the winding is divided between two commutators; these can then be activated individually, in parallel, or in series. Servo motors generally operate for brief periods of time, but also over the entire range represented by the unit's characteristic curve.

Each motor must be built specifically for the operating conditions anticipated for the individual vehicle. Ferrite magnets must be selected for the lowest potential temperature, as it is here that the resistance to demagnetization is lowest. When circumstances demand, thermostats can also be included to provide protection against overheating.

Automotive actuators must be small and light. Motor volume is directly proportional to torque requirement. At the same time, the power output is proportional to torque multiplied

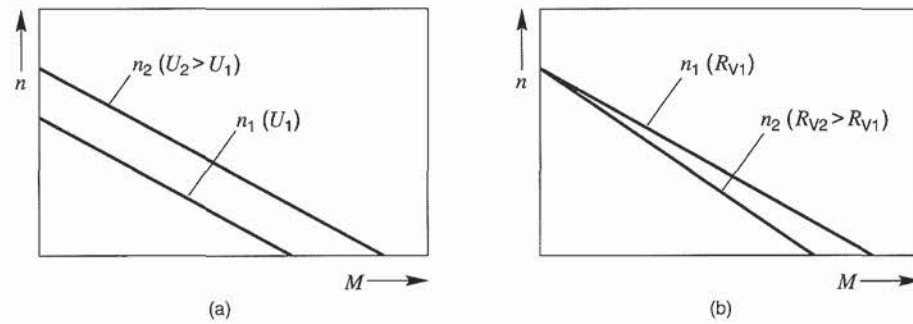


FIGURE 10.20 Speed variations in dc motors.

by rotating speed. Thus, the output can be increased by raising the operating speed; here the accompanying rise in noise levels is the limiting factor. Small motors are equipped with gear-drive units to obtain the required levels of actuating force.

Magnetostrictive Actuators. Ferromagnetic materials respond to increased magnetic field strength by expanding or contracting (magnetostrictive effect). This is due to the Weiss' domains turning in the field direction. The maximum contraction obtained with iron is $-8 \mu\text{m/m}$. Highly magnetostrictive materials composed of rare-earth/iron alloys display a maximum elongation of 1500 to 2000 $\mu\text{m/m}$. Maximum potential elongation is obtained at the optimal mechanical pre-tension T_0 (Fig. 10.21).

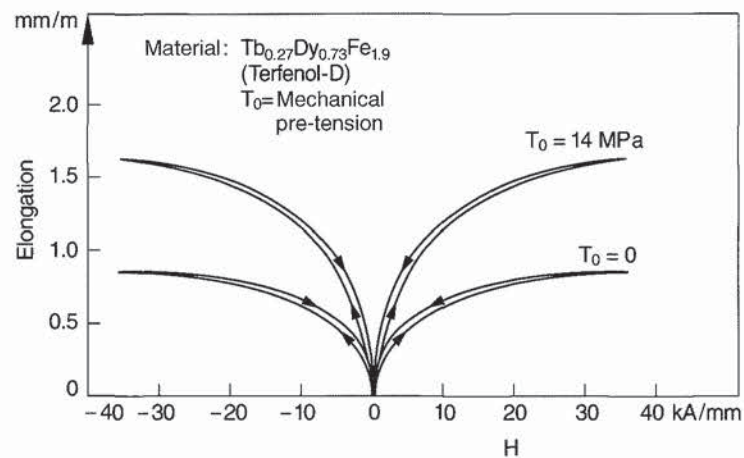


FIGURE 10.21 Magnetostrictive form variations as a function of field strength.

The specific advantages of the magnetostrictive transformer are high actuator forces, rapid response, good rigidity, and a high level of electromechanical efficiency.

The disadvantages include the small variations in length, the high power loss associated with generation of the large maximum field strengths which the unit requires (also in static operation), the length variation with hysteresis, the expense, and the limited availability of the requisite materials. The material is also brittle and difficult to machine.

The commercial availability of the transformers is limited to units designed for research purposes. We are not familiar with any applications in production motor vehicles.

10.2.2 Electrical Actuators

Piezoelectric Actuators. When mechanical compression and tension are brought to bear on a piezoelectric body, they produce an asymmetrical displacement in the crystal structure and in the charge centers of the affected crystal ions. The result is charge separation. An electric voltage proportional to the mechanical pressure can be measured at the metallic electrodes (direct piezoelectric effect).

If electric voltage is applied to the electrodes on this same body, it will respond with a change in shape; the volume remains constant. This reciprocal piezoelectric effect can be exploited to produce actuators. Sintered ceramics, lead-zirconate-titanate (PZT), are the commonly used materials for these applications. The precise composition can be modified to obtain the desired material characteristics. The magnitude of the shape change depends on the electric field strength E . The relevant equation is $E = U / s$ (U = voltage, s = electrode gap). Single-element actuators require field strengths of up to 2 kV/mm and therefore very high voltage to achieve maximum travel (see Fig. 10.22).

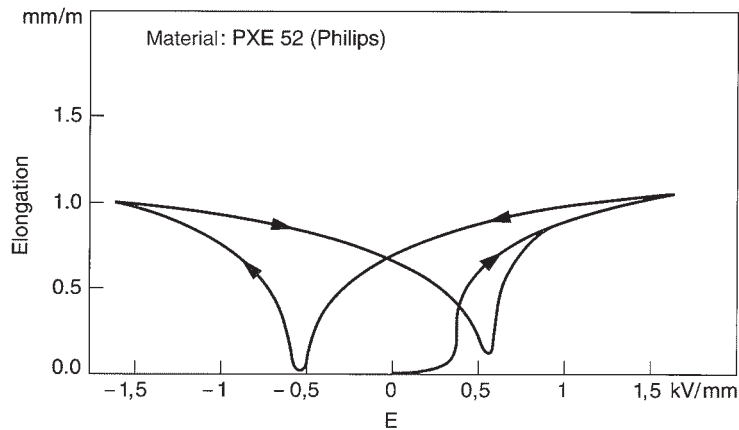


FIGURE 10.22 Form changes as a function of electric field strength.

Stacked-design translational devices consist of piezoelectric layers of between 0.3 and 1 mm in thickness, featuring a metallic electrode between each layer. This design is employed to lower the voltage (down to, for instance, 800 V) while simultaneously increasing the excursion rate. The layers are electrically parallel and form a series circuit (see Fig. 10.23a).

Flex elements are formed by joining two layers with varying intrinsic rates of elongation. The elongation occurs along the vertical axis of the direction in which the field strength is projected (transverse effect). Flex elements display larger excursion rates with lower actuating forces (see Fig. 10.23b).

New manufacturing techniques make it possible to produce multilayer piezoelectric devices with thinner layers; these can be used to obtain the required field strength at voltages as low as approximately 100 V and below.

However, due to the numerous parallel elements, the advantages associated with the low control voltage are obtained only at the price of increased capacitance and higher operating currents.

The positive attributes of the piezoelectric actuator include a high dynamic response level, substantial actuator force, voltage-proportional elongation, excursion with no power consumption in static operation, and (practically) no wear in the piezoelectric element.

The corresponding liabilities include minimal elongation changes, high operating voltage, hysteresis during elongation, a temperature-sensitive stroke, and a drift in operating response as the unit ages. The material itself is brittle and difficult to machine.

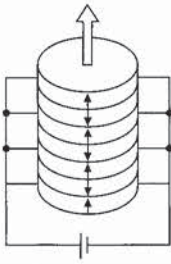
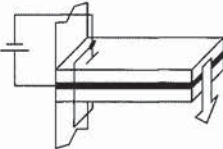
| | a | b |
|--|---|---|
| Elongation Δl | Parallel to electrical field | Perpendicular to electrical field |
| Design types |  |  |
| Typical regulation distance and elongation | $\frac{\Delta l}{l_0} = 0.17\%$ | $\Delta l \leq 1000 \mu\text{m}$ and more |
| max. statical load | $\leq 35\,000 \text{ N}$ | $\leq 0.01 \dots 0.05 \text{ N}$ |
| Typical operation voltage | 150 ... 1000 V 50 ... 150 V (multilayer) | 10 ... 300 V |

FIGURE 10.23 Design and specifications of different transformer versions.

Piezoelectric actuators are applied in precision positioning devices and as active oscillation dampers. Potential automotive applications (with a voltage supply of 12 V) have yet to be thoroughly investigated. However, it is expected that the piezoelectric actuator—and the multilayer stacked-design device in particular—will gain popularity in closed-loop automotive control systems, where they will serve as a replacement for the conventional actuator in applications requiring a higher level of performance.

Electrostatic Actuators. In the past, use of electrical field forces was restricted to some measurement devices and to the acceleration of charged particles. Microactuator technology makes it possible to apply these small forces in mechanical drive devices. These devices combine high switching speeds with much smaller energy loss than that found in electromagnetic actuators. The disadvantages are the force/travel limitations and the high operating voltages. At present, microactuators are rarely encountered outside the research laboratories; thus, the electrostatic actuator's current commercial significance is negligible.

Electrorheological Fluids. The electrorheological effect is based on polarization processes in minute particles suspended in a fluid medium. These particles modify the fluid's viscosity according to the orientation in the electrical field. The effect can be employed to adjust the viscosity between "freely flowing" and "rigid." Reaction times are measured in ms. Among the disadvantages are interference factors, temperature sensitivity, high voltages, control powers of several hundred watts, and the price, which is still high. The electrorheological effect is exploited in controlled transfer and damping elements.

10.2.3 Thermal Actuators

Temperature-Sensitive Bimetallic Elements. The temperature-sensitive bimetallic element is composed of at least two bonded components of varying thermal-expansion coefficients. When heat is applied, the components expand at different rates, causing the bimetallic element to bend. When electrically generated heat is applied, these devices become actuators.

The passive component is characterized by a lower thermal-expansion coefficient. Meanwhile, the active component should maintain a constant coefficient of thermal expansion over the largest possible range.

The passive element in the most common type of temperature-sensitive bimetallic device is invar (FeNi_{36}), while the active component is an alloy of iron, nickel, and manganese ($\text{FeNi}_{20}\text{Mn}_6$). Common element configurations include strips, coils, spirals, and wafers. Temperature-sensitive bimetallic devices are readily available and inexpensive. They can be applied at temperatures of up to roughly 650°C , and display a high degree of consistency in their shape-change response (up to several million cycles). The drawbacks include the modest actuator forces, the low work potential for a given volume (energy density), and the fact that only a single type of shape modification (flexural) is possible.

Memory Alloys. Memory alloys are metallic materials which exhibit a substantial degree of “shape memory.” The explanation for this phenomenon can be found in the reversible, thermoelastic martensitic transformation, in which two different crystal structures are adopted. As long as the temperature remains below the transformation threshold, the structure remains martensitic. However, when the alloy is heated beyond the transformation temperature, it responds by becoming austenitic.

The element’s shape is changed permanently by the one-way effect. If the element is heated to beyond the transformation temperature, it returns to its former shape. If the component is then reshaped after cooling, the entire process can be repeated. Thermomechanical pretreatment processes can be employed to achieve a two-way effect. The component then assumes one defined shape when heated, and another when cooled.

Yet another phenomenon is superelasticity. Application of loads produces an extension of up to 10 percent; the effect is reversed once the load is removed. However, because this effect is extremely sensitive to temperature, it has yet to be employed in the construction of actuators. The materials are commercially available, the base materials are nickel-titanium (NiTi –) and copper-zinc-aluminum alloys (CuZnAl –). The transformation temperatures of these alloys lie between -100 and $+100^\circ\text{C}$, with the one-way effect also being obtained outside this range.

The benefits of memory alloys include the high effective output for a given volume and the ability to complete work cycles within a minimal temperature interval of 10 to 30°C . The memory components can be formed to suit the particular application. The wire’s resistance can be employed for direct heating. The material itself can be formed with or without physical machining, and can also be welded. Among the disadvantages must be counted the limited thermal range of application and the high price.

Memory alloys are used as drive, final-control, and triggering elements in various technical applications (automotive, household appliances, heating and climate control, medical technology, etc.). The forms assumed by the actual components include triggering wires, coil springs, and flex and torsion elements.

The memory element can be used as sensor and actuator—for instance, in a liquid medium—in which temperature changes will induce shape changes in the component.

Expansion Elements. The expansion element exploits the volume-versus-temperature response of specific solid and fluid media which exhibit large coefficients of thermal expansion. The volumetric response is converted to a stroke motion. The expansion medium is housed in a rigid container. The motion is converted to a stroke using diaphragms or elastomer inserts. Electrically controlled expansion elements find application as actuators. Expansion elements are inexpensive and robust, and combine large stroke travel with substantial positioning forces.

However, these devices are only suitable for application within a limited temperature range. Their dynamic response is also less than overwhelming. Expansion elements are widely applied in automotive technology (for instance, choke actuators on carbureted engines).

10.3 AUTOMOTIVE ACTUATORS

10.3.1 Antilock Braking

(See Chap. 15 and **traction control systems**, Chap. 16.)

Both antilock braking systems (ABS) and traction control systems (ASR) limit the rate of slip between tire and road surface. These systems enhance vehicle stability and steering response while maintaining optimal braking and acceleration characteristics. ABS and ASR employ a single set of actuators to modulate braking pressure. In addition, ASR devices supplement braking intervention by adjusting engine output.

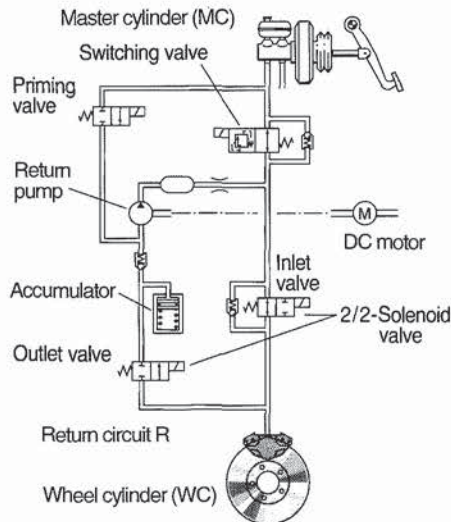


FIGURE 10.24 ABS/ASR hydraulic circuitry.

Actuators for Braking Intervention. Braking pressure is regulated normally via 2/2 solenoid valves (valves with two ports and two switch positions, see Fig. 10.24). When no current is applied, the inlet valve remains open and the outlet valve is closed, allowing unrestricted wheel braking.

ABS/ASR systems modulate pressure by controlling two 2/2 solenoids for each wheel or for two wheels of one axle. With no current, the inlet valve remains open while the outlet valve stays closed. To maintain pressure, current is applied to the inlet valve. Pressure release is obtained by transmitting current to both valves.

Various pulse sequences applied to the inlet valve generate a step-by-step increase of the wheel braking pressure (wheel brake pressure modulation).

Using the same pulse sequence for the outlet valve while the inlet valve remains closed, a step-by-step brake pressure decrease in the wheel cylinders is achieved. Switching and priming valves of a 2/2 type can be incorporated in the circuit to provide the additional functions required for the ASR (Fig. 10.25).

Solenoid Valve Design. One part of the magnetic circuit is located in the hydraulic chamber; here the armature and the pole piece simultaneously serve as valve elements in a design known as the wet solenoid. The solenoid coil and the other part of the magnetic iron circuit are located outside the hydraulic chamber. This design requires the presence of a pressure-resistant sealing element. This element must also be nonmagnetic, in order to ensure that the magnetic flux flows through the working gap and the armature in the desired fashion.

The solenoid circuit is designed to provide reliable switching and pressure maintenance at maximum temperature (maximum coil resistance), minimum voltage, and maximum pressure. At the same time, armature clearance and residual gap must both be adequate to ensure that the valve continues to function at low temperatures (brake-fluid viscosity changes exponentially (by three powers of ten) in the range between -40 and $+120$ °C). The maximum operating pressures can extend in extreme cases to more than 200 bar. Typical switching times are 4 to 10 ms. Dynamic response is evaluated according to the pressure variation at a specified control pulse. The duty-cycle requirements for ABS are minimal, but ASR switching and priming valves must be capable of 100 percent permanent duty. The maximum cycle numbers correspond to several million actuations.

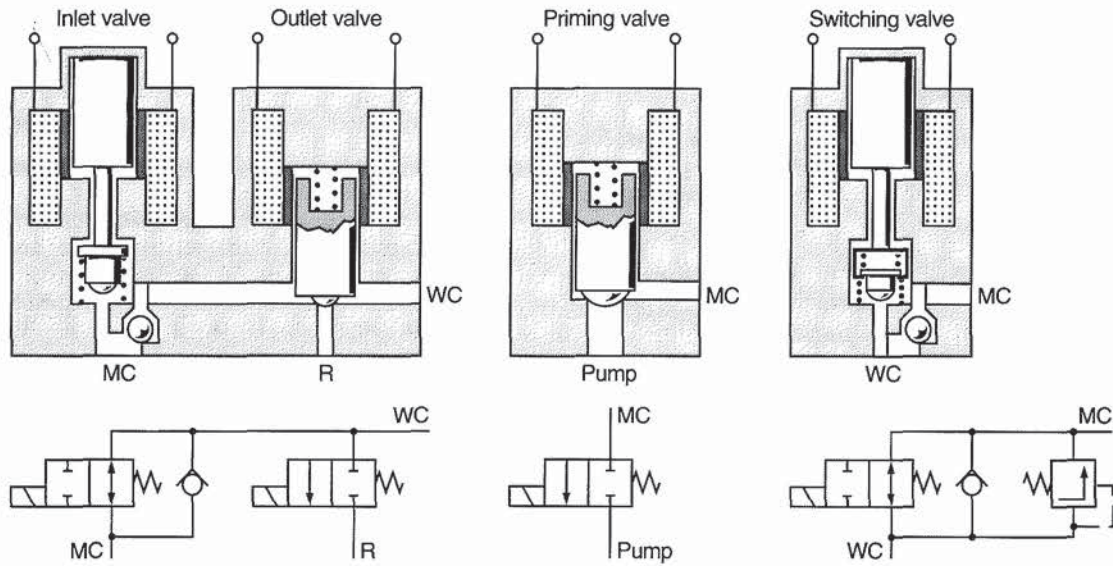


FIGURE 10.25 2/2 solenoid valves for ABS/ASR.

ETC with Throttle-Aperture Adjustment. Either of two standard methods can be employed for throttle regulation. Electronic Throttle Control (ETC) systems feature an actuator (servo motor) mounted directly at the throttle valve. On systems incorporating a traction-control actuator, the actuator (servo motor) is installed in the throttle cable (Bowden cable).

The design configuration of the electronic throttle-control actuator is illustrated in Fig. 10.26. To enhance clarity and facilitate understanding, all rotating components (except the throttle plate) are portrayed as linear-motion devices. The throttle shaft travels between two

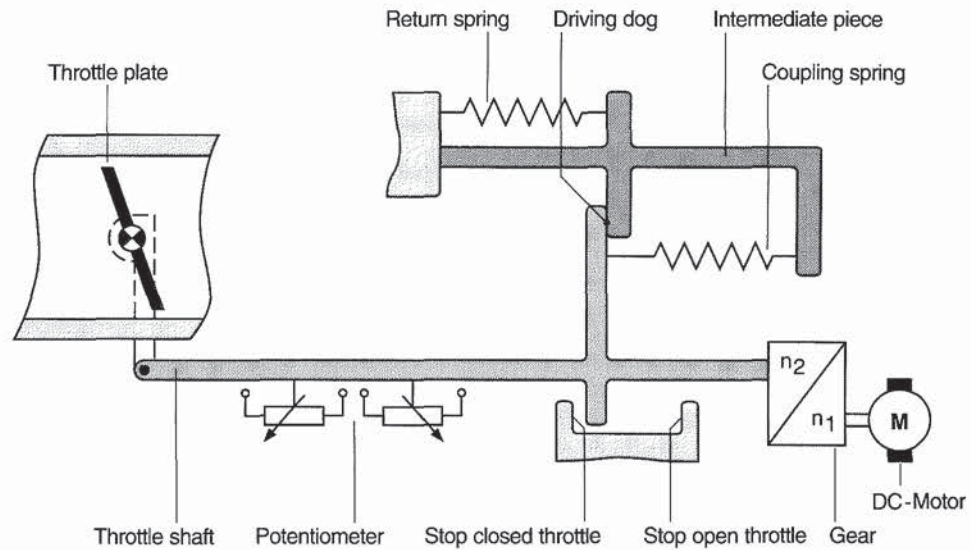


FIGURE 10.26 Operation of electronic throttle control.

motion limiters; these define the closed throttle and maximum aperture positions. The shaft is powered by a dc motor via a dual-gear drive. When the motor is off, a return spring pulls the intermediate piece back toward the idle-air stop. The driving dog pushes the throttle shaft toward the idle position. The coupling spring holds it in a defined idle position. This position corresponds to an idle speed ensuring adequate engine power to maintain power-steering and brake operation in the event of system failure.

Current can be applied to the dc motor in either direction. One direction opens the throttle plate and tensions the return spring. The other direction closes the throttle plate. When the throttle plate closes all the way, the coupling spring is tensioned. Two potentiometric throttle-position sensors are included in a design calculated to provide redundant system capacity. The electronic control unit uses the signals from these sensors to regulate motor current for the desired throttle position; the signals thus represent part of a closed-loop control system.

Traction-Control Actuator. The actuator can be installed in any of several locations within the engine compartment. No modifications to the throttle body are required.

Figure 10.27 illustrates the operating principles in a simplified linear flow pattern (the actuator components are actually rotary elements). The ends of the Bowden cable sections are connected to rotary cam/linkage spring assemblies.

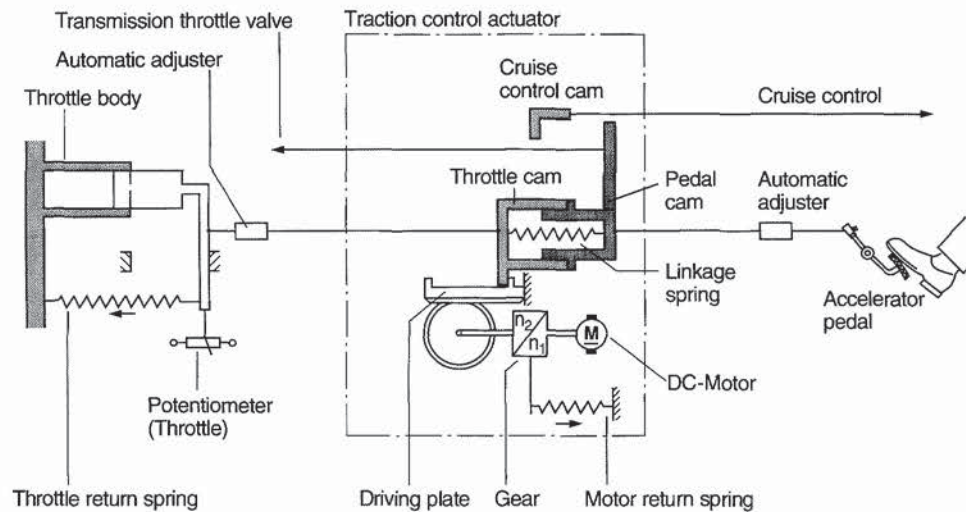


FIGURE 10.27 Operation of a traction-control actuator located between the accelerator pedal and throttle body.

Under normal operating conditions, the pressure applied at the accelerator pedal is relayed through the Bowden cable and linkage spring coupling to open the throttle valve. The servo motor comes to life when the ABS/ASR control unit transmits a command to reduce the throttle-valve aperture. The servo motor pulls the engagement mechanism to the left via gear drive and Bowden cable. Once the initial take-up range has been covered, the linkage is activated to reduce the throttle-valve opening. The servo motor is deactivated as soon as the ASR no longer requires throttle-valve regulation. A return spring then brings the motor back into its original position, allowing the traction control actuator to drive back to its original at rest position.

The traction-control actuator can also be used in conjunction with a cruise-control system. A separate cam connects the Bowden cable for the cruise control to the actuator assembly. This layout is employed to retain the option of traction-control intervention when the cruise-control system is activated.

Because the linkage spring must be considerably stronger than the throttle-return spring, it exerts a perceptible effect on the resistance at the accelerator pedal.

Another approach to engine intervention is embodied in a design in which the linkage spring is integrated within the throttle body. Yet a further option is to install a second throttle valve which remains open during normal operation; a separate Bowden cable is installed between this throttle body and the actuator to regulate the valve for active traction-control duties. Because the linkage spring is installed parallel to the throttle-return spring, the preload is substantially lower than that generated by the design described here; there is almost no perceptible feedback at the accelerator pedal. Actuator weight and dimensions are also reduced substantially.

10.3.2 Fuel-Injection for Spark-Ignition Engines

(See Chap. 12.)

Electronically controlled fuel injection systems meter fuel with the assistance of electromagnetic injectors. The injector's opening time determines the discharge of the correct amount of fuel.

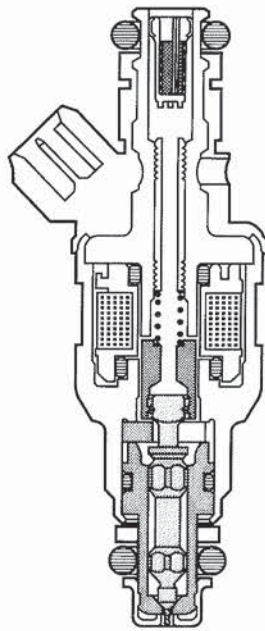


FIGURE 10.28 Injector unit for multipoint fuel injection system.

On single-point injection units, one injector unit is installed at a central location upstream from the throttle valve. Multipoint injection systems feature a separate injector at each cylinder (Fig. 10.28). This type of injector is located in the manifold tract just above the intake port into which it discharges its fuel.

Operating Requirements. The injectors are 2/2 valves with coaxial fuel inlet and lateral plug. They operate with minimal strokes of less than $\frac{1}{10}$ mm.

Besides the precise opening and closing, the reliable sealing and the discharge pattern which an individual injector provides are all largely determined by the design of its metering apparatus, thus exercising a major effect on starting and response, fuel consumption, and emissions.

Electromagnetic injectors have to fulfill the demand for precise fuel metering, consistent linear response at minimal quantities, extended dynamic flow range (DFR), good spray formation and atomization, positive seal at injector seat, resistance to corrosion, operating consistency, and low noise.

Low-resistance injectors with current-controlled output stages achieve shorter switching times. See Table 10.1.

10.3.3 Fuel Injection for Diesel Engines

Distributor-Type Fuel Injection Pumps contain rotary solenoid actuators for injection quantity, and two position valves for engine operation and shutoff.

The fuel quantity injected by an in-line pump is a function of control-rack position and pump speed (Fig. 10.29).

TABLE 10.1 Typical Injector Specifications

| | Units | Multipoint injection | Single-point injection |
|--|----------------|----------------------|------------------------|
| Line pressure . . . max. | kPa | 200–380 | 100–300 |
| Static flow at 250 kPa, at 100 kPa, | g/min g/min | 100–430 — | — 200–520 |
| Opening time | ms | 1.5 | 0.75 |
| Closing time | ms | 0.8 | 0.65 |
| Variation ratio (DFR) | | 1:10 | 1:16 |
| Durability >mio.cycle | | 1000 | 1000 |
| Needle/armature weight | g | 4.3 | 2.7 |
| Length | mm | 77 | 53 |

The control rack of an EDC in-line pump is shifted by a linear-motion solenoid with a conic armature and base for long stroke application (see pages 10.5 and 10.6). The actuator is attached directly to the pump.

When no current is applied to the linear-motion solenoid, a spring pushes the control rack into the stop position and thus interrupts fuel delivery. As current increases, the control-rack travel and, with it the injection quantity, increase.

Typical operating data of the solenoid actuator are (full load, stationary condition): rack travel 13 mm, spring force 32 N, ECU current output 6 A, 200 Hz. By pulsation of the ECU-current, the actuator friction is minimized. Maximum rack travel is about 20 mm.

The electronically controlled unit injector (Fig. 10.30) has been developed to meet the future emissions regulations by realizing high injection pressures and precise control of start of injection and injection quantity.

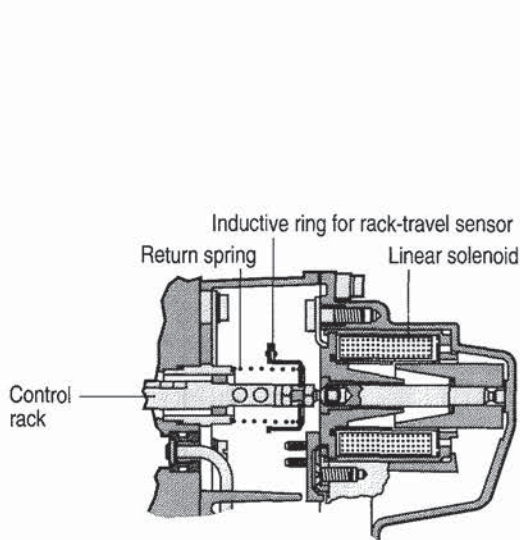


FIGURE 10.29 EDC linear-solenoid actuator.

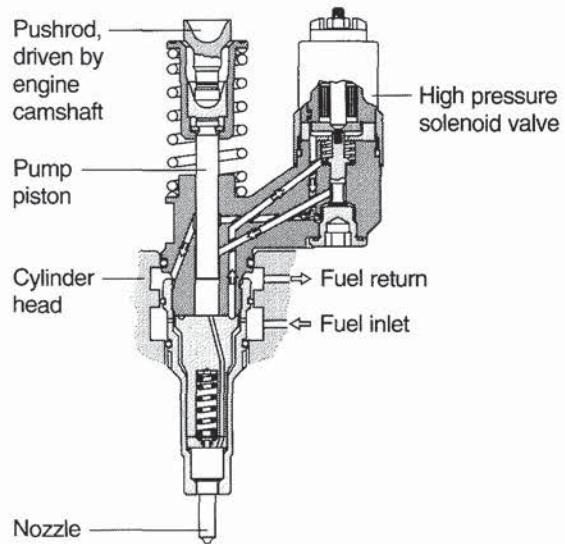


FIGURE 10.30 Unit injector.

The unit injector combines injection pump and injection nozzle into a single unit, which is installed directly into the engine cylinder head and driven by the engine camshaft. High injection pressures of 1600 bar and more are readily attainable due to low dead volume of compressible fuel.

In order to control start and end of injection, each unit injector contains a time-controlled high-speed solenoid valve. When the valve is open, the unit injector plunger delivers fuel to the low-pressure fuel supply circuit without any injection into the engine cylinder. When the solenoid valve is closed, fuel is delivered to the nozzle for injection into the engine cylinder. Thus, the fuel injection quantity is determined by the time interval between closing and opening of the valve.

Typical switching times for a medium duty/heavy duty truck application are: closing period at rated power, 1000 μ s; opening period at rated power, 600 μ s. The whole injection process must be completed within a period of about 1 to 2 ms. Consequently, the solenoid-valve motion must occur with an accuracy of less than 10 μ s in order to ensure compliance with the usual tolerances for fuel injection quantity and start of injection.

10.3.4 Actuators for Passenger Safety

(See Chap. 24.) Pyrotechnical actuators are used for passenger-restraint systems such as the air bag and the automatic seat belt tensioner. When an accident occurs, the actuators inflate the air bag (or tension the seat belt) at precisely the right instant. Specifications call for the belts to be fully tensioned ~ 10 ms after ignition, while ~ 30 ms are allowed between the ignition point and total inflation for the air bag.

Air bag actuators are available in various sizes, according to vehicle type and application (driver or passenger side), and they are dimensioned to generate gas volumes of between 30 and 200 dm³. The gases and gas mixtures used for these devices are nontoxic. The section following describes the operating principles for various actuator types.

Pyrotechnical Air Bag Inflator (Gas Generator). Figure 10.31 is an example of a driver-type inflator. When sufficient current is sent through the initiator, or squib, a thin metal filament covered by a sensitive pyrotechnic charge heats up and ignites this charge (Fig. 10.31a). The ignition of the squib provides enough energy to light a booster charge, whose combustion

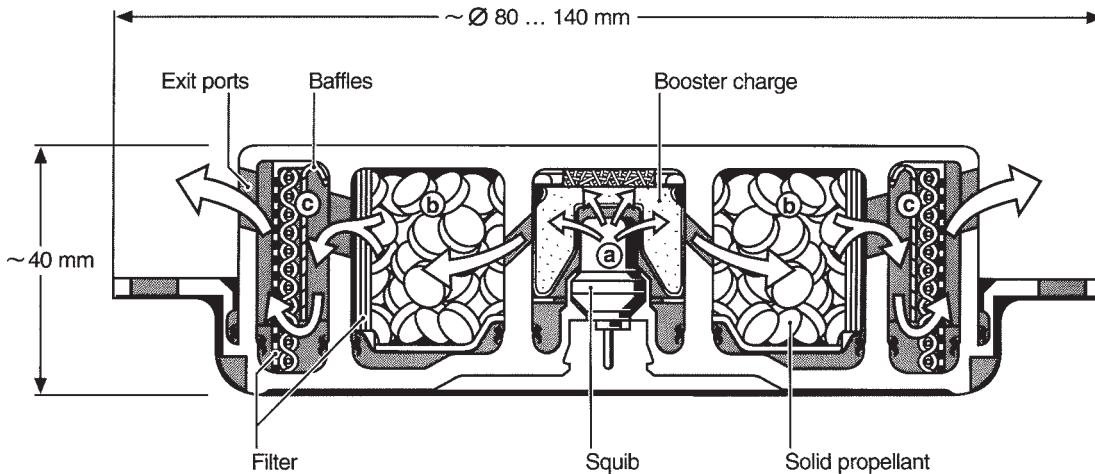


FIGURE 10.31 Gas generator.

builds up adequate pressure and heat to start the chemical reaction, converting the solid propellant, or gas generant, into gas (Fig. 10.31*b*). The resulting nontoxic hot gas flows over a series of screens, filters, and baffles, cooling down prior to leaving the inflator through exit ports located inside the air bag (Fig. 10.31*c*). The duration of this process is less than one-tenth of a second.

Hybrid (Compressed Gas and Pyrotechnic) Air Bag Inflator. Figure 10.32 is an example of a passenger-type tubular inflator. When sufficient current is sent through the initiator, or squib, a thin metal filament covered by a sensitive pyrotechnic charge heats up and ignites this charge (Fig. 10.32*a*). The ignition of the squib provides enough energy to propel a projectile through a rupture disk, allowing the escape of stored nontoxic compressed gas (Fig. 10.32*b*). The projectile also strikes two primers, lighting a solid pyrotechnic mass, which in turn heats the remaining stored gas (Fig. 10.32*c*). The expanding heated gas flows out of the inflator through exit ports located inside the air bag (Fig. 10.32*d*). The duration of this event is less than one-tenth of a second.

10.3.5 Actuators for Electronic Transmission Control

Continuous operation actuators are used to modulate pressure, while switching actuators function as supply and discharge valves for shift-point control.

In automatic transmissions, response times of 2 ms must be ensured in circuits with flow diameters of up to 2.4 mm, carrying up to 4 dm³ per minute at a differential pressure of 200 kPa, all within a temperature range extending from -40 to 150 °C; pressure can increase up to 2000 kPa.

On/Off Solenoids. Various versions of the on/off solenoid valve are in use (two-port, three-port, open base state, closed base state). These valves are normally employed for shifting gears, but can also serve in special applications such as control of converter lockup mechanisms or reverse lockouts. Substantial weight savings can be obtained from the use of plastics. On/off valves are controlled through basic switching output stages. Peak-and-hold control strategies can provide weight and size savings.

Variable-Pressure Solenoids (Pressure Regulators). Pressure regulation must remain precise during switching operations and when holding line pressure. Here, analog valves have

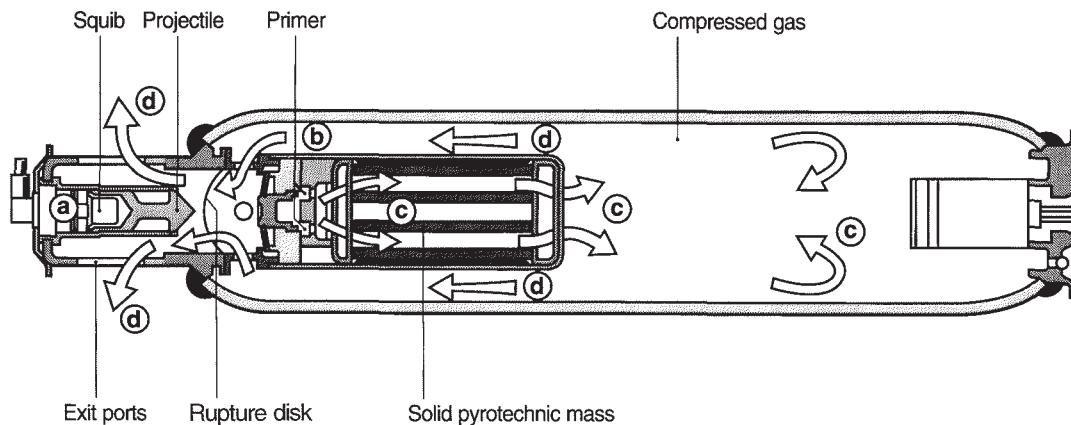


FIGURE 10.32 Hybrid air bag inflator.

proven extremely effective. Extremely stable output pressures are achieved by recirculating the controlled pressure to the valve element, making it possible to maintain stable output pressures in the face of interference factors like downstream leakage, supply-pressure fluctuations, and viscosity variations in the hydraulic fluid. Figure 10.33 shows a typical version of the three-way pressure-control valve, the spool valve. This design provides flow rates of $4 \text{ dm}^3/\text{min}$ at pressure differentials of 2 bar. In order to limit the effects of hysteresis on the pressure/flow response characteristic, mechanical friction must be minimized and materials with low coercive field force must be employed and heat-treating processes are also needed to minimize material-related hysteresis. Choppers in the current-controlled end stage reduce power loss and induce friction-reducing micromovement in the armature. Pressure regulators are also available as seat valves.

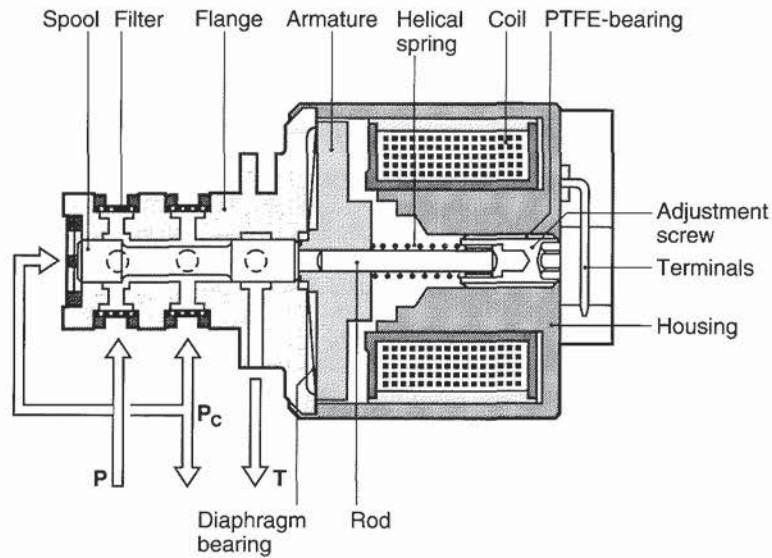


FIGURE 10.33 Variable-pressure solenoid.

PWM Solenoids (Pulse-Width Modulated Solenoid Valves). On/off poppet valves are particularly well suited for direct actuation from microcomputers. The component layout is less complicated than that found in proportional valves, allowing reductions in manufacturing costs. Because microcomputers operate on the basis of discrete time, equidistant setpoint selection, direct valve actuation via constant-frequency pulse represents the optimum design configuration.

When the solenoid-actuated valve is switched on and off at a constant supply pressure, the resulting average outlet pressure is a function of the ratio between open and closed states. However, this design lacks the proportional valve's ability to compensate for interference due to such factors as system leakage, temperature, and fluctuations in supply pressure. This type of actuator thus represents a reasonably priced alternative for applications in which the control pressure is not the controlled variable, but rather is used as a manipulated variable.

These units can be used in automatic transmissions to select gear ratios, or to reduce torque-converter slip losses by modulating the contact pressure of the lockup clutch. Simple switching output stages or peak-and-hold circuits govern the electric control signal to the PWM valve. When used in conjunction with the appropriate valve design, this type of control can be used to obtain cycle frequencies in excess of 100 Hz. In some applications, such as continuously variable transmissions (CVT), a life expectancy of 2×10^9 cycles is demanded.

10.3.6 Actuators for Headlight Vertical Aim Control

Devices enabling adjustment of headlight range enhance safety by maintaining the correct aim under all vehicle-load conditions. Range adjustment can be manual, with a driver-operated switch, or it can be automatic. The same headlight-adjustment actuators are employed for both designs. The actuator is mounted directly on the headlamp bracket or housing, and adjusts the headlight insert or the reflector.

The actuators are dc or step motors producing a rotary motion which gear-drive units then convert to linear movement. Due to the fixed relationship between the motor's incremental response (steps) and the attendant linear motion, no travel sensor is required with step motors. The total adjustment range extends as far as 8 mm. A single step corresponds to a turning angle of 15 degrees, or an adjustment travel of 0.03 mm. The motor returns to the initial (zero) position (mechanical travel limiter) each time the system is activated in order to prevent step losses.

The step motor combines the following advantages:

- Extremely precise positioning through digital control.
- High adjustment speeds of up to 8 mm/s; different control frequencies can be selected to obtain variations. This system allows graduated adjustment at constant vehicle speeds (consistent lighting) and rapid response during acceleration and braking.

10.4 TECHNOLOGY FOR FUTURE APPLICATION

The motivation to develop new actuators is created by the potential advantages of new manufacturing and driving techniques in combination with new materials. The following examples illustrate representative fields of innovation.

10.4.1 Micromechanical Valves

Micromechanics technology stems from the adaptation of production methods employed in microelectronics. Lithographic miniaturization procedures and etching and assembly techniques make it possible to manufacture minute structures with a high degree of precision. Micromechanical production methods have already become established in the field of sensor manufacture. Electronic circuitry and sensors can be manufactured from the same material (primarily silicon) in simultaneous production processes to furnish integrated components; the benefits associated with this process represent numerous potential advantages.

In automotive applications, microactuators display potential as elements in open-loop control systems where low control power is to be converted, for instance, regulating the flow of fluids in hydraulic or pneumatic systems and metering fuel.

For micromechanical manufacturing, valve designs are required in which planar units with relatively low structure heights are stacked. The energy conversion principles employed to operate the valves correspond to the planar structure (e.g., electrostatic drive, electrothermal or piezoelectric flux converters).

The pressure-balanced seat valve is a basic example of this kind of microvalve (Fig. 10.34). This type of microvalve is produced in a manufacturing process entailing sequential structuring and bonding of four wafers. Depending on the required dimensions for the single valve and the resulting surface requirement, as many as several hundred elements can be produced simultaneously on each wafer stack. Further efforts must be directed to solving packaging problems before these microstructures can be used to control fluid supply and discharge processes.

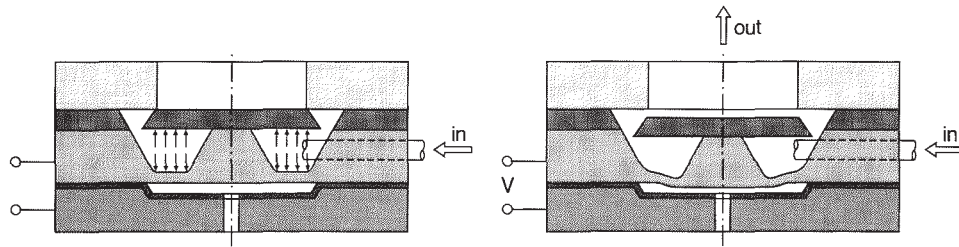


FIGURE 10.34 Pressure-compensated seat valve.

10.4.2 Positive-Engagement Friction Drives

Single piezoelectric actuators provide high dynamic positioning response over short actuating distances. The search for suitable mechanisms employing active piezoceramics to extend the effective travel range has given rise to a multiplicity of drive concepts sharing common attributes:

- Combination of single high-frequency motions (up to the ultrasonic range) to achieve a continuous drive movement
- Output element actuation using friction engagement

Ultrasonic Motor. Of all the designs utilizing piezoelectric actuator technology, the ultrasonic traveling wave device has reached the most advanced stage of development (Fig. 10.35). A stator ring featuring teeth on the upper surface, and made of a material providing low material damping (bronze), is flex-mounted on an end shield via a central diaphragm. A flat piezoceramic ring is bonded to the underside of the stator ring. This piezoring is polarized along the vertical axis of the ring plane. The direction of the polarization changes segmentally (Fig. 10.36).

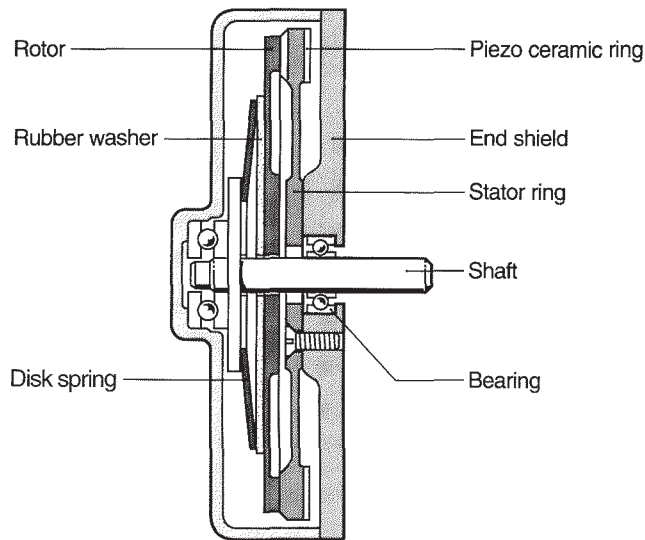


FIGURE 10.35 Traveling-wave motor, Shinsei type.

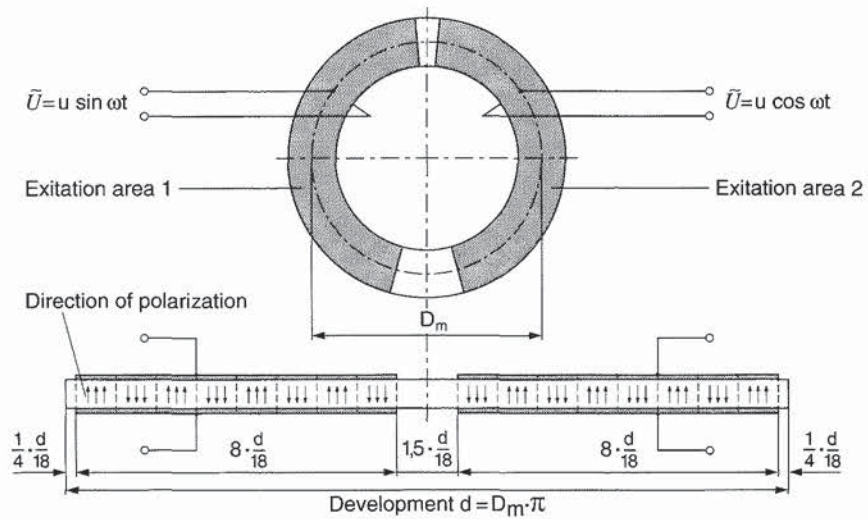


FIGURE 10.36 Segmentation and control of the piezoring.

The electrical contacts are arranged to provide two excitation regions, each featuring eight segments and two small zones. The zone length corresponds to either $\frac{1}{2}$ or $\frac{1}{8}$ segments. Thus a segment of the excitation zone extends through $\frac{1}{8}$ of the stator's circumference. When voltage is applied to an excitation region, the piezos of one polarization direction contract along the circumference direction (lateral piezo effect), while the piezos of the opposite polarization orientation expand. This effect produces a wave-shaped flux in the stator ring in the affected region.

If the region is then excited with ac voltage (for example, 100 V at approximately 40 kHz in existing motors), the result is an oscillation pattern which extends to encompass the entire stator ring. Excitation in the frequency of the ninth flex mode of the stator provokes a standing wave on the entire stator. Resonance step-up is employed to achieve amplitudes of 20 μm .

If an excitation current is now applied at the second excitation region with ac voltage at a 90° lateral displacement, the two waves overlap to form a traveling wave.

In addition to the up and down motion, one point on the upper surface of the stator produces—by means of tilting movement of those teeth which are situated above the neutral axis—a motion along the periphery ($\pm 2 \mu\text{m}$). When the two motions combine, the surface points move in an elliptical pattern (Fig. 10.37).

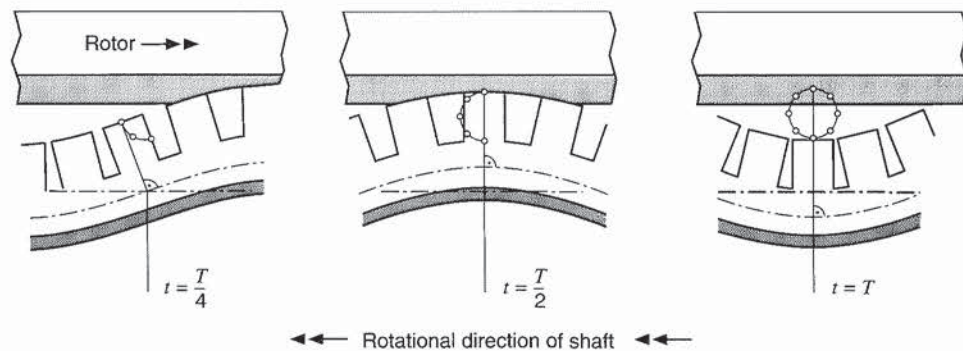


FIGURE 10.37 Drive mechanism.

A disc spring and a rubber washer are pressing the disk-shaped rotor in Fig. 10.35 against the stator. The elliptical motion of the stator teeth drives the rotor through friction contact with its contact layer. Speed is adjusted by, for example, varying the excitation frequency, with the stator's oscillation amplitude being monitored.

The salient characteristics of the ultrasonic motor are: high torque (up to 1.3 Nm), low rpm range (30 . . . 130 rpm), bidirectional operation, substantial characteristic retension force, free of clearance, no run-on, potentially precise positioning, noiseless operation, and flat unit configuration.

Ultrasonic motors are suitable for use as direct-drive devices. The disadvantages include the substantial, high-frequency control voltage, and the limitations on service life due to wear on the friction surface.

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GLOSSARY

Actuator The part of an open-loop or closed-loop control system which connects the electronic control unit with the process. The actuator consists of a transformer and a final-control element. Electric positioning signals are converted to mechanical output.

Closed-loop control A process by which a variable is continuously measured, compared with a reference variable, and changes as a result of this comparison in such a manner that the deviation from the reference variable is reduced. The purpose of closed-loop control is to bring the value of the output variable as close as possible to the value specified by the reference variable in spite of disturbances. In contrast to open-loop control, a closed-loop control system acts to offset the effect of all disturbances.

Commutator The commutator is a current switcher. For dc machines, the commutator switches the armature windings so that the resultant force always acts in the same rotary direction. This requires a reversal of the armature winding connection every 180°. The current supply to the armature is via brushes which contact the commutator.

Eddy current In metals moving in an inhomogeneous magnetic field or located in a changing magnetic field, induced currents circulate throughout the volume. Because of their general circulatory nature, these currents are referred to as eddy currents.

Ferrite magnet In small transformers where eddy current losses must be kept to a minimum, the cores are made of ferrites which are complex oxides of iron and other metals. These materials are ferromagnetic, but have relatively high resistivity.

Final-control element The second or last stage of an actuator to control mechanical output.

Numeric field calculation A method of numerically calculating fields with the help of computer programs, such as the methods of finite differences or finite elements.

Open-loop control A process within a system in which one or more input variables act on output variables based on the inherent characteristics of the system. An open control loop is a series of elements that act on one another as links in a chain. In an open control loop, only disturbances that are measured by the control unit can be addressed. The open loop has no effect on other disturbances.

Peripheral magnetic voltage The line integral of the magnetic field strength around a closed path.

$$V_m = \oint \mathbf{H} \cdot d\mathbf{s}$$

According to Ampere's law, the peripheral magnetic voltage is equal to the magnetomotive force Θ .

Piezoelectric effect The direct piezoelectric effect is the ability of a piezoelectric crystal to produce an electric voltage when subjected to a force. The inverse piezoelectric effect is the ability of a piezoelectric crystal to deform when subjected to an electric voltage.

Pilot-controlled actuator An actuator that uses one or more additional energy sources to transform the input signal to an output signal. The pilot-controlled actuator consists of a chain of energy positioners and energy transformers that produces an amplification due to their series configuration.

Self-induction Every current is surrounded by a magnetic field with field lines that are interlinked with the current lines. This leads to an induced source voltage in the conductor or coil when the current strength is changed. This phenomenon is called self-induction.

Weiss' domains Ferromagnetic materials have strong interaction among the atoms. Spontaneous local magnetization can occur, even though no external magnetic field is present. These so-called Weiss' domains, sized from 0.01 to 1 mm, are small elementary magnets, which are randomly distributed in the material and are first directed when an external field is applied.

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ABOUT THE AUTHOR

Klaus Müller, after studying mechanical engineering, was employed at the University of Karlsruhe, Germany, investigating the field dynamic behavior of air conditioning system components. In 1976, he joined Robert Bosch GmbH, Stuttgart, where he began his work in advanced engineering of planar oxygen sensors, combustion sensors, and signal evaluation. This was followed by product development of hydraulic units for antilock braking systems and traction control.

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CONTROL SYSTEMS

CHAPTER 11

AUTOMOTIVE MICROCONTROLLERS

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A microcontroller can be found at the heart of almost any automotive electronic control module or ECU in production today. Automotive systems such as antilock braking control (ABS), engine control, navigation, and vehicle dynamics all incorporate at least one microcontroller within their ECU to perform necessary control functions. Understanding the various features and offerings of microcontrollers that are available on the market today is important when making a selection for an application. This chapter is intended to provide a look at various microcontroller features and provide some insight into their characteristics from an automotive application point of view.

11.1 MICROCONTROLLER ARCHITECTURE AND PERFORMANCE CHARACTERISTICS

A microcontroller can essentially be thought of as a single-chip computer system and is often referred to as a single-chip microcomputer. It detects and processes input signals, and responds by asserting output signals to the rest of the ECU. Fabricated upon this highly integrated, single piece of silicon are all of the features necessary to perform embedded control functions. Microcontrollers are fabricated by many manufacturers and are offered in just about any imaginable mix of memory, I/O, and peripheral sets. The user customizes the operation of the microcontroller by programming it with his or her own unique program. The program configures the microcontroller to detect external events, manipulate the collected data, and respond with appropriate output. The user's program is commonly referred to as code and typically resides on-chip in either ROM or EPROM. In some cases where an excessive amount of code space is required, memory may exist off-chip on a separate piece of silicon. After power-up, a microcontroller executes the user's code and performs the desired embedded control function.

Microcontrollers differ from microprocessors in several ways. Microcontrollers can be thought of as a complete microcomputer on a chip that integrates a CPU with memory and various peripherals such as analog-to-digital converters (A/D), serial communication units (SIO, SSIO), high-speed input and output units (HSIO, EPA, PWM), timer/counter units, and

11.3

standard low-speed input/output ports (LSIO). Microcontrollers are designed to be embedded within event-driven control applications and generally have all necessary peripherals integrated onto the same piece of silicon. Microcontrollers are utilized in applications ranging from automotive ABS to household appliances in which the microcontroller's function is pre-defined and limited user interface is required.

Microprocessors, on the other hand, typically require external peripheral devices to perform their intended function and are not suited to be utilized in single-chip designs. Microprocessors basically consist of a CPU with register arrays and interrupt handlers. Peripherals such as A/D and HSIO are rarely integrated onto microprocessor silicon. Microprocessors are designed to process large quantities of data and have the capability to handle large amounts of external memory. Although microprocessors are typically utilized in applications which are much more human-interface and I/O intensive such as personal computers and office workstations, they are beginning to find their way into embedded applications.

Choosing a microcontroller for an application is a process that takes careful investigation and thought. Items such as memory size, frequency, bus size, I/O requirements, and temperature range are all basic requirements that must be considered when choosing a microcontroller. The microcontroller family must possess the performance capability necessary to successfully accomplish the intended task. The family should also provide a memory, I/O, and frequency growth path that allows easy upgradability to meet market demands. Additionally, the microcontroller must meet the application's thermal requirements in order to guarantee functionality over the intended operating temperature range. Items such as these must all be considered when choosing a microcontroller for an automotive application.

11.1.1 Block Diagram

Usually the first item a designer will see when opening a microcontroller data book or data sheet is a block diagram. A block diagram provides a high-level pictorial representation of a microcontroller and depicts the various peripherals, I/O, and memory functions the microcontroller has to offer. The block diagram gives the designer a quick indication if the particular microcontroller will meet the basic memory, I/O, and peripheral needs of their application. Figure 11.1 shows a block diagram for a state-of-the-art microcontroller. It depicts 32 Kbytes

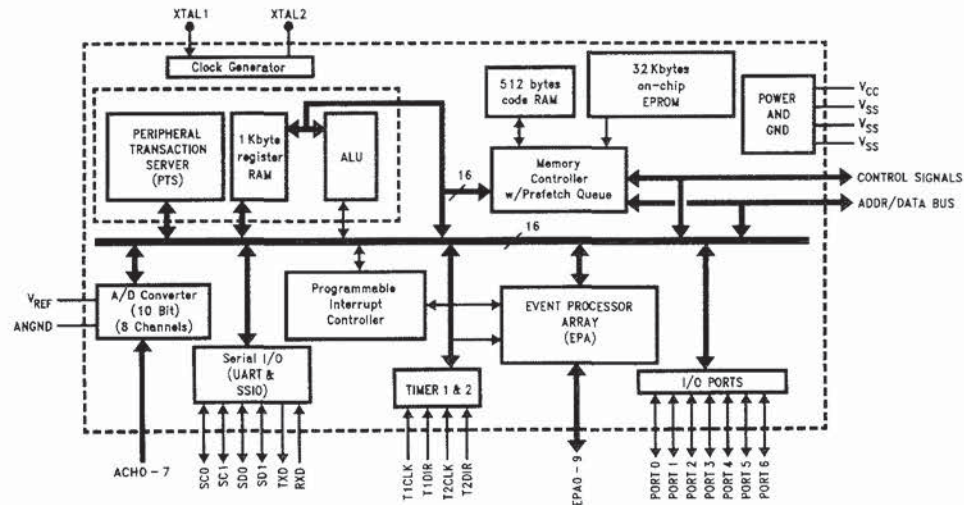


FIGURE 11.1 Microcontroller block diagram.

of EPROM, 1 Kbyte of register RAM, 6 I/O ports, an A-to-D converter, 2 timers, high-speed input/output (I/O) channels, as well as many other peripherals. These features may be “excessive” to a designer looking for a microcontroller to implement in an automotive trip-computer application but would be excellently suited for automotive ABS/traction control or engine control.

11.1.2 Pin-Out Diagram

A microcontroller’s pin-out diagram is used to specify the functions assigned to pins relative to their position on a given package. An example pin-out diagram is shown in Fig. 11.2. Note that most pins have multiple functions assigned to them. Pins that can support more than one function are referred to as multifunction pins. The default function for multifunction pins is normally that of low-speed input and output (discussed later in this chapter). If the user should wish to select the secondary or special function associated with the pin, he or she can do so by writing to the appropriate special function register. There are some exceptions. A good example is pins used for interfacing to external memory. If the device is instructed to power-up executing from external memory as opposed to on-chip memory, the address data bus and associated control pins will revert to their special function as opposed to low-speed I/O.

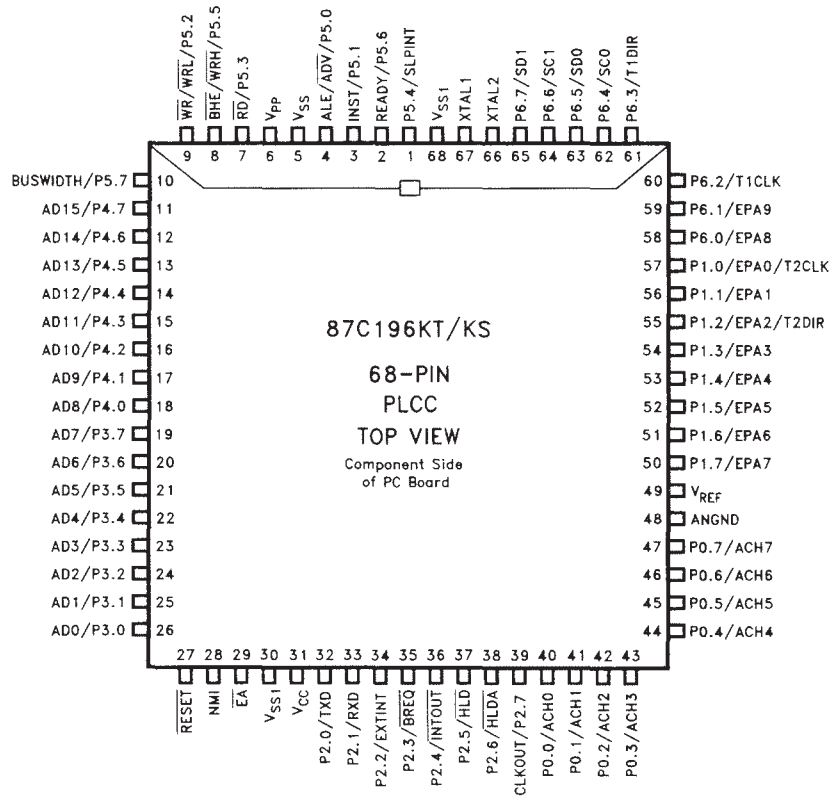


FIGURE 11.2 Microcontroller pin-out diagram.

11.1.3 Central Processing Unit

The central processing unit or CPU can be thought of as the brain of a microcontroller. The CPU is the circuitry within a microcontroller where instructions are executed and decisions are made. Mathematical calculations, data processing, and control signal generation all take place within the CPU. Major components of the CPU include the arithmetic logic unit (ALU), register file, instruction register, and a microcode engine. The CPU is connected to the bus controller and other peripherals via a bidirectional data bus.

Microcontrollers are, for the most part, digital devices. As digital devices, microcontrollers utilize a binary numbering system with a base of 2. Binary data digits or *bits* are expressed as either a logic "1" (boolean value of true) or a logic "0" (boolean value of false). In a 5-V system, a logic "1" may be simply defined as a +5-V state and a logic "0" may be defined as a 0-V state. A bit is a single memory or register location that can contain either a logic "1" or a logic "0" state. Bits of data can be arranged as a *nibble* (4 bits of data), a *byte* (8 bits of data), or as a *word* (16 bits of data). It should also be noted that, in some instances, a word may be defined as the data width that a given microcontroller can recognize at a time, be it 8 bits or 16 bits. For purposes of this chapter, we will refer to a word as being 16 bits. Data can also be expressed as a double word which is an unsigned 32-bit variable with a value between 0 and 4,294,967,295. Most architectures support this data only for shifts, dividends of a 32-by-16 divide, or for the product of a 16-by-16 multiply.

The most common way of referring to a microcontroller is by the width of its CPU. This indicates the width of data that the CPU can process at a time. A microcontroller with a CPU that can process 8 bits of data at a time is referred to as an 8-bit microcontroller. A microcontroller with a CPU that can process 16 bits of data at a time is referred to as a 16-bit microcontroller. With this in mind, it is easy to see why 16-bit microcontrollers offer higher performance than their 8-bit counterparts. Figure 11.3 illustrates a typical 16-bit CPU dia-

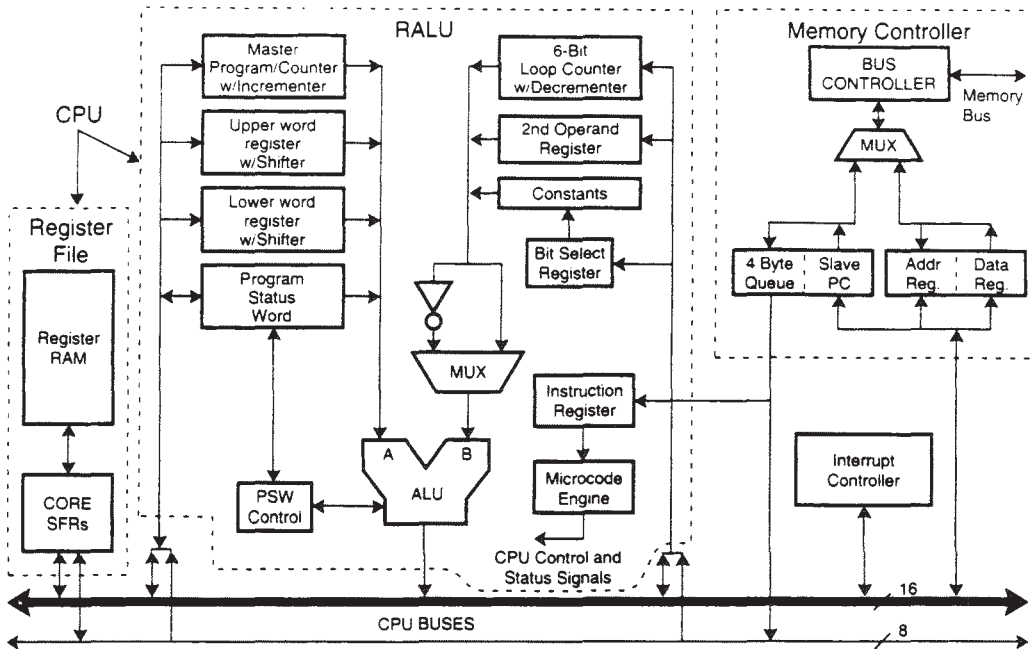


FIGURE 11.3 16-bit CPU.

gram. The microcode engine controls the CPU. Instructions to the CPU are taken from the instruction queue and temporarily stored in the instruction register. This queue is often referred to as a *prefetch queue* and it decreases execution time by staging instructions to be executed. The microcode engine then decodes the instructions and generates the correct sequence of events to have the ALU perform the desired function(s).

Arithmetic Logic Unit. The ALU is the portion of the CPU that performs most mathematical and logic operations. After an instruction is decoded by the microcode engine, the data specified by the instruction is loaded into the ALU for processing. The ALU then processes the data as specified by the instruction.

Register File. The register file consists of memory locations that are used as temporary storage locations while the user’s code is executing. The register file is implemented as RAM and consists of both RAM memory locations and special function registers (SFRs). RAM memory locations are used as temporary data storage during execution of the user’s code. After power-up, RAM memory locations default to a logic “0” and data in SFR locations contain default values as specified by the microcontroller manufacturer.

Special Function Registers. SFRs allow the user to configure and monitor various peripherals and functions of the microcontroller. By writing specific data to an SFR, the users can configure the microcontroller to meet the exact needs of their application. Figure 11.4 shows an example of a serial port SFR used for configuration. Note that each bit location within the SFR determines a specific function and can be programmed to either a logic “1” or “0”. If more than two configuration choices are possible, two or more bits will be combined to produce the multiple choices. An example of this would be the mode bits (M1 and M2) in the example SFR (Fig. 11.4). Bit locations marked “RSV” are reserved and should be written to with a value as indicated by the manufacturer.

| SP_CON (1FBBH) | | | | | | | |
|----------------|---|---|-----|-----|-----|----|----|
| 7 | 6 | 5 | 4 | 3 | 2 | 1 | 0 |
| 0 | 0 | PAR | TB8 | REN | PEN | M2 | M1 |
| M2, M1 | Mode | Function | | | | | |
| | 00 | Mode 0: Synchronous | | | | | |
| | 01 | Mode 1: Standard asynchronous | | | | | |
| | 10 | Mode 2: Asynchronous (receiver interrupt on 9th bit = 1)* | | | | | |
| | 11 | Mode 3: Asynchronous (9th bit = parity or data)** | | | | | |
| PEN | Parity Enable. Enables the Parity function for Mode 1 or Mode 3; cannot be enabled for Mode 2. | | | | | | |
| REN | Receiver Enable. Enables the receiver to write to SBUF_RX. | | | | | | |
| TB8 | Transmission Bit 8. Set the ninth data bit for transmission (Modes 2 and 3). Cleared after each transmission; not valid if parity is enabled. | | | | | | |
| PAR*** | 0 = even parity 1 = odd parity | | | | | | |
| Bits 6, 7 | Reserved; write as zeros for future product compatibility. | | | | | | |

* Mode 2: Asynchronous (receiver: interrupt on 9th bit = 1; transmitter: 9th bit = TB8)
 ** Mode 3: Asynchronous (receiver: always interrupt on 9th bit; transmitter: 9th bit = parity for PEN = 1
 *** Par bit only available on 8XC196KT and KS devices. 9th bit = TB8 for PEN = 0
 For 8XC196KR, JR, KQ, JQ devices, this bit should be written as a zero to maintain compatibility with future devices.

FIGURE 11.4 Special function control register example.

| SP_STAT (1FB9H) | | | | | | | |
|-----------------|----|----|----|-----|----|---|---|
| 7 | 6 | 5 | 4 | 3 | 2 | 1 | 0 |
| RB8/RPE | RI | TI | FE | TXE | OE | X | X |

Bits 0, 1 Reserved; ignore data.
 OE Set on buffer overrun error.
 TXE Set on transmitter empty. When set may write 2 bytes to transmit buffer.
 FE Framing error; set if no STOP bit is found at the end of a reception. When set may write 1 byte to transmit buffer.
 TI Transmit interrupt; set at the beginning of the STOP bit transmission.
 RI Receive interrupt; set after the last data bit is received.
 RPE (Parity enabled) Receive parity error (Modes 1 and 3 only); set if parity is enabled and a parity error occurred.
 RB8 (Parity disabled) Received Bit 8 (Modes 2 and 3 only); set if the 9th bit is high on reception.

FIGURE 11.5 Special function status register example.

Some SFRs can be read by the user to determine the current status of a given peripheral. Figure 11.5 shows an example of a serial port status register that, when read, indicates the current status of the microcontroller’s serial port. Note that each bit location corresponds to a particular state of the serial port. Bit locations marked “RSV” are reserved and should be ignored when read.

Register Direct vs. Accumulator-Based Architectures. Microcontroller architectures can be classified as either the register-direct or accumulator-based type. These terms refer to the means by which the CPU must handle data when performing mathematical, logical, or storage operations.

Register-direct architectures allow the programmer to essentially use most, if not all, of the microcontroller’s entire RAM array as individual accumulators. That is, the programmer can perform mathematical or storage operations directly upon any of the RAM locations. This simplifies task switching because program variables may be left in their assigned registers while servicing interrupts. Figure 11.6 illustrates a register-to-register type architecture (such

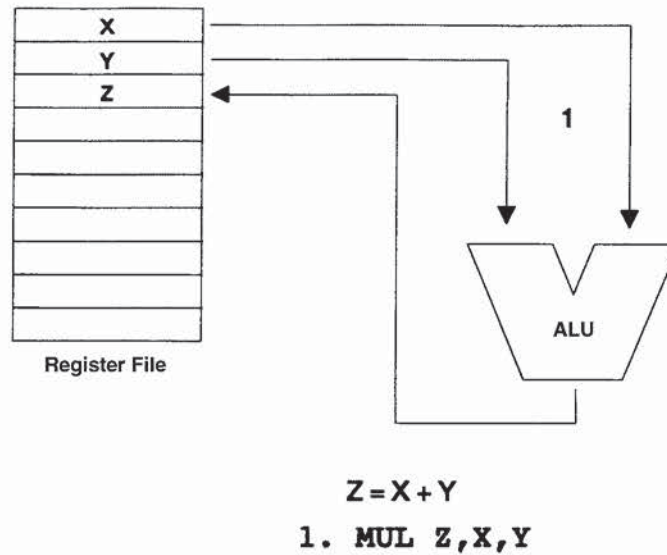


FIGURE 11.6 Register-to-register architecture example.

as Intel's MCS®-96). This architecture essentially has 232 "accumulators" (more are available through a windowing mechanism) of which any can be operated on directly by the RALU. The true advantage of this type of architecture is that it reduces accumulator bottleneck and speeds throughput during program execution.

Accumulator-based architectures require the user to first store the data to be manipulated into a temporary storage location, referred to as an "accumulator," prior to performing any type of data operation. After the operation is completed, the user program must then store the result to the desired destination location. Figure 11.7 depicts an example of an accumulator-based architecture.

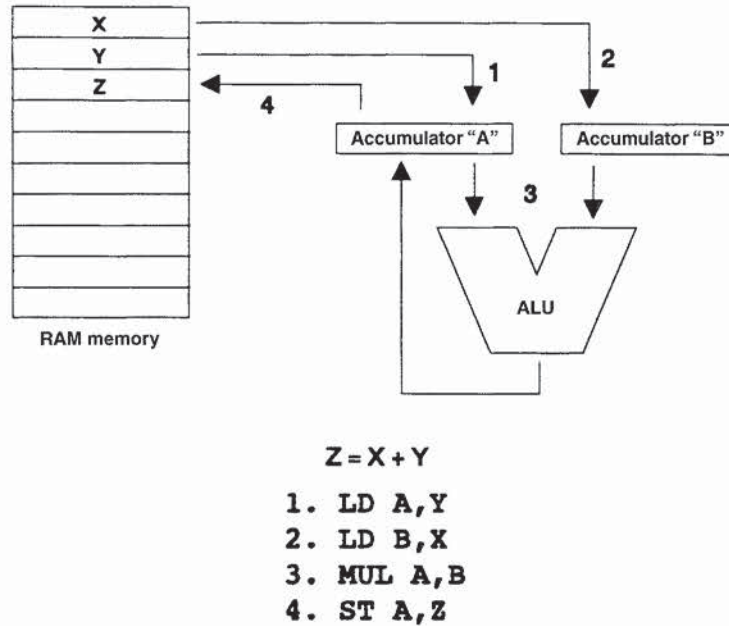


FIGURE 11.7 Accumulator-based architecture.

Program Counter. The Program Counter (PC) controls the sequencing of instructions to be executed. The PC is a 16-bit register located within the CPU which holds the address of the next instruction to be executed. After an instruction is fetched, the PC is automatically incremented to point to the next instruction.

| | |
|------------------------------|-------|
| SP starting address (SP+12): | |
| (SP+10): | 80FFh |
| (SP+8): | A5A5h |
| (SP+6): | 6E20h |
| (SP+4): | 5555h |
| (SP+2): | 0000h |
| SP ending address (SP): | 8000h |

FIGURE 11.8 Stack pointer example.

Stack and Stack Pointer. The stack is an area of memory (typically user-assigned) that is used to store data temporarily in a FILO (first-in, last-out) fashion. The stack is primarily used for storing program information (such as the program counter or interrupt mask registers) when an interrupt service routine is invoked. It is also sometimes used to pass variables between subroutines. The stack is typically accessed through PUSH and POP instructions. Execution of the PUSH instruction "pushes" the contents of the specified operand onto the stack whereas the

POP instruction “pops” the contents of the specified operand off of the stack. The stack pointer (SP) is a register which points to the next available word location on the stack. Consider the example shown in Fig. 11.8 which shows the contents of the stack after the following code sequence is executed:

| | |
|--------------|--|
| PUSH #80FFh | pushes immediate data 80FFh onto stack |
| PUSH #0A5A5h | pushes immediate data A5A5h onto stack |
| PUSH 82h | pushes data @ 82h (assume it's 6E20h) onto stack |
| PUSH #5555h | pushes immediate data 5555h onto stack |
| PUSH 4Eh | pushes data @ 4Eh (assume it's 0000h) onto stack |
| PUSH #8000h | pushes immediate data 8000h onto stack |

Continuing with the preceding example, if a POP instruction were executed, the data at the current SP address (SP) would be “popped” off the stack and stored to the address specified by the instruction's operand. Executing the POP instruction results in the SP being incremented by 2.

Program Status Word and Flags. The program status word (PSW) is a collection of boolean flags which retain information concerning the state of the user's program. These flags are set or cleared depending upon the result obtained after executing certain instructions as specified by the microcontroller manufacturer. PSW flags are not directly accessible by the user's program; access is typically through instructions which test one or more of the flags to determine proper program flow. Following is a summary of common PSW flags as supported by Intel's MCS-96® architecture:

Z: The *Zero* flag is set when an operation generates a result equal to zero. The Z flag is never set by the add-with-carry (ADDC/ADDCB) or subtract-with-carry (SUBC/SUBCB) instructions, but is cleared if the result is nonzero. These two instructions are normally used in conjunction with ADD/ADDB and SUB/SUBB instructions to perform multiple-precision arithmetic. The operation of the Z flag for these instructions leaves it indicating the proper result for the entire multiple-precision calculation.

N: The *Negative* flag is set when an operation generates a negative result. Note that the N flag will be in the algebraically correct state even if overflow occurs. For shift operations, the N flag is set to the same value as the most significant bit of the result.

V: The *overflow* flag is set when an operation generates a result that is outside the range for the destination data type. For shift-left instructions, the V flag is set if the most significant bit of the operand changes at any time during the shift. For an unsigned word divide, the V flag is set if the quotient is greater than 65,535. For a signed word divide, the V flag is set if the quotient is less than -32,768 or greater than 32,767.

VT: The *overflow Trap* flag is set when the V flag is set, but it is only cleared by instructions which are specially designated to clear the VT flag (such as CLRVT, JVT, and JNVT). The VT flag allows for testing possible overflow conditions at the end of a sequence of related arithmetic operations. This is normally more efficient than testing the V flag after each instruction.

C: The *Carry* flag is set to indicate either (1) the state of the arithmetic carry from the most significant bit of the ALU for an arithmetic operation or (2) the state of the last bit shifted out of an operand for a shift. Arithmetic borrow after a subtract operation is the complement of the C flag (i.e., if the operation generated a borrow, then C = 0).

ST: The *Sticky* bit flag is set to indicate that, during a right shift, a 1 has been shifted first into the C flag and then shifted out. The ST flag can be used along with the C flag to control rounding after a right shift. Imprecise rounding can be a major source of error in a numerical calculation; use of both the C and ST flags can increase accuracy as described in the following paragraphs.

Consider multiplying two 8-bit quantities and then scaling the result down to 12 bits:

MULUB AX, CL, DL (CL * DL = AX)
SHR AX, #4 (AX is shifted right by 4 bits)

If the C flag is set after the shift, it indicates that the bits shifted off the end of the operand were greater than or equal to one-half the least significant bit of the 12-bit result. If the C flag is cleared after the shift, it indicates that the bits shifted off the end of the operand were less than half the LSB of the 12-bit result. Without the ST flag, the rounding decision must be made on the basis of the C flag alone. (Normally the result would be rounded up if the C flag is set.) The ST flag allows a finer resolution in the rounding decision as shown here:

| C | ST | Bits shifted off |
|---|----|---|
| 0 | 0 | Value = 0 |
| 0 | 1 | $0 < \text{Value} < \frac{1}{2} \text{LSB}$ |
| 1 | 0 | Value = $\frac{1}{2} \text{LSB}$ |
| 1 | 1 | Value $> \frac{1}{2} \text{LSB}$ |

Jump instructions are the most common instructions to utilize PSW flags for determining the operation to perform. Instructions that test PSW flags are very useful when program flow needs to be altered dependent upon the outcome of an arithmetic operation. The most common example of this would be for program loops that are to be executed a certain number of times. Following are examples of several MCS-96 instructions whose operation is dependent upon the state of one or more program status word flags:

- JC (Jump if C flag is set.) If the C (carry) bit is set, the program will jump to the address location specified by the operand. If the C flag is cleared, control will pass to the next sequential instruction.
- JGT (Jump if signed greater than.) If both the N (negative) and the Z (zero) flags are clear, the program will jump to the address location specified by the operand. If either of the flags is set, control will pass to the next sequential instruction.
- JLE (Jump if signed less than or equal.) If either the N or Z flags is set, the program will jump to the address location specified by the operand. If both the N and Z flags are cleared, control will pass to the next sequential instruction.

11.1.4 Bus Controller

The bus controller serves as the interface between the CPU and the internal program memory and the external memory spaces. The bus controller maintains a queue (commonly called the prefetch queue) of prefetched instruction bytes and responds to CPU requests for data memory references. The prefetch queue decreases execution time by staging instructions to be executed. The capacities of prefetch queues vary but for the MCS-96 architecture, it is 4 bytes deep.

When using a logic analyzer to debug code it is important to consider the effects of the prefetch queue. It is not possible to accurately determine when an instruction will execute by simply watching when it is fetched from external memory. This is because the prefetch queue is filled in advance of instruction execution. It is also important to consider the effects when a jump or branch occurs during program execution. When the program sequence changes because of a jump, interrupt, call, or return, the PC is loaded with the new address, the queue is flushed and processing continues. Consider the situation in which the external address/data bus is being monitored when a program branch occurs. Because of the prefetch queue, it will appear as if instructions past the branch point were executed, when in fact they were only loaded into the prefetch queue.

11.1.5 Frequency of Operation

Microcontrollers are being offered in an ever-increasing range of operating frequencies. Most high-end automotive applications currently use microcontrollers operating in the 12- to 20-MHz range, with 24 MHz becoming not so uncommon. Microcontrollers with frequencies as high as 30 and 32 MHz are available as prototypes and will soon be available for production. Operating frequency becomes especially important when a microcontroller must perform high-speed event control such as required in ABS braking and engine control. Applications such as these typically have to detect, calculate, and respond to external events within a given amount of time. In ABS applications, this time is commonly referred to as loop time and defines the amount of time that the microcontroller has to execute the main loop of the software algorithm to achieve optimal performance.

Operating frequency can be directly related to the speed at which a microcontroller will execute the user's code. For instance, let's look at how long it takes for a particular microcontroller to execute the following generic subroutine. For this example, consider the execution times rather than the operations each instruction is performing.

```
{6}  PUSHF
{3}  NOTB  PTS_COUNT_EPA1
{5}  ADDB  NUM_OF_PULSES_1, PTS_COUNT_EPA1, #00h
{5}  SUB   INV_SPEED_1, FTIME_1, ITIME_1
{27} DIV  INV_SPEED_1, NUM_OF_PULSES_1
{5}  LD   Temp1+2, #Speed_high_constant
{5}  LD   Temp1, #Speed_low_constant
{27} DIV  Temp1, INV_SPEED_1
{4}  ST   Temp1, EPA1_FREQ
{11} RET
```

In this example, the numbers in brackets {} denote how many state times it will take the microcontroller to execute the given line of code. A state time is the basic time measurement for all microcontroller operations. For this MCS-96 family microcontroller, a state time is based on the crystal frequency divided by two. A state time for other microcontrollers may be based upon the crystal frequency divided by three. For this particular microcontroller, a state time can be calculated by the following formula (other microcontroller families use similar formulas):

$$1 \text{ state time} = 1[(\text{frequency of operation})/2]$$

Applying this formula, 1 state time = 125 ns when operating at 16 MHz, and 167 ns when operating at 12 MHz. The example code sequence takes the microcontroller 98 state times to execute. This equates to 16.37 μ s to execute at an operating frequency of 12 MHz. At 16 MHz, it takes only 12.25 μ s for the microcontroller to execute the subroutine. An operating frequency of 16 MHz results in the microcontroller executing approximately 34 percent more instructions in a given time than at a frequency of 12 MHz.

Another consideration when choosing an operating frequency is the clocking resolution of on-chip timer/counters. The maximum clocking rate of on-chip timer/counters is limited by the frequency the microcontroller is being clocked at. As an example, if an on-chip timer/counter is set up to increment/decrement at a rate determined by CLOCK/4, this would result in 333 ns resolution at 12 MHz. However, if the clock speed were increased to 16 MHz, a higher and more desirable resolution of 250 ns is achieved.

11.1.6 Instruction Set

An often overlooked feature that gives a microcontroller the capability to perform desired operations and manipulate data is its instruction set. A microcontroller's instruction set con-

sists of a set of unique commands which the programmer uses to instruct the microcontroller on what operation to perform.

An *instruction* is a binary command which is recognized by the CPU as a request to perform a certain operation. Examples of typically supported operations are loads, moves, and stores which transfer data from one memory location to another. There are also jumps and branches which are used to alter program flow. Arithmetic instructions include various multiples, divides, subtracts, additions, increments, and decrements. Instructions such as ANDs, ORs, XORs, shifts, and so forth, allow the user to perform logical operations upon data. In addition to these basic instructions, microcontrollers often support specialized instructions unique to their architecture or intended application.

Instructions can be divided into two parts, the *opcode* and *operand*. The opcode (sometimes referred to as the machine instruction) specifies the operation to take place and the operand specifies the data to be operated upon. Instructions typically consist of either 0, 1, 2, or 3 operands to support various operations. As an example, consider the following MCS-96 architecture instructions:

PUSHF (0 operands) is an instruction that pushes the program status word (PSW) onto the stack. Since this instruction operates on a predefined location, no operand is necessary.

Format: PUSHF

PUSH (1 operand) is an instruction that pushes the specified word operand onto the stack.

Format: PUSH (SRC)

ADD (2 operands) adds two words together and places the result in the destination (left-most) operand location.

Format: ADD (DST),(SRC)

ADD (3 operands) adds two words together as the 2-operand ADD instruction, but in this case, a third operand is specified as the destination.

Format: ADD (DEST),(SRC1),(SRC2)

Instructions support one or more of six basic addressing types to access operands within the address space of the microcontroller. If programmers wish to take full advantage of a microcontroller architecture, it is important that they fully understand the details of the supported addressing types. The six basic types of addressing modes are termed register-direct, indirect, indirect with autoincrement, immediate, short-indexed, and long-indexed. The following descriptions describe these modes as they are handled by hardware in register-to-register architectures.

The *register-direct* addressing mode is used to directly access registers within the lower 256 bytes of the on-chip register file. The register is selected by an 8-bit field within the instruction and the register address must conform to the operand type's alignment rules. Depending upon the instruction, typically up to three registers can take part in the calculation.

Examples:

ADD AX,BX,CX AX = BX + CX

MUL AX,BX AX = AX*BX

INCB CL CL = CL + 1

The *indirect addressing* mode accesses a word in the lower register file containing the 16-bit operand address. The indirect address can refer to an operand anywhere within the address space of the microcontroller. The register containing the indirect address is selected by an 8-bit field within the instruction. An instruction may contain only one indirect reference; the remaining operands (if any) must be register-direct references.

Examples:

LD BX,[AX] BX = mem_word(AX)

In this example, assume that before execution:

contents of AX = 2FC2h

contents of 2FC2h = 3F26h

Then after execution,

contents of BX = 3F26h

ADDB AL,BL,[CX] AL = BL + mem_byte(CX)

The *indirect with autoincrement* addressing mode is the same as the indirect mode except that the variable that contains the indirect address is autoincremented after it is used to address the operand. If the instruction operates on bytes or short integers, the indirect address variable is incremented by one; if it operates on words or integers, the indirect address will be incremented by two.

Examples:

LD BX,[AX]+ BX = mem_word(AX)

AX = AX + 2

ADDB AL,BL,[CX]+ AL = BL + mem_byte(CX)

CX = CX + 1

For the *immediate addressing* mode, an operand itself is in a field in the instruction. An instruction may contain only one immediate reference; the remaining operand(s) must be register-direct references.

Example:

ADD AX,#340 AX = AX + 340 (decimal)

For the *short-indexed addressing* mode, an 8-bit field in the instruction selects a word variable (which is contained in square brackets) in the lower register file that contains an address. A second 8-bit field in the instruction stream is sign-extended and summed with the word variable to form an operand address.

Since the 8-bit field is sign-extended, the effective address can be up to 128 bytes before the address in the word variable and up to 127 bytes after it. An instruction may contain only one short-indexed reference; the remaining operand(s) must be register-direct references.

Example:

LD AX,4[BX] AX = mem_word(BX + 4)

In this example, assume that before execution:

contents of BX = A152h

The operand address is then A152h + 04h = A156h

The *long-indexed addressing* mode is like the short-indexed mode except that a 16-bit field is taken from the instruction and added to the word variable to form the operand. No sign extension is necessary. An instruction may contain only one long-indexed reference and the remaining operand(s) must be register-direct references.

Examples:

ST AX,TABLE[BX] mem_word(TABLE + BX) = AX

AND AX,BX,TABLE[CX] AX = BX and mem_word(TABLE + CX)

11.1.7 Programming Languages

The two most common types of programming languages in use today for automotive microcontrollers are *assembly languages* and *high-level languages (HLLs)*. Program development begins with the user writing code in either an assembly language or an HLL. This code is written as a text file and is referred to as a source file. The source file is then assembled or compiled using the appropriate assembler/compiler program. The assembler translates the source code into object code and creates what is referred to as an object file. The object file contains machine language instructions and data that can be loaded into an evaluation tool for debugging and validation. The object can also be converted into a hex file for EPROM programming or ROM mask generation as discussed later in this chapter. The program development process is illustrated in Fig. 11.9.

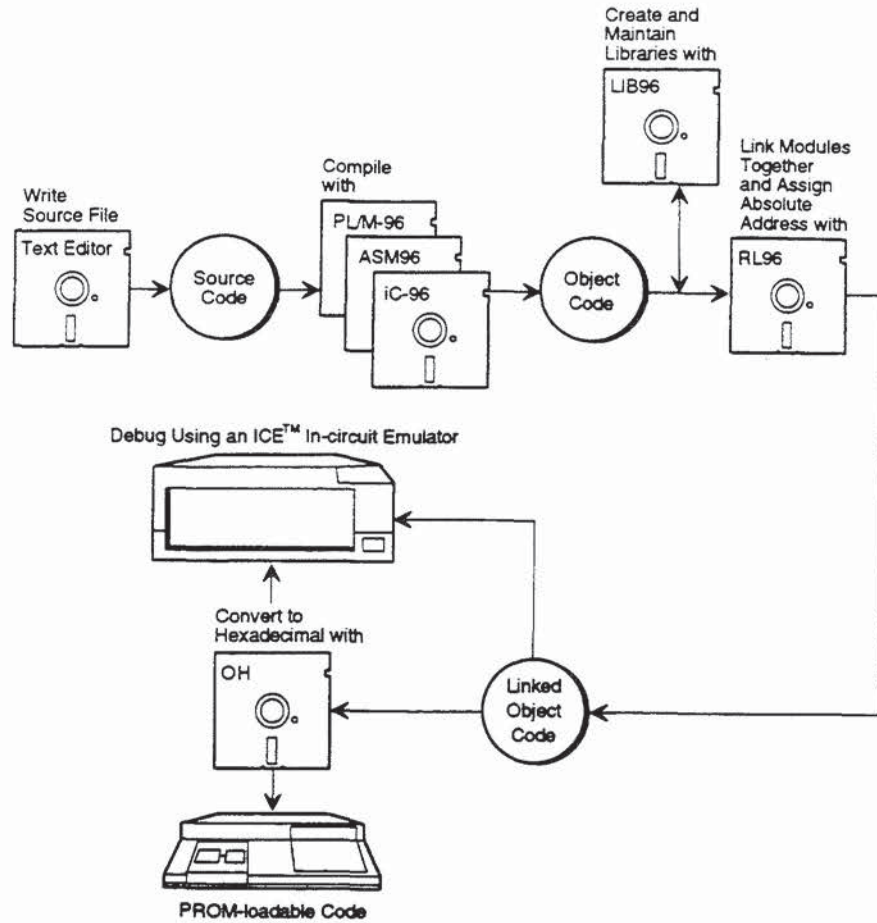


FIGURE 11.9 The program development process.

Assembly Language Programming. An assembly language is a low-level programming language that is specific to a given microcontroller family. Assemblers translate language operation codes (mnemonics) directly into machine instructions that instruct the microcontroller

on what operation to perform. Because the programmer is essentially using the microcontroller's machine code to write assembly language programs, more precise control of the device can be achieved through the direct manipulation of individual bits within registers. Because of their efficiency, assembly language programs require less code space than high-level languages. Assembly language programs consist of three parts: machine instructions, assembler directives, and assembler controls.

A *machine instruction* is a machine code that can be executed by the microcontroller's CPU. The collection of machine instructions that a particular microcontroller can execute is referred to as its instruction set. An example of a machine instruction is the opcode for the MULB instruction (Fig. 11.10) from Intel's MCS-96 assembly language. MULB is the mnemonic that represents the machine instruction which performs the specified multiplication operation. When executed by the microcontroller, the MULB opcode results in the multiplication of the two byte operands with the result being placed in a word destination location.

MULB (Three Operands)

| | | | | | | |
|-----------------------|--|----------|----------|------|------|------|
| Format | MULB wreg.breg.baop | | | | | |
| Operation | The second and third byte operands are multiplied using signed arithmetic and the 16-bit result is stored into the destination (leftmost) operand. The sticky bit flag is undefined after the instruction is executed. $(DEST) \leftarrow (SRC1) * (SRC2)$ | | | | | |
| Opcode Pattern | <table border="1" style="display: inline-table; border-collapse: collapse;"> <tr> <td style="padding: 2px;">11111110</td> <td style="padding: 2px;">010111aa</td> <td style="padding: 2px;">baop</td> <td style="padding: 2px;">breg</td> <td style="padding: 2px;">wreg</td> </tr> </table> | 11111110 | 010111aa | baop | breg | wreg |
| 11111110 | 010111aa | baop | breg | wreg | | |
| Flags Affected | ST | | | | | |
| Examples | MULB DELTA, TIMER1, #2 MULB ALPHA, BETA, GAMMA MULB ALPHA, DELTA, 10[GAMMA] | | | | | |

FIGURE 11.10 Machine instruction example: MULB.

Assembler directives allow the user to specify auxiliary information (such as storage reservation, location counter control, definition of nonexecutable code, object code relocation, and flow of assembler processing) that determines the manner in which the assembler generates object code from the user's source file input.

Assembler controls set the mode of operation for the assembler and direct the flow of the assembly process. Assembler controls can be classified into primary controls and general controls. Primary controls are set at the beginning of the assembly process and cannot be changed during the assembly. Primary controls allow the user to specify items such as print options, page lengths and widths, error messages, and cross-referencing. General controls can be specified in the invocation line or on control lines anywhere in the source file and can appear any number of times in the program. General controls either cause an immediate action or an immediate change of conditions in which the condition specified remains in effect until another general control causes it to change.

High-level Language Programming. Unlike low-level languages (such as assembly languages), a high-level language is a general purpose language that can support numerous microcontroller architectures. The most common high-level language used for automotive

applications is C. C programs are written with statements rather than specific instructions from a microcontroller's instruction set. High-level languages utilize a software program known as a *compiler* to translate the user's source code into the specific microcontroller's machine language. Each microcontroller family has its own unique compiler to support selected high-level languages. Although high-level languages tend to be less efficient than assembly languages, their advantage lies in ease of writing code and better debugging capability. The use of statements as opposed to specific instructions better suits high-level languages toward control of procedures (to implement complex software algorithms) as opposed to the microcontroller itself.

11.1.8 Interrupt Structure

The interrupt structure is one of the more important features of an automotive microcontroller. Applications such as automotive ABS and engine control can be referred to as event-driven control systems. Event-driven control systems require that normal code execution be halted to allow a higher-priority task or event to take place. These higher-priority tasks are known as interrupts and can initiate a change in the program flow to execute a specialized routine. When an interrupt occurs, instead of executing the next instruction, the CPU branches to an interrupt service routine (ISR). The branch can occur in response to a request from an on-chip peripheral, an external signal, or an instruction. In the simplest case, the microcontroller receives the request, performs the desired operation and returns to the task that was interrupted.

ISRs are typically serviced via software but it is becoming common for microcontroller manufacturers to implement special on-chip hardware ISR functions for commonly performed operations. These ISRs are typically microcoded or *hardwired* into the microcontroller as described later in this section.

Software, or Normal, Servicing of Interrupts. The software servicing of interrupts is fairly straightforward as shown in Fig. 11.11. When an interrupt source is enabled by the user and a

NORMAL INTERRUPT RESPONSE



HARDWIRED INTERRUPT RESPONSE USING PTS PERIPHERAL

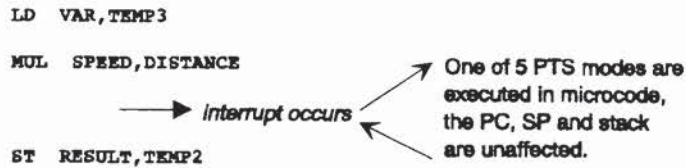


FIGURE 11.11 Comparison of normal interrupts and hardwired interrupts.

valid interrupt event occurs, the CPU will fetch the starting address of the ISR from the interrupt vector table. The interrupt vector table is a dedicated section of memory that contains the user-programmed start address of the various ISRs. After fetching the ISR address, the CPU automatically pushes the current program counter (PC) onto the stack and loads the PC with the ISR beginning address. This results in the program flow vectoring to the ISR address. The user-programmed ISR is then executed. The last instruction within the ISR is a return instruction that pops the old PC off the stack. This results in program flow continuing from where it was interrupted.

Interrupt mask registers allow the user to prevent or *mask* undesirable interrupts from occurring during various sections of the program. This is a very desirable feature and allows for custom tailoring of the interrupt structure to meet the needs of a particular application. Enabling or disabling of all interrupts (known as globally enabling/disabling) is typically supported with a software instruction such as DI (globally disable all interrupts) or EI (globally enable all interrupts).

Hardware, or Microcoded, Interrupt Structures. Hardware interrupt structures differ from software interrupts in that the user doesn't have to provide the ISR to be executed when the interrupt occurs. With a hardware interrupt structure, the ISR is predefined by being hardwired or *microcoded* into the microcontroller. This is advantageous because it requires less code space and requires less CPU overhead. Stack operations are not necessary since interrupt vectors do not have to be fetched. Most microcontroller manufacturers have their own proprietary solution for hardware ISR's, which are all somewhat similar to one another. For purposes of this section, we will briefly describe the peripheral transaction server as implemented on members of Intel's MCS-96 family of microcontrollers.

The PTS provides a microcoded hardware interrupt handler which can be used in place of a normal ISR. The PTS requires much less overhead than a normal ISR since it operates without modification of the stack. Any interrupt source can be selected by the user to trigger a PTS interrupt in place of a normal ISR. The PTS is similar to a direct memory access (DMA) controller in that when a PTS interrupt, or *cycle*, occurs, data is automatically moved from one location of memory to another as specified by the user. Figure 11.11 compares a regular ISR to a PTS interrupt cycle.

The PTS allows for five modes of operation; single-byte transfer, multiple-byte transfer, PWM, PWM toggle, and A/D scan mode. Each mode is configurable through an 8-byte, user-defined PTS control block (PTSCB) located in RAM. The user may enable virtually any normal interrupt source to be serviced by a PTS interrupt by simply writing to the appropriate bit in an SFR known as the PTS_SELECT register. When a PTS interrupt is enabled and the event occurs, a microcoded interrupt service routine executes in which the contents of the PTSCB are read to determine the specific operation to be performed. More details on the PTSCB can be found in the application example found in this section.

The major advantage of the PTS for automotive applications is its fast response time. The PTS is ideally suited for transferring single or multiple bytes/words of data in response to an interrupt. An example of this is the serial port example which will be described shortly. Another example of the usefulness of the PTS (using A/D scan mode) would be if the user wanted to automatically store A/D conversion results every time a conversion completed within a user-defined scan of A/D channels. The PTS could also be configured to automatically transfer a block of data between memory locations every time an interrupt occurs.

Application Example of PTS Single-Byte Transfer Mode. This example shows how the PTS can be used to automatically transmit and receive 8-byte messages over the serial port. Data to be transmitted and received data are stored in separate tables. The use of the PTS for this purpose greatly reduces CPU overhead and code-space requirements. The layout of the user-defined PTSCB for single-byte transfer mode is shown in Fig. 11.12. PTS_DEST within the PTSCB contains the destination address for the data transfer and PTS_SOURCE contains the source address for the transfer.

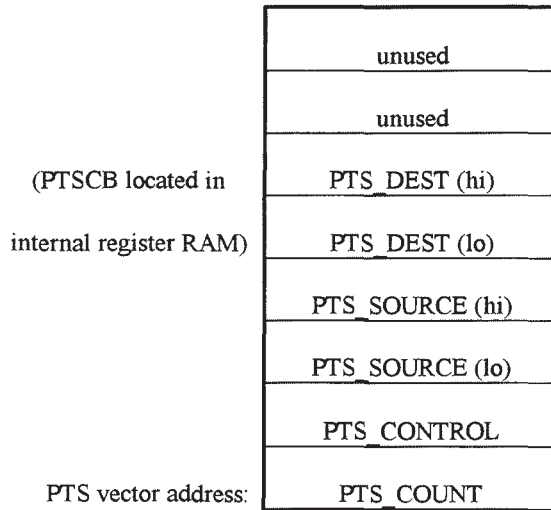


FIGURE 11.12 PTS control block for single-byte transfer mode.

Two PTSCBs are set up for this example, one in response to receive (RX) interrupts and one in response to transmit (TX) interrupts. The RX PTSCB’s PTS_DEST is initialized with the start address of the receive data table and the TX PTSCB’s PTS_DEST is initialized with the address of the serial port’s transmit buffer.

PTS_CONTROL is a byte that specifies the PTS operation to be performed. Its layout is shown in Fig. 11.13.

PTS_COUNT is a down counter that is used to keep track of how many PTS interrupts or cycles have occurred since the last initialization. PTS_COUNT is initialized by the user to any value below 256 and is decremented everytime the corresponding PTS cycle occurs. It is often used to keep track of how many pieces of data have been transferred. In this example, PTS_COUNT is used to determine when a complete 8-byte message has been transmitted or received. After PTS_COUNT expires, an “end-of-PTS” or “normal” ISR occurs, in which the user utilizes the data as required by the application. When an interrupt source is enabled by the user to be a PTS interrupt, the following sequence of events occurs every time the corresponding interrupt occurs:

1. Instead of a normal interrupt, the user has selected it to do a PTS cycle.
2. The microcoded PTS routine fetches the PTS_CONTROL byte from the PTSCB whose start address is specified by the user in the PTS interrupt vector table. The microcoded PTS routine then:
 - reads data to be transferred from address specified by PTS_SOURCE
 - writes the data to address specified by PTS_DEST
 - optionally increments/updates PTS_SOURCE and PTS_DEST addresses
 - decrements PTS_COUNT
3. When PTS_COUNT reaches “0”, an end of PTS interrupt occurs and the normal ISR is executed in which the user utilizes the received data as necessary (for RX interrupts) or reloads the transmit table with new data (for TX interrupts).

Interrupt Latency. Interrupt latency is defined as the time from when the interrupt event occurs (not when it is acknowledged) to when the microcontroller begins executing the first

PTS CONTROL BYTE (for single and multiple-byte transfers)

| | | | | | | | |
|----|----|----|-----|----|----|----|----|
| 7 | 6 | 5 | 4 | 3 | 2 | 1 | 0 |
| M2 | M1 | M0 | B/W | SU | DU | SI | DI |

| | | |
|-------------|------------------------|-------------------------------------|
| M2, M1, M0: | <u>Mode</u> | <u>Function</u> |
| | 000 | PTS Block Transfer |
| | 100 | PTS Single Transfer |
| B/W: | Byte/Word: | "0" = Word; "1" = Byte |
| SU: | Source Update: | "1" = update source address |
| DU: | Destination Update: | "1" = update destination address |
| SI: | Increment Source: | "1" = Increment Source address |
| DI: | Increment Destination: | "1" = Increment Destination address |

FIGURE 11.13 PTS control byte for single- and multiple-byte transfer modes.

instruction of the interrupt service routine. Interrupt latency must be carefully considered in timing-critical code as is found in many automotive applications.

There is a delay between an interrupt's triggering and its acknowledgment. An interrupt is not acknowledged until the currently executing instruction is finished. Further, if the interrupt signal does not occur at least some specified (assume four for this discussion) state times before the end of the current instruction, the interrupt may not be acknowledged until after the next instruction has been executed. This is because an instruction is fetched and prepared for execution a few state times before it is actually executed. Thus, the maximum delay between interrupt generation and its acknowledgment is approximately four state times plus the execution time of the next instruction.

It should also be noted that most microcontrollers have protected instructions (such as RETURN, PUSH, POP) which inhibit interrupt acknowledgment until after the following instruction is executed. These instructions can increase interrupt-to-acknowledgment delay.

When an interrupt is acknowledged, the interrupt pending bit is cleared and a call is forced to the location indicated by the corresponding interrupt vector. This call occurs after the completion of the current instruction, except as noted previously. For the MCS-96 architecture, the procedure of fetching the interrupt vector and forcing the call requires 16 state times. The stack being located in external memory will add an additional two state times to this number.

Latency is the time from when an interrupt is generated (not acknowledged) until the microcontroller begins executing interrupt code. The maximum latency occurs when an inter-

rupt occurs too late for acknowledgment following the current instruction. The worst case is calculated assuming that the current instruction is not a protected one. The worst-case latency is the sum of three terms:

1. The time for the current instruction to finish (assume four state times).
2. The state times required for the next instruction. This time is basically the time it takes to execute the longest instruction used in the user's code (assume it's a 16-state DIV instruction).
3. The response time (assume 16 states, 18 for an externally located stack).

Thus, for this scenario, the maximum delay would be $4 + 16 + 16 = 36$ state times. This equates to approximately $4.5 \mu\text{s}$ for a MCS-96 microcontroller operating at 16 MHz. This latency can increase or decrease depending upon the longest execution-time instruction used. Figure 11.14 illustrates an example of this worst-case scenario.

Interrupt latency can be reduced by carefully selecting instructions in areas of code where interrupts are expected. Using a protected instruction followed immediately by a long instruction increases the maximum latency because an interrupt cannot occur after the protected instruction.

11.1.9 Fabrication Processes

The basic fabrication processes that are widely used for automotive microcontrollers today are NMOS (N-channel metal-oxide semiconductor) and CMOS (complementary MOS). The scope of this chapter does not allow for an in-depth discussion of these processes, although a brief description of the structures used to build on-chip circuitry will be discussed. These terms refer to the components used in the construction of MOSFET (MOS field effect transistor) inverters which are the basis of logic on digital devices. NMOS inverters are constructed of N-channel transistors only, whereas CMOS inverters are constructed of both N-channel and P-channel transistors. This section will describe the basic operation of each inverter along with its pros and cons.

Simply stated, a P-channel transistor conducts when a logic "0" is applied to its gate. Conversely, N-channel transistors conduct when a logic "1" is applied to their gate. Figures 11.15 and 11.16 show a simplified cross-sectional view and the electrical symbol for N- and P-channel devices, respectively.

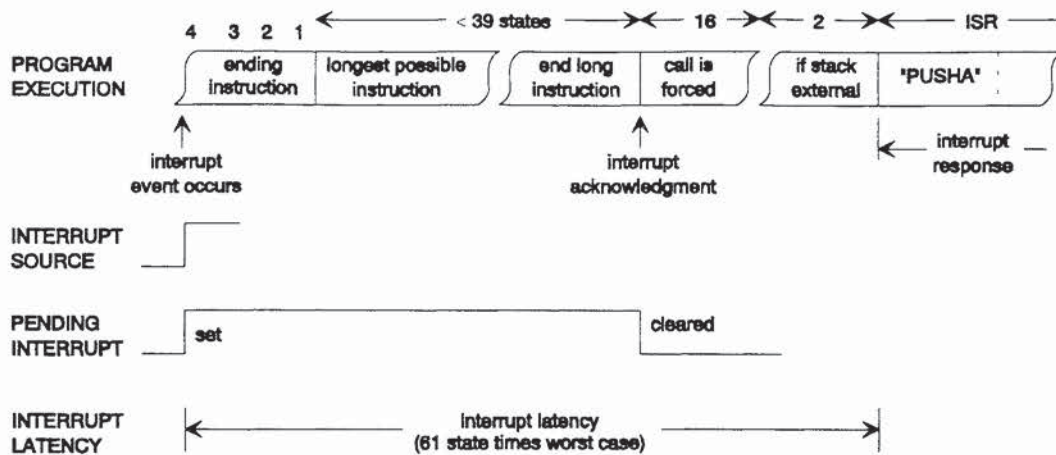


FIGURE 11.14 Worst case interrupt latency example.

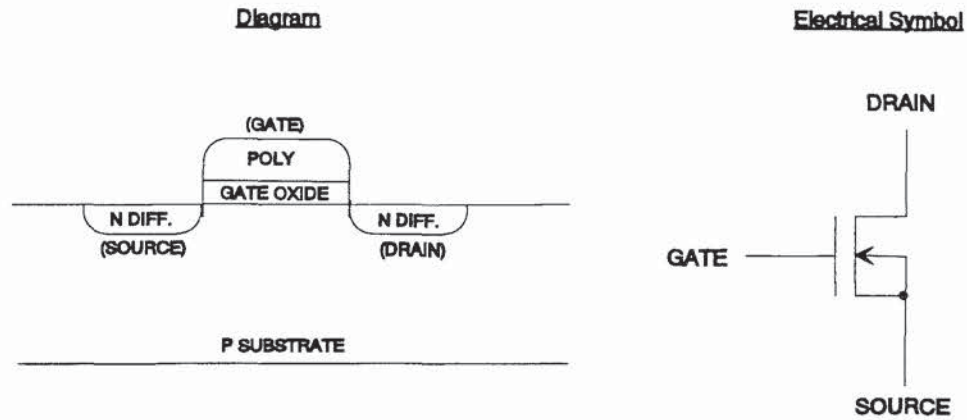


FIGURE 11.15 N-channel transistor.

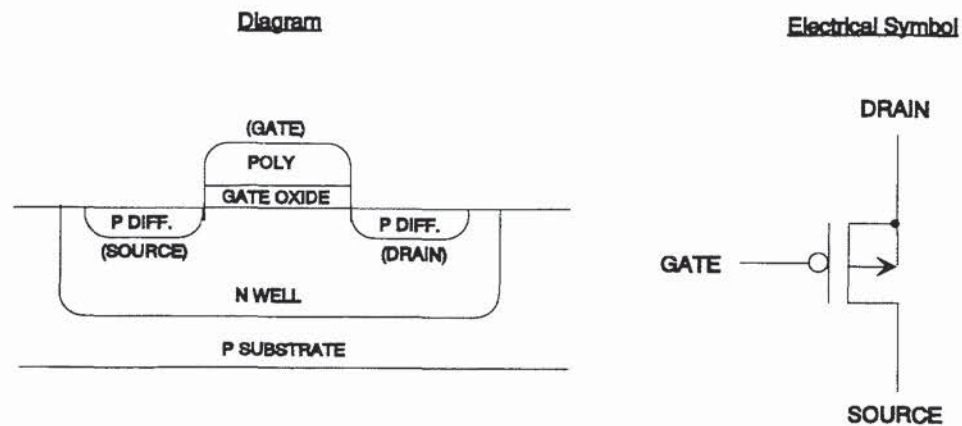


FIGURE 11.16 P-channel transistor.

NMOS Inverters. NMOS inverters are constructed of two NMOS transistors in which one is utilized as a resistance (Q2) and the other is utilized as a switch (Q1). A depletion-mode NMOS transistor is commonly utilized for the resistance device. A basic NMOS inverter is shown in Fig. 11.17. Note that Q2 is always on and acts as a resistor.

When a logic “0” is applied to the inverter’s input, Q1 is turned off, which results in Q2 driving a logic 1 at the output. When a logic “1” is applied to the inverter’s input, Q1 is turned on and overcomes Q2. This results in a logic “0” at the output.

NMOS microcontrollers are still produced in large quantities today. An advantage of NMOS processes is the simplistic circuit configuration which results in higher chip densities. NMOS devices are also less sensitive to electrostatic discharge (ESD) than CMOS devices. An inherent disadvantage of NMOS design is the slower switching speeds and higher power dissipation due to the dc current path from power to ground through Q1 and Q2 when the inverter is driving a logic “0”.

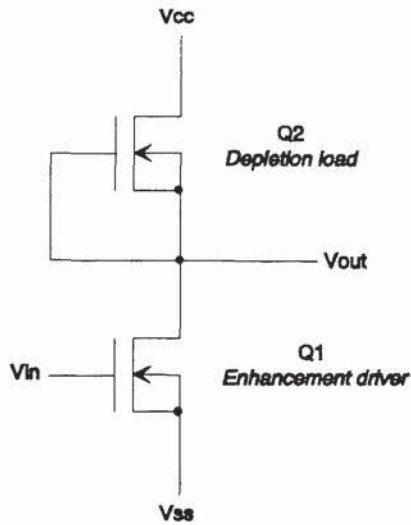


FIGURE 11.17 NMOS inverter.

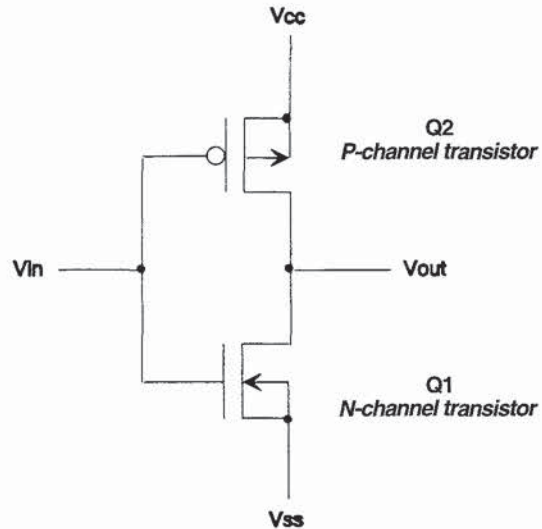


FIGURE 11.18 CMOS inverter.

CMOS Inverters. The CMOS is the most widely used process for automotive microcontrollers today. CMOS inverters are constructed of both P-channel and N-channel transistors that have their inputs tied together as shown in Fig. 11.18. When a logic “0” is applied to the inverter’s input, Q1 is turned off and Q2 is turned on, which results in Q2 driving a logic “1” at the output. When a logic “1” is applied to the inverter’s input, Q2 is turned off and Q1 is turned on, which results in Q1 driving a logic “0” at the output. Note that only one of these two devices will conduct at a time when the input is “1” or “0”. While the input switches, both Q1 and Q2 may conduct for a short time resulting in a small amount of power dissipation.

The main advantages of CMOS logic are greatly improved switching times and lower power consumption, which is due to the complementary design of the inverter. A disadvantage of CMOS logic is that it is more expensive due to its increased complexity and more demanding fabrication process. CMOS logic is more susceptible to ESD damage, although microcontroller manufacturers have countered this by incorporating very effective ESD protection devices onto the silicon.

11.1.10 Temperature Range

Another important factor that must be considered when choosing a microcontroller is the temperature range in which it will be required to operate. The two most common temperature specifications specified by microcontroller manufacturers are *ambient temperature under bias* (TA) and *storage temperature*. These specifications are based upon package thermal characteristics as determined through device and package testing. Storage temperature refers to the temperature range that a microcontroller can be subjected to during periods of nonoperation. Storage temperature specifications are more extreme than ambient temperature under bias temperatures and are usually all the same regardless of the specified ambient temperature range. The common storage temperature range in industry is -60 to +150 °C. While powered-down, a given microcontroller must not be subjected to temperatures that exceed its specified storage temperature range.

Ambient temperature under bias (TA) refers to the temperature range that the microcontroller is guaranteed to operate at within a given application. While powered-up or operating, a microcontroller must not be subjected to temperatures that exceed its specified ambient temperature range. The most common ambient temperature ranges in industry are:

| | |
|------------|----------------|
| Commercial | 0 to +70 °C |
| Extended | -40 to +85 °C |
| Automotive | -40 to +125 °C |

11.2 MEMORY

Microcontrollers execute customized programs that are written by the user. These programs are stored in either on-chip or off-chip memory and are often referred to as the *user's code*. On-chip memory is actually integrated onto the same piece of silicon as the microcontroller and is accessed over the internal data bus. Off-chip memory exists on a separately packaged piece of silicon and is typically accessed by the microcontroller over an external address/data bus.

A memory map shows how memory addresses are arranged in a particular microcontroller. Figure 11.19 shows a typical microcontroller memory map.

| Address | Memory Function | | |
|-------------------------|---|--|---------------|
| 0FFFFh 0A000h | External Memory | | |
| 9FFFh 2080h 207Fh | Internal ROM/EPROM or External Memory | | |
| 2000h | Internal ROM/EPROM or External Memory (Interrupt vectors, CCB's, Security Key, Reserved locations, etc.) | | |
| 1FFFh 1F00h | Internal Special Function Registers (SFR's) | | |
| 1EFFh 0600h | External Memory | | |
| 05FFh 0400h | INTERNAL RAM (Address with indirect or indexed modes.) (Also know as Code RAM) | | |
| 03FFh 0100h | Register RAM | Upper Register File (Address with indirect or indexed modes or through windows.) | Register File |
| 00FFh 0018h | Register RAM | Lower Register File (Address with direct, indirect or indexed modes.) | |
| 0017h 0000h | CPU SFRs | | |

FIGURE 11.19 Microcontroller memory map.

Memory is commonly referred to in terms of Kbytes of memory. One Kbyte is defined as 1024 bytes of data. Memory is most commonly arranged in bytes which consist of 8 bits of data. For instance, a common automotive EPROM is referred to as a "256k × 8 EPROM". This EPROM contains 256-Kbytes 8-bit memory locations or 2,097,152 bits of information.

11.2.1 On-Chip Memory

On-chip microcontroller memory consists of some mix of five basic types: random access memory (RAM), read-only memory (ROM), erasable ROM (EPROM), electrically erasable ROM (EEPROM), and flash memory. RAM is typically utilized for run-time variable storage and SFRs. The various types of ROM are generally used for code storage and fixed data tables.

The advantages of on-chip memory are numerous, especially for automotive applications, which are very size and cost conscious. Utilizing on-chip memory eliminates the need for external memory and the "glue" logic necessary to implement an address/data bus system. External memory systems are also notorious generators of switching noise and RFI due to their high clock rates and fast switching times. Providing sufficient on-chip memory helps to greatly reduce these concerns.

RAM. RAM may be defined as memory that has both read and write capabilities so that the stored information can be retrieved (read) and changed by applying new information to the cell (write). RAM found on microcontrollers is that of the static type that uses transistor cells connected as flip-flops. A typical six-transistor CMOS RAM cell is shown in Fig. 11.20. It consists of two cross-coupled CMOS inverters to store the data and two transmission gates, which provide the data path into or out of the cell. The most significant characteristic of static memory is that it loses its memory contents once power is removed. After power is removed, and once it is reapplied, static microcontroller RAM locations will revert to their default state of a logic "0". Because of the number of transistors used to construct a single cell, RAM memory is typically larger per bit than EPROM or ROM memory.

Although code typically cannot be executed from register RAM, a special type of RAM often referred to as *code RAM* is useful for downloading small segments of executable code. The difference between code and register RAM is that code RAM can be accessed via the

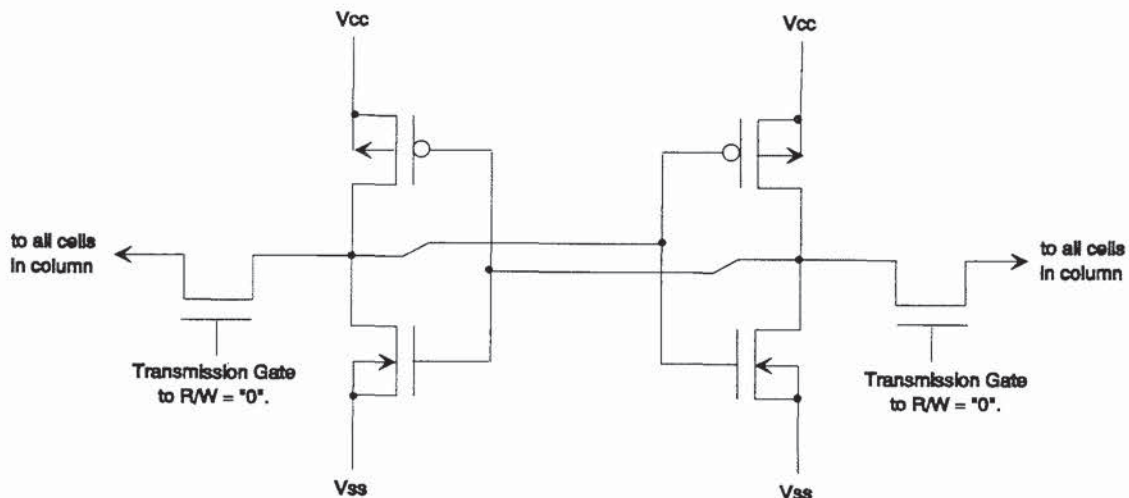


FIGURE 11.20 CMOS RAM memory cell.

memory controller, thus allowing code to be executed from it. Code RAM is especially useful for end-of-line testing during ECU manufacturing by allowing test code to be downloaded via the serial port peripheral.

ROM. Read-only memory (ROM), as the name implies, is memory that can be read but not written to. ROM is used for storage of user code or data that does not change since it is a non-volatile memory that retains its contents after power is removed. Code or data is either entered during the manufacturing process (masked ROM, or MROM) or by later programming (programmable ROM, or PROM); either way, once entered it is unalterable.

A ROM cell by itself (Fig. 11.21) is nothing more than a transistor. ROM cells must be used in a matrix of word and bit lines (as shown in Fig. 11.22) in order to store information. The word lines are connected to the address decoder and the bit lines are connected to output buffers. The user's code is permanently stored by including or omitting individual cells at word and bit line junctions within the ROM array. For MROMs, this is done during wafer fabrication. For PROMs, this is done by blowing a fuse in the source/drain connection of each cell. To read an address within the array, the address decoder applies the address to the memory matrix. For any given intersection of a word and bit line, the absence of a cell transistor allows no current to flow and causes the transistor to be off. This indicates an unprogrammed ROM cell. The presence of a complete cell conducts and is sensed as a logical "0", indicating a programmed cell. The stored data on the bit lines is then driven to the output buffers.

MROMs are typically used for applications whose code is stable and in volume production. After the development process is complete and the user's program has been verified, the user submits the ROM code to the microcontroller manufacturer. The microcontroller manufacturer then produces a mask that is used during manufacturing to permanently embed the program within the microcontroller. This mask layer either enables or disables individual ROM cells at the junctions of the word and bit lines. An advantage of MROM microcontrollers is that they come with user code embedded, which saves time and money since post-production programming is not necessary. A disadvantage of MROM devices is that, since the mask with the user code has to be supplied early in the manufacturing process, throughput time (TPT) is longer.

Some versions of ROM (such as Intel's Quick-ROM) are actually not ROMs, but rather EPROMs, which are programmed at the factory. These devices are packaged in plastic devices, which prevents them from being erased since ultraviolet light cannot be applied to the actual EPROM array. Throughput time for QROMs is faster since the user code isn't required until after the actual manufacturing of the microcontroller is complete. As with

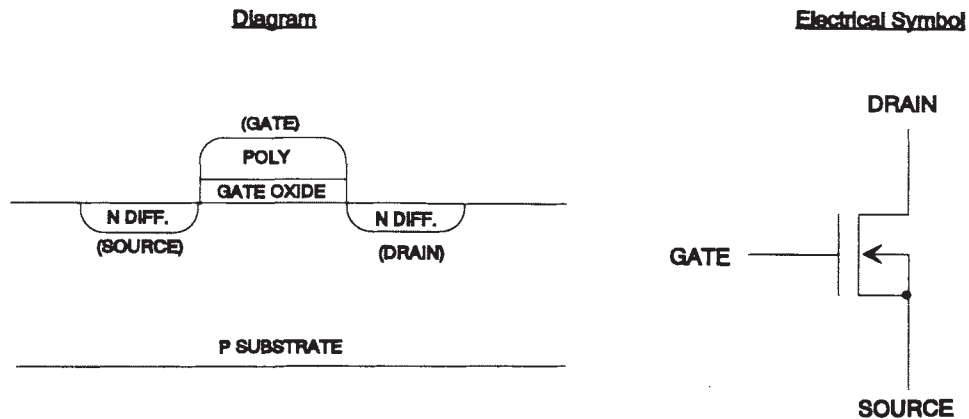


FIGURE 11.21 ROM memory cell.

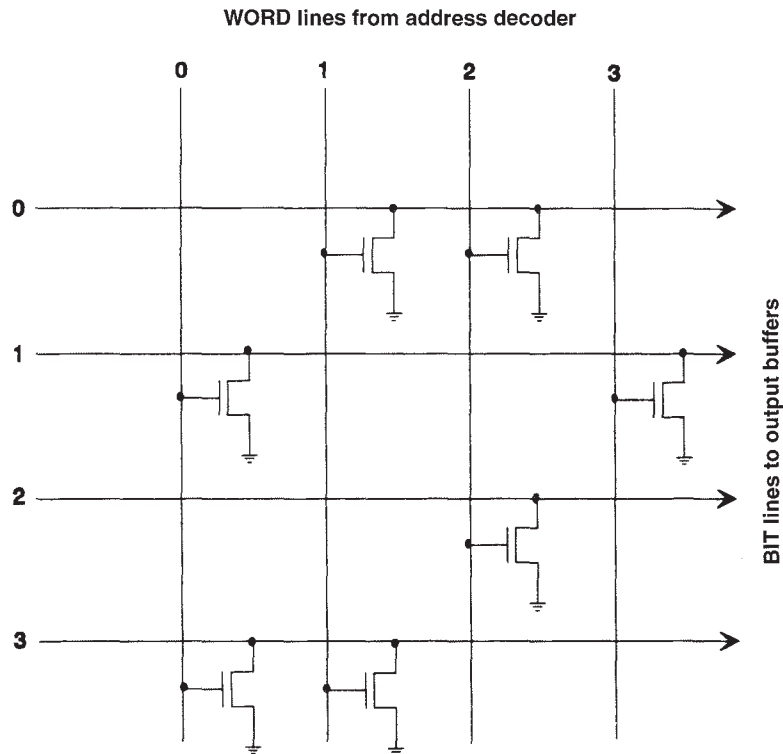


FIGURE 11.22 Simplified ROM memory matrix.

MROMs, the user supplies the ROM code to the microcontroller manufacturer. Instead of creating a mask with the ROM code, the manufacturer programs it into the device just prior to final test.

EPROM. EPROM devices are typically used during application development since this is when user code is changed often. EPROMs are delivered to the user unprogrammed. This allows the user to program the code into memory just prior to installation into an ECU module. Many EPROM microcontrollers actually provide a mechanism for in-module programming. This feature allows the user to program the device via the serial port while it is installed in the module. EPROM devices come assembled in packages either with or without a transparent window. Windowed devices are true EPROM devices that allow the user to erase the memory contents by exposing the EPROM array to ultraviolet light. These devices may be reprogrammed over and over again and thus are ideally suited for system development and debug during which code is changed often. EPROM devices assembled in a package without a window are commonly referred to as *one-time programmable devices* or OTPs. OTPs may only be programmed once, since the absence of a transparent window prevents UV erasure. OTPs are suited for limited production validation (PV) builds in which the code will not be erased.

A typical EPROM cell is shown in Fig. 11.23. It is basically an N-channel transistor that has an added poly1 floating gate to store charge. This floating gate is not connected and is surrounded by insulating oxide that prevents electron flow. The mechanism used to program an EPROM cell is known as *hot electron injection*. Hot electron injection occurs when very high drain (9-V) and select gate (12-V) voltages are applied. This gives the negatively charged electrons enough energy to surmount the oxide barrier and allows them to be stored on the gate.

This has the same effect as a negative applied gate voltage and turns the transistor off. When the cell is unprogrammed, it can be turned on like a normal transistor by applying 5 V to the poly2 select gate. When it is programmed, the 5 V will not turn on the cell. The state of the cell is determined by attempting to turn on the cell and detecting if it turns on. Erasure is performed through the application of ultraviolet (UV) light, which gives just the right amount of energy necessary for negatively charged electrons to surmount the oxide barrier and leave the floating gate.

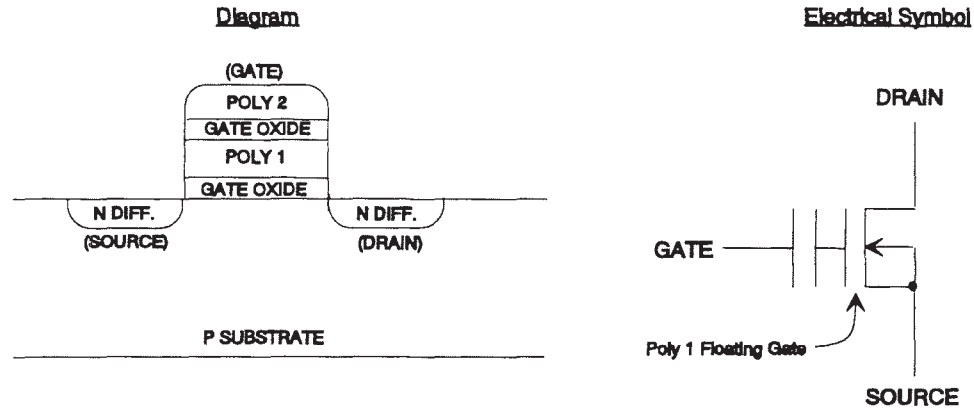


FIGURE 11.23 EPROM memory cell.

Flash. Flash memory is the newest nonvolatile memory technology and is very similar to EPROM. The key difference is that flash memory can be electrically erased. Once programmed, flash memory contents remain intact until an erase cycle is initiated via software. Like EEPROM, flash memory requires a programming and erase voltage of approximately 12.0 V. Since a clean, regulated 12-V reference is not readily available in automotive environments, this need is often provided for through the incorporation of an on-chip charge pump. The charge pump produces the voltage and current necessary for programming and erasure from the standard 5-V supply voltage. The advantage of flash is in its capability to be programmed *and* erased in-module without having to be removed. In-module reprogrammability is desirable since in-vehicle validation testing doesn't always allow for easy access to the microcontroller. Flash also allows for last-minute code changes, data table upgrades, and general code customization during ECU assembly. Since a flash cell is nearly identical in size to that of an EPROM cell, the high reliability and high device density capable with EPROM is retained. The main disadvantage of flash is the need for an on-chip charge pump and special program and erase circuitry, which adds cost.

A flash memory cell is essentially the same as an EPROM cell, with the exception of the floating gate. The difference is a thin oxide layer which allows the cell to be electrically erased. The mechanism used to erase data is known as *Fowler-Nordheim tunneling*, which allows the charge to be transferred from the floating gate when a large enough field is created. Hot electron injection is the mechanism used to program a cell, exactly as is done with EPROM cells. When the floating gate is positively charged, the cell will read a "1", when negatively charged, the cell will read a "0".

EEPROM. EEPROM (electrically erasable and programmable ROM, commonly referred to as E²ROM) is a ROM that can be electrically erased and programmed. Once programmed, EEPROM contents remain intact until an erase cycle is initiated via software. Like flash, programming and erase voltages of approximately 12 V are required. Since a clean, regulated 12-V reference is not readily available in automotive environments, this requirement is satisfied using an on-chip charge pump as is done for flash memory arrays. Like flash, the advantage of EEPROM is its

capability to be programmed and erased in-module. This allows the user to erase and program the device in the module without having to remove it. EEPROM's most significant disadvantage is the need for an on-chip charge pump. Special program and erase circuitry also adds cost.

An EEPROM cell is essentially the same as an EPROM cell with the exception of the floating gate being isolated by a thin oxide layer. The main difference from flash is that Fowler-Nordheim electron tunneling is used for *both* programming and erasure. This mechanism allows charge to be transferred to or from the floating gate (depending upon the polarity of the field) when a large enough field is created. When the floating gate is positively charged, the cell will read a "1"; when negatively charged, the cell will read a "0".

11.2.2 Off-Chip Memory

Off-chip memory offers the most flexibility to the system designer, but at a price; it takes up additional PCB real estate as well as additional I/O pins. In cost- and size-conscious applications, such as automotive ABS, system designers almost exclusively use on-chip memory. However, when memory requirements grow to sizes in excess of what is offered on-chip (such as is common in electronic engine control), the system designer must implement an off-chip memory system. Off-chip memory is flexible because the user can implement various memory devices in the configuration of his choice. Most microcontrollers on the market today offer a wide variety of control pins and timing modes to allow the system designer flexibility when interfacing to a wide range of external memory systems.

Accessing External Memory. If circuit designers must use external memory in their applications, the type of external address/data bus incorporated onto the microcontroller should be considered. If external memory is not used, this will have, if any, impact upon the application. There are two basic types of interfaces used in external memory systems. Both of these are parallel interfaces in which bits of data are moved in a parallel fashion and are referred to as *multiplexed* and *demultiplexed* address/data buses.

Multiplexed Address/Data Buses. As the name implies, multiplexed address/data buses allow the address as well as the data to be passed over the same microcontroller pins by multiplexing the two in time. Figure 11.24 illustrates a typical multiplexed 16-bit address/data bus system as is implemented with Intel's 8XC196Kx family of microcontrollers.

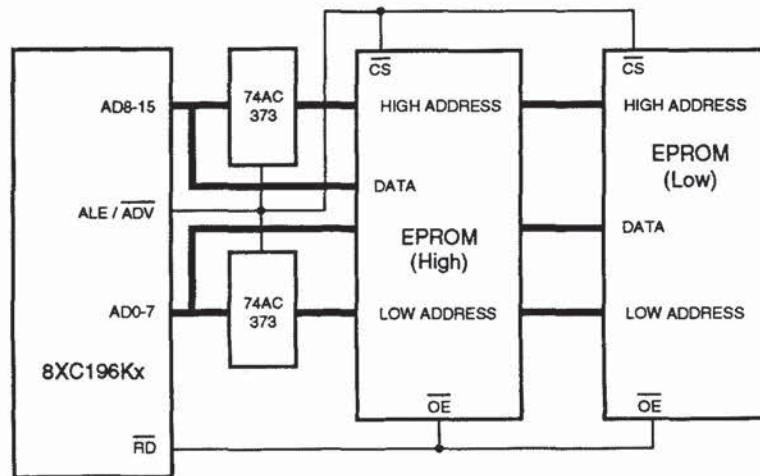


FIGURE 11.24 Multiplexed address/data bus system.

During a multiplexed bus cycle (refer to Fig. 11.25), the address is placed on the bus during the first half of the bus cycle and then latched by an external address data latch. The signal to latch the address comes from a signal generated by the microcontroller, called address latch enable (ALE). The address must be present on the bus for a specified amount of time prior to ALE being asserted. After the address is latched, the microcontroller asserts either a read (RD#) or a write (WR#) signal to the external memory device.

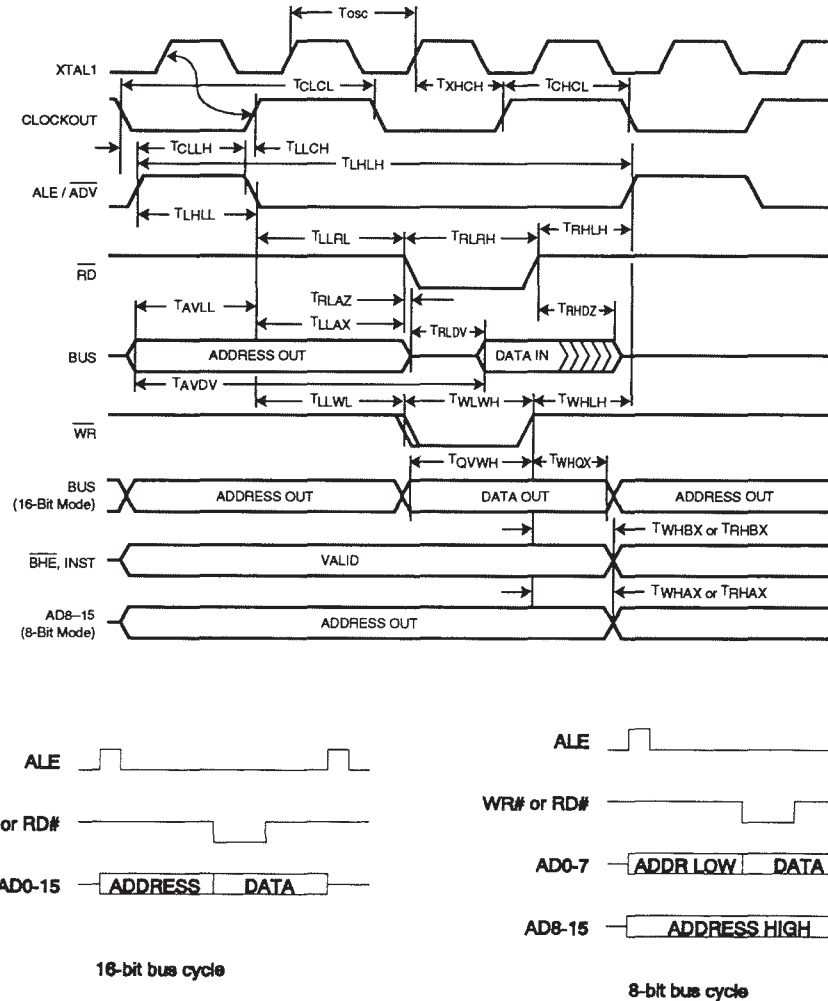


FIGURE 11.25 Multiplexed bus cycle and timing diagram.

For a read cycle, the microcontroller will pull its RD# output pin low and float the bus to allow the memory device to output the data located at the address latched on its address pins. The data returned from external memory must be on the bus and stable for a specified setup time before the rising edge of RD#, which is when the microcontroller latches the data.

For a write cycle, the microcontroller will pull its WR# pin low and then output data on the bus to be written to the external memory. After a specified setup time, the microcontroller will

release its $\overline{WR}\#$ signal, which signals to the memory device to latch the data on the bus into the address location present on its address pins.

Advantages of multiplexed address/data bus systems are that fewer microcontroller pins are required since address and data share the same pins. For a true 16-bit system, this translates into a multiplexed system requiring 16 fewer pins (for address and data) than would be required by a demultiplexed system. A disadvantage is that an external latch is required to hold the address during the second half of the bus cycle; this adds to the component count.

Demultiplexed Address/Data Buses. Microcontrollers with demultiplexed address/data buses implement separate, dedicated address and data buses as shown in Fig. 11.26.

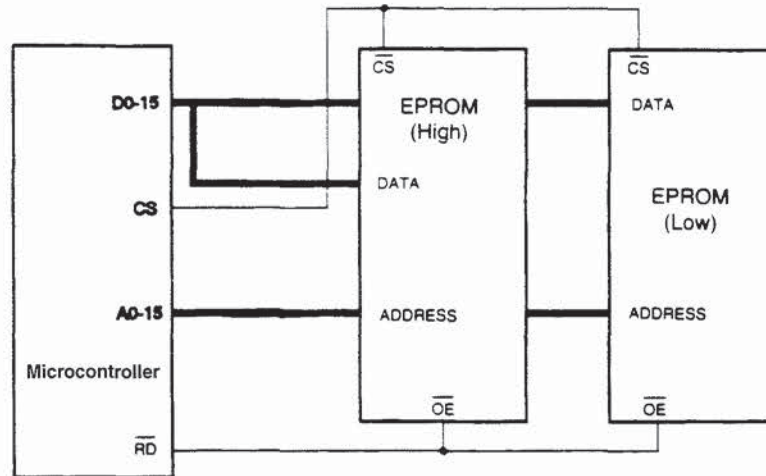


FIGURE 11.26 Typical demultiplexed address/data bus system.

The operation of a demultiplexed address/data bus is basically the same as the multiplexed type with the exception of not having an ALE signal to latch the address for the second half of the bus cycle. The operation of the $\overline{RD}\#$, $\overline{WR}\#$, address, and data lines is essentially the same as for that of a multiplexed system.

During a demultiplexed bus cycle, the microcontroller places the address on the address bus and holds it there for the entire bus cycle. For a read of external memory, the microcontroller asserts the $\overline{RD}\#$ signal (or $\overline{WR}\#$ for a write signal) just as would be done for a multiplexed bus cycle. The memory device will respond accordingly by either placing the data to be read on the data bus or by latching the data to be written off of the data bus. Figure 11.27 illustrates a simplified demultiplexed bus cycle.

An advantage of multiplexed address/data bus systems is that external data latches are not necessary, which saves on system component count. A disadvantage, as mentioned earlier, is that more microcontroller pins must be allocated for the interface, which leaves fewer pins for other I/O purposes.

11.3 LOW-SPEED INPUT/OUTPUT PORTS

Low-speed input/output (LSIO) ports allow the microcontroller to read input signals as well as provide output signals to and from other electronic components such as sensors, power drivers,

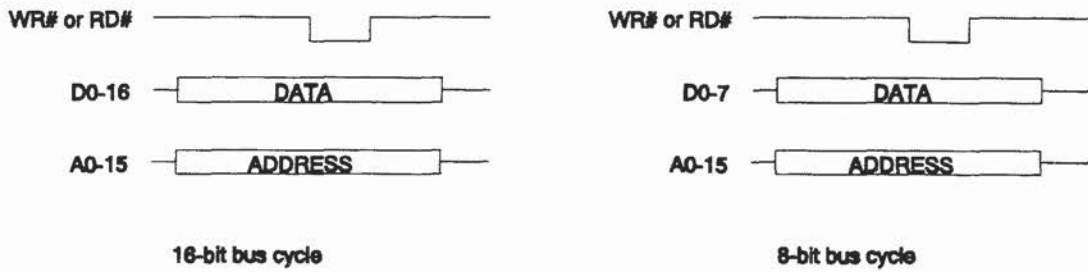


FIGURE 11.27 Demultiplexed bus cycle.

digital devices, actuators, and other microcontrollers. The term “low-speed” is used to describe these ports because unlike high-speed I/O (HSIO) ports which are interrupt driven, LSIO port data must be manually read and written by the user program. Interrupt-driven I/O is typically not possible on port pins configured for LSIO operation. It is common for modern high-performance microcontrollers to utilize multifunctional port pins which can be configured for a special function as well as LSIO. LSIO ports most commonly consist of eight port pins in parallel, which are supported by byte registers. For example, by writing to a single-byte special function register, an entire port can be configured, read, or written. Manipulating individual bits in the port register allows the user flexibility in accessing either single or multiple port pins.

11.3.1 Push-Pull Port Pin Configuration

The term *push-pull*, or *complementary*, output is commonly used to define a port pin that has the capability to output either a logic “1” or “0”. Figure 11.28 shows a basic push-pull port pin configuration. Referring to Fig. 11.28, writing a “1” to the data output register enables the P-channel MOSFET and pulls the pin to +5 V, thus driving a logic “1” at the port pin. When a “0” is written

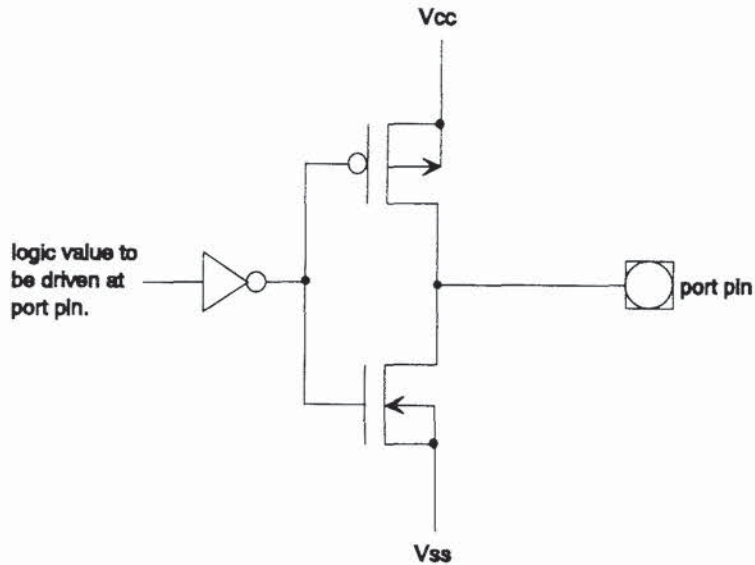


FIGURE 11.28 Push-pull port pin.

to the data register, the N-channel MOSFET is enabled and thus provides a current path to ground which results in a logic 0 at the port pin. Note that during this time the P-channel pull-up MOSFET is disabled to prevent contention at the port pin. Also note that the port logic design does not allow both the P-channel and the N-channel devices to be driving at the same time.

11.3.2 Open-Drain Port Pin Configuration

Open-drain port pins (Fig. 11.29) are useful for handshaking signals over which multiple devices will have control. The fact that the P-channel transistor is either omitted or disabled dictates the need for an external pull-up resistor. An example of an application for open-drain port pins would be for a bus contention line between two microcontrollers communicating on a common bus. During normal operation, the line is pulled high by the external pull-up resistor to signal to either microcontroller that no contention exists. If one of the microcontrollers should detect contention on the bus, it simply outputs a logic “0”, which signals the contention to the other processor. To output the “0”, the port only has to overcome the external pull-up which the user should appropriately size to match the port drive specifications.

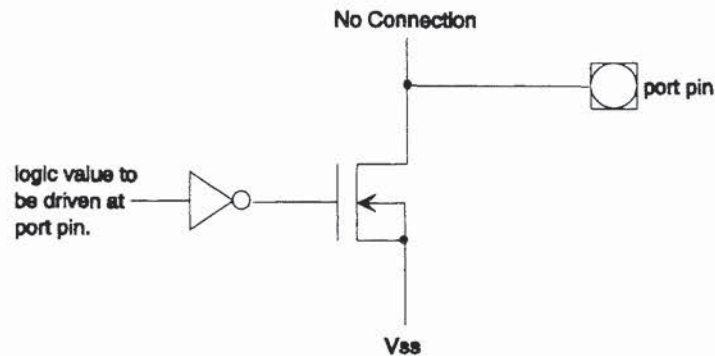


FIGURE 11.29 Open-drain port pin.

11.3.3 High-Impedance Input Port Pin Configuration

High impedance, or “Hi-z,” port pins (Fig. 11.30) are used strictly as inputs since no drivers exist on these types of pins. Hi-z refers to the relatively high input impedance of the port pin. This high input impedance prevents the port pin circuitry from actively loading the input signal. Note that the pin is connected to the gates of a CMOS inverter, which drives internal circuitry. Usually a certain amount of hysteresis is built into these pins and is specified in the data sheet.

11.3.4 Quasi Bidirectional Port Pin Configuration

Quasi bidirectional (QBD) port pins are those that can be used as either input or output without the need for direction control logic. QBD port pins can output a strong low value or a weak high value. The weak high value can be externally overridden, providing an input function. Figure 11.31 shows a QBD port pin diagram and its transfer characteristic.

Writing a “1” to the port pin disables the strong low driver (Q2) and enables a very weak high driver (Q3). To get the pin to transition high quickly, a strong high driver (Q1) is enabled for one state time and then disabled (leaving only Q3 active).

It is important to keep in mind that since the port pin can be externally overridden with a logic “0”, reading the port pin could falsely indicate that it was written as a logic “0”.

The ability to overdrive the weak output driver is what gives the quasi bidirectional port pin its input capability. To reduce the amount of current that flows when the pin is externally pulled low, the weak output driver (Q4) is turned off when a valid logic "0" is detected. The input transfer characteristic of a quasi bidirectional port pin is shown in Fig. 11.31.

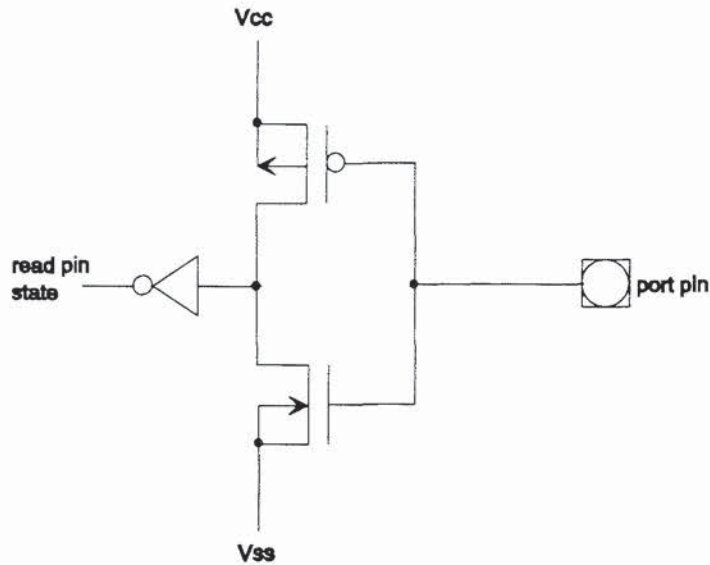


FIGURE 11.30 High-impedance input port pin.

11.3.5 Bidirectional Port Example

The following example describes the operation of a state-of-the-art bidirectional port structure. This particular structure is used upon newer members of Intel's MCS-96 automotive microcontroller family. A single port consists of eight multifunction, parallel port pins (see Fig. 11.32), which are controlled (on a by-pin basis) with four special function registers referred to as Px_PIN, Px_REG, Px_MODE, and Px_DIR. As is common with other high-performance microcontrollers, the pins of this port are shared with alternate special functions controlled by other on-chip peripherals. The Px_MODE register allows the programmer to choose either LSIO or the associated special function for any given port pin. Writing a "1" to the appropriate bit selects the corresponding pin as special function whereas a "0" selects LSIO. The function of the Px_PIN and Px_REG registers is fairly straightforward. In order to read the value on the pin, the user simply reads the Px_PIN register. To write a value to the Px_REG register, the user simply writes the desired output value to the Px_REG register. The Px_DIR register allows the user to configure the port pin as either input or output.

In order to prevent an undefined pin state during reset, port pins revert to a default state during reset. For the Intel Kx bidirectional port structure, this state is defined as a weak logic "1". The transistor that drives this state is labeled as WKPU in Fig. 11.32 and is asserted in reset until the user writes to the Px_MODE register to configure the port pin.

Ports such as this offer the user much flexibility in assigning their function within an application. Following are three examples that depict how these ports may be configured by the user by writing values to the appropriate bit within the port SFR. Also note that the eight pins of a port may be configured individually on a pin-by-pin basis.

To configure a given port pin as a high-impedance input pin, the user must write the following values to the corresponding bit within the port SFR.

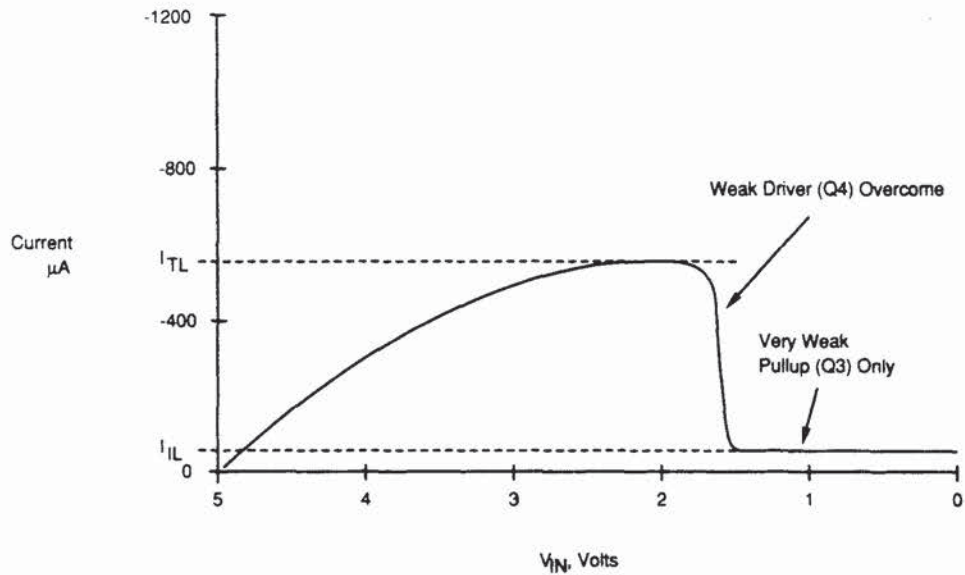
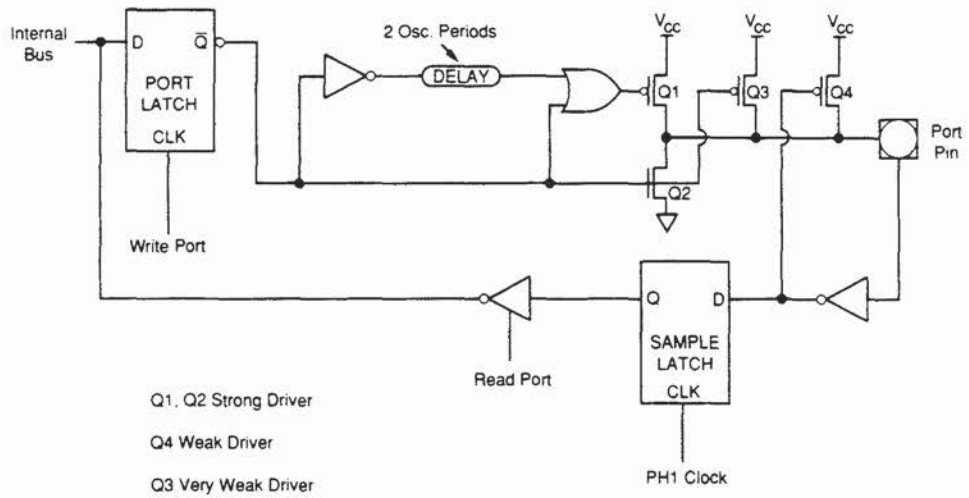


FIGURE 11.31 Quasi bidirectional port pin and transfer characteristic.

- Px_MODE: "0" selects the pin as LSIO and disables weak pull-up.
- Px_DIR: "1" disables operation of the N-channel transistor.
- Px_REG: "1" disables the N-channel transistor.

To configure a given port pin for push-pull operation, the following values must be written to the corresponding bit within the port SFR.

11.4.1 High-Speed Input and Output Peripheral

High-speed input/output peripherals typically consist of a given number of capture/compare modules, a timer/counter structure, control and status SFRs, and an interrupt structure of some type. Figure 11.33 shows a block diagram of the EPA peripheral. The main components of the EPA are ten capture/compare channels, two compare only channels, and two timer/counters. The capture/compare channels are configured independently of each other. The two timer/counters are shared between the various capture/compare channels. Each capture/compare channel has its own dedicated SFR's: EPAX_TIME and EPAX_CON (x designates the channel number).

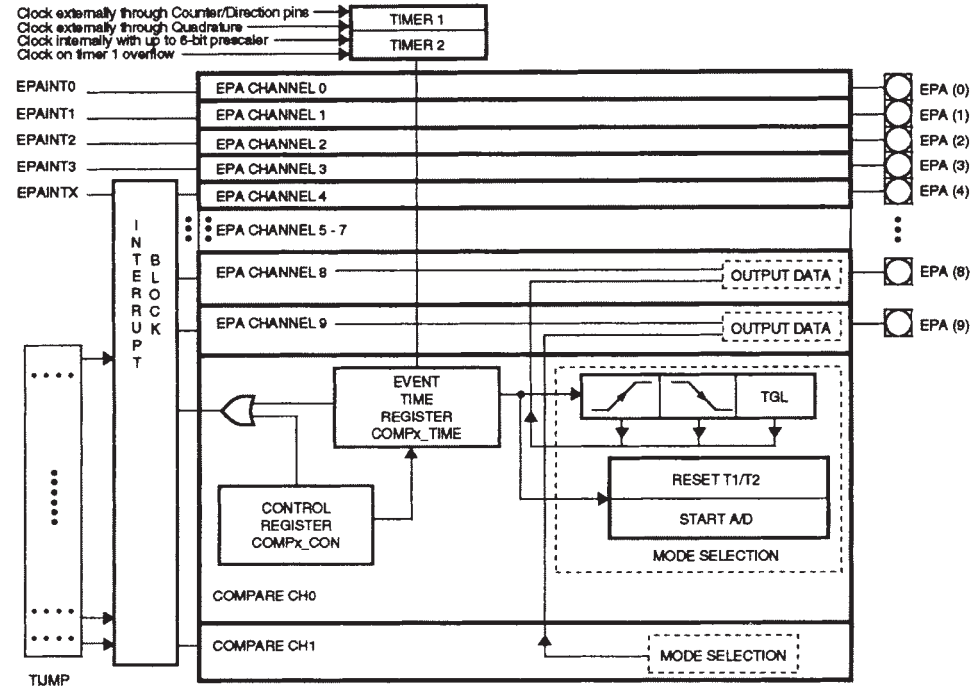


FIGURE 11.33 Example HSIO peripheral: Intel's EPA peripheral.

11.4.2 Timer/Counter Structures

High-performance microcontrollers typically integrate one or more timer/counters onto their silicon. A microcontroller's timer/counter structure provides a time base to which all HSIO events are referenced. Timers are clocked internally, whereas counters are clocked from an external clock source. Timers are often very flexible structures, in which programmers have the capability to configure the timer/counters to meet their application's particular needs. The 87C196KT has two 16-bit timer/counters referred to as TIMER1 and TIMER2. As 16-bit timer/counters, each timer has the capability of counting to 2^{16} or 65,536 before overflowing. The user has the option of triggering an interrupt upon overflow of a timer/counter. Each of these two timers can be independently configured using the TxCONTROL SFR as shown in Fig. 11.34, where x specifies either 1 or 2 for Timer1 or Timer2, respectively.

Bits number 3, 4, and 5 are the mode bits that allow the user to configure the clocking source and direction of each timer/counter. The clock rate can be based either upon the fre-

TxCONTROL SFR

| | | | | | | | |
|----|----|----|----|----|----|----|----|
| 7 | 6 | 5 | 4 | 3 | 2 | 1 | 0 |
| CE | UD | M2 | M1 | M0 | P2 | P1 | P0 |

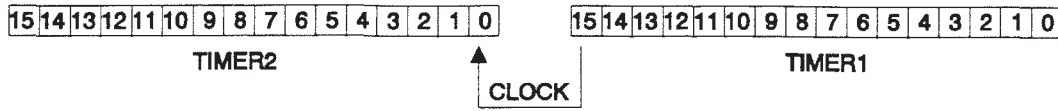
CE: Count Enable: "0" = disable timer, "1" = enable timer

UD: Up/Down: "0" = count up, "1" = count down

| MODE: | <u>M2, M1, M0</u> | <u>Clock source</u> | <u>Direction determined by:</u> |
|-------|-------------------|--|---------------------------------|
| | 0 0 0 | XTAL/4 | state of UD bit |
| | 0 0 1 | TxCLK pin | state of UD bit |
| | 0 1 0 | XTAL/4 | state of TxDIR pin |
| | 0 1 1 | TxCLK pin | state of TxDIR pin |
| | 1 0 0 | Timer1 overflow | state of UD bit |
| | 1 1 0 | Timer1 overflow | same as Timer1 |
| | 1 1 1 | Quadrature clocking using TxCLK and TxDIR pins | |

| Prescale: | <u>P2, P1, P0</u> | <u>Clock prescale values</u> |
|-----------|-------------------|---|
| | 0 0 0 | ÷ by 1 (250 ns @ 16 MHz xtal frequency) |
| | 0 0 1 | ÷ by 2 (500 ns @ 16 MHz xtal frequency) |
| | 0 1 0 | ÷ by 4 (1 µs @ 16 MHz xtal frequency) |
| | 0 1 1 | ÷ by 8 (2 µs @ 16 MHz xtal frequency) |
| | 1 0 0 | ÷ by 16 (4 µs @ 16 MHz xtal frequency) |
| | 1 0 1 | ÷ by 32 (8 µs @ 16 MHz xtal frequency) |
| | 1 1 0 | ÷ by 64 (16 µs @ 16 MHz xtal frequency) |
| | 1 1 1 | reserved |

FIGURE 11.34 Timer control SFR example.



Overflow of TIMER1 clocks TIMER2 thus creating a 32-bit TIMER.

FIGURE 11.35 Cascading of timer/counters.

quency that the microcontroller is being clocked at the XTAL pins or upon the input frequency on another pin referred to as TxCLK. The user also has the option of either having the logic level of another pin (TxDIR) or the UD bits in TxCONTROL determine the direction (up/down) that the timer/counter is clocked.

For those applications that require a 32-bit timer/counter, the user has the option (using the mode bits) to direct the overflow of TIMER1 to clock TIMER2. This is known as cascading and essentially creates a 32-bit timer/counter as shown in Fig. 11.35.

11.4.3 Input Capture

Input capture refers to the process of capturing a current timer value when a specific type of event occurs. An excellent example of high-speed input capture can be illustrated with a basic automotive ABS input capture algorithm that calculates the frequency of a wheel speed input. The signals from the wheel speed sensors are input into the microcontroller's EPA pins as square waves. Consider the generic wheel speed input capture example shown in Fig. 11.36.

Two timers (1 and 2) are used in this example. Timer1 is used in conjunction with an EPA channel to provide a 5-ms software timer (this is a compare function that will be discussed in the next section). The 5 ms is the main loop time used in generic ABS algorithms. Timer2 is used in conjunction with one or more EPA channels to capture the relative times at which edges occur on wheel speed inputs. The EPA is configured to capture falling edges and initiate an interrupt, which stores the event time and increments an edge count. To simplify this example, we will consider only a single input channel.

The process starts by EPA interrupts being enabled after Timer1 starts a new 5-ms timer count. The first falling edge causes an interrupt that stores the event time (T_2) into a variable *initial time* and increments an edge count. The next edge causes an interrupt in which the event time (T_2+x) is stored into a variable called *final time* and increments the edge count.

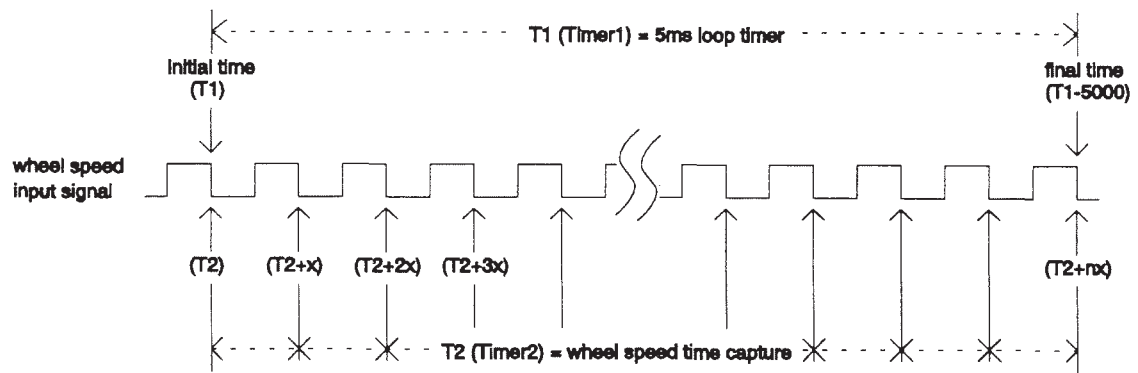


FIGURE 11.36 Input capture example using EPA peripheral.

Subsequent edges' event times are also stored into *final time* until Timer1's 5-ms count expires. At this point, final time contains the time at which the last edge to occur was captured. The average period of the input waveform can then be calculated with the following equation:

$$\text{input period} = (\text{final time} - \text{initial time}) / \text{edge count}$$

11.4.4 Output Compare

Output compare refers to the process of generating an event when a timer value matches a predetermined time value. The event may be to generate an interrupt, toggle an output pin, perform an A/D conversion, and so forth. Following is an example that shows the steps necessary to generate an event every 50 μs :

1. Enable the output compare channel's interrupt.
2. Initialize the timer to count up at 1 μs per timer tick.
3. Initialize the output compare channel to re-enable and reset the timer (to zero) when a timer match occurs.
4. Initialize the output compare channel to produce the desired event when a timer match occurs.
5. Write 32h (50 decimal) to the appropriate output compare channel's time register.
6. Enable the timer to start the process.
7. A compare channel interrupt will be generated every 50 μs .

Since the example re-enables and zeros the timer, the event will occur continuously until the user's program halts the process.

Software Timers. Software timers such as the 5-ms timer used in the ABS wheel speed capture example can be set up easily using a compare channel and a timer. The following software timer procedure is very similar to that used in the previous output compare example:

1. Enable the compare channel's interrupt.
2. Initialize the timer to count up at 1 μs per timer tick.
3. Initialize the output compare channel to re-enable and reset the timer (to zero) when a timer match occurs.
4. Initialize the output compare channel to produce an interrupt (5-ms ISR) when a timer match occurs.
5. Write 1388h (5000 decimal) to the appropriate output compare channel's time register.
6. Enable the timer to start the process.
7. An compare channel interrupt will be generated every 5 ms.

11.4.5 Pulse-Width Modulation (PWM)

Pulse-width modulation (PWM) peripherals provide the user with the ability to generate waveforms that have specified frequencies and duty cycles. PWM waveforms are typically used to generate pulsed waveforms used for motor control or they may be filtered to produce a smooth analog signal. HSIO peripherals typically provide for PWM waveform generation, although the methods are not usually as efficient as dedicated PWM peripherals. A basic example of creating a PWM waveform using an HSIO peripheral's output compare function is described in Sec. 11.4.4.

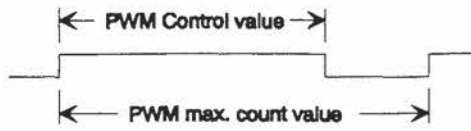


FIGURE 11.37 PWM waveform time values.

PWM Peripheral. The components of a basic automotive microcontroller’s PWM peripheral include a counter (typically 8-bit), a comparator, a holding register, and a control register. The counter typically has a prescaler that allows the user to select the clock rate of the counter, which allows for selectable PWM frequencies. Without

prescaling capability, an 8-bit counter would only allow for a period of 256 state times. The PWM control register determines how long the PWM output is held high during the pulse, effectively controlling the duty cycle as shown in Fig. 11.37. For an 8-bit PWM counter, the value written to the PWM control register can be from 0 to 255 (equating to 255 state times with no prescaling). Note that PWM peripherals do not typically allow for a 100 percent duty cycle because the output must be reset when the counter reaches zero.

The operation of a PWM peripheral is rather simple. The PWM control register’s value (assume 8-bit for this example) is loaded into a holding register when the 8-bit counter overflows. The comparator compares the contents of the holding register to the counter value. When the counter value is equal to zero, the PWM output is driven high. It remains high until the counter value matches the value in the holding register, at which time the output is pulled low. When the counter overflows, the output is again switched high. Figure 11.38 shows typical PWM output waveforms.

| Duty Cycle | PWM Control Register Value | Output Waveform |
|------------|----------------------------|-----------------|
| 0% | 00 | |
| 10% | 25 | |
| 50% | 128 | |
| 90% | 230 | |
| 99.6% | 255 | |

FIGURE 11.38 PWM output waveforms.

11.5 SERIAL COMMUNICATIONS

It is often necessary for automotive microcontrollers to have the capability to communicate with other devices both internal and external to the ECU. Within an ECU a microcontroller may have to communicate with other devices such as backup processors, shift registers, watchdog timers, and so forth. It is not uncommon for automotive microcontrollers to communicate with devices external to the ECU, such as other modules within the vehicle and even diagnostic computers at a service station. All of these communication examples require a large quantity of data to be transmitted/received in a short period of time. Also consider that this communication must utilize as few pins of the microcontroller as possible in order to save valuable PCB board space. These requirements all support the need for serial communications.

Serial communications provides for efficient transfer of data while utilizing a minimum number of pins. Serial communications is performed by transferring a group of data bits, one at a time, sequentially over a single data line. Each transmission of a group of bits (typically a

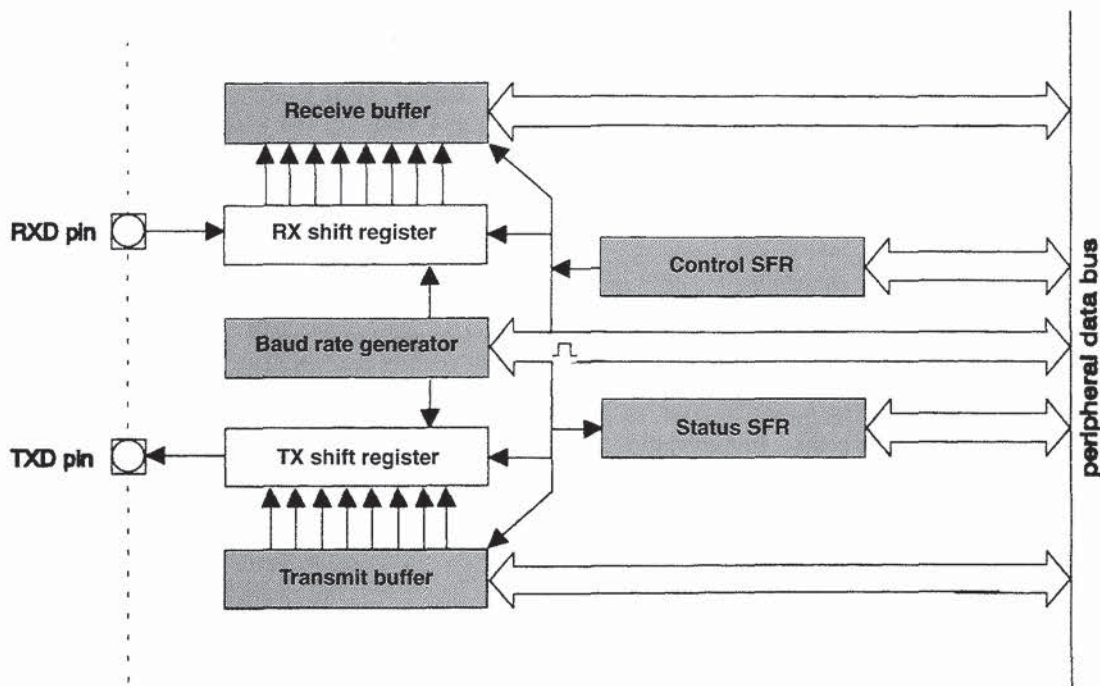


FIGURE 11.39 Serial port block diagram.

byte of data) is known as a data frame. This transfer of data takes place at a given speed, which is referred to as the baud rate and is typically specified in bits/second.

A typical microcontroller serial port consists of data buffers, data registers, and a baud rate generator. Interface to the outside world takes place via the transmit (TXD) and receive (RXD) pins. A block diagram for a typical serial port peripheral is shown in Fig. 11.39. By writing to the serial port control register, users are able to customize the operation of the serial port to their particular application's requirements.

The baud rate generator is used to provide the timing necessary for serial communications and determines the rate at which the bits are transmitted. In synchronous modes, the baud rate generator provides the timing reference used to create clock edges on the clock output pin. In asynchronous modes, the baud rate generator provides the timing reference used to latch data into the RX pin and clock it out of the TX pin.

11.5.1 Synchronous Serial Communications

Sometimes an application does not allow asynchronous serial communications to take place due to variations in clock frequency, which results in unacceptable baud rate error. Some applications simply require some sort of shift register I/O. Synchronous communication involves an additional clock pin, which is used to signal the other device that data being transferred are valid and ready to be read. Often when the user configures the serial port to work in a synchronous mode, the TXD pin automatically reverts to supplying the clock and the RXD pin automatically becomes the data pin. This configuration prevents an additional pin from having to be reserved for use as a serial clock pin. When a synchronous data transfer is initiated, a series of eight clock pulses is emitted from the clock pin at a predetermined baud rate as shown in Fig. 11.40.

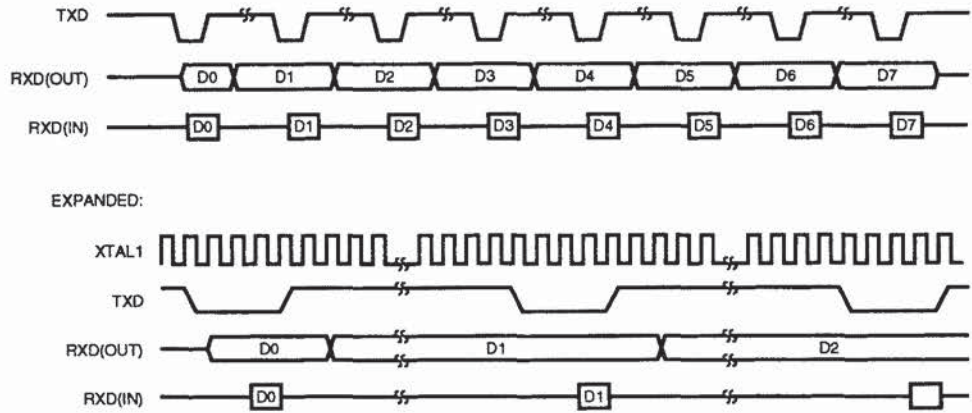


FIGURE 11.40 Synchronous serial mode data frame.

An example of synchronous serial communications is shown in Fig. 11.41. Assume that processor A is to transfer a byte of data to processor B. The program executing in processor A initiates a serial transmission by writing the data byte to be transmitted into the transmit buffer. Assuming microcontroller A’s serial port is enabled for transmission, writing to the transmit buffer results in a series of eight clock pulses to be emitted from microcontroller A’s clock pin. The first falling edge of the clock will signal to processor B that bit 0 (LSB) is ready to be read into its receive buffer. Microcontroller A will place the next data bit on the TXD pin with each rising clock edge. With B’s serial port enabled for reception, each falling edge will result in another data bit being shifted into B’s receive buffer. When B’s receive buffer is full, the received data byte will be loaded into its receive register and will signal its CPU that the reception has been completed and the data is ready for use.

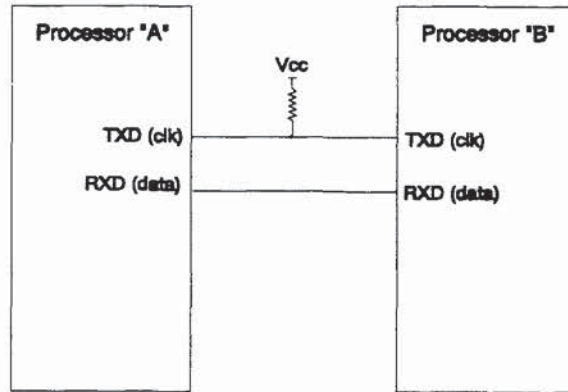


FIGURE 11.41 Synchronous serial communications example.

Shift Register Based I/O Expansion. A common application for synchronous serial transmission is shift register based I/O expansion as shown in Fig. 11.42. In this circuit, a 74HC164 8-bit serial-in/parallel-out shift register is used to provide eight parallel outputs with a single serial input. The 74HC165 8-bit parallel-in/serial out shift register shown provides a single serial input resulting from eight parallel input signals. This allows the system designer to

A parity function is also implemented, which provides for a simple method of error-detection. Data transmitted will consist of either an odd or even number of logical “1”s. If even parity is enabled, the parity bit will either be set to a “1” or a “0” to make the number of “1”s in the data byte even. If odd parity is enabled, the parity bit will be set to the appropriate value to make the number of “1”s in the data byte odd. For instance, consider the data byte 11010010b. If even parity is enabled, the parity bit will be set to a “0” since there is already an even number of “1”s. If odd parity were enabled, the parity bit would be set to a “1” since another “1” would be needed to provide an odd number of “1”s. If the parity function is enabled (usually through a serial port control register), the parity bit is sent instead of the eighth data bit and parity is checked on reception. The occurrence of parity errors is typically flagged in a serial port status register to alert the microcontroller to corrupted data in the receive register.

Multiprocessor Asynchronous Serial Communications Modes. Two other common serial communications modes which are used on automotive microcontrollers are the asynchronous 9th-bit recognition mode and the asynchronous 9th-bit mode. These two modes are commonly used together for multiprocessor communications where selective selection on a data link is required. Both modes are similar to the standard asynchronous mode with the exception of an additional ninth data bit in the data frame as shown in Fig. 11.44.

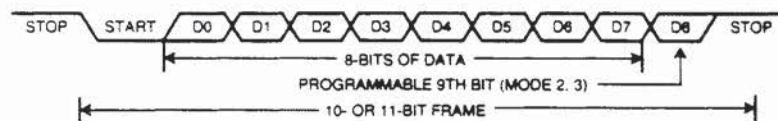


FIGURE 11.44 Asynchronous 9th-bit data frame.

The 9th-bit recognition mode consists of a start bit, nine data bits (LSB first), and a stop bit. For transmission, the ninth bit can be set to “1” by setting a corresponding bit in the serial port control register before writing to the transmit buffer. During reception, the receive interrupt bit is *not* set unless the ninth data bit being received is set to a logic “1”.

The 9th-bit mode uses a data frame identical to that of the 9th-bit recognition mode. In this mode, a reception will always cause a receive interrupt, regardless of the state of the ninth data bit.

A multiprocessor data link is fairly simple to implement using these two modes. Microcontrollers within the system are connected as shown in Fig. 11.45. The master microcontroller is set to the 9th-bit recognition mode so that it is always interrupted by serial receptions. The slave microcontrollers are set to operate in the 9th-bit recognition mode so that they are interrupted on receptions only if the ninth data bit is set. Two types of data frames are used: address frames, which have the ninth bit set, and data frames, which have the ninth bit cleared. When the master processor wants to transmit a block of data to one of several slaves, it first sends out an address frame which identifies the target slave. Slaves in the 9th-bit recognition mode are not interrupted by a data frame, but an address frame interrupts all slaves. Each slave can examine the received byte and see if it is being addressed. The addressed slave then switches to the 9th-bit mode to receive data frames, while the slaves that were not addressed stay in the 9th-bit recognition mode and continue without interruption.

11.6 ANALOG-TO-DIGITAL CONVERTER

Analog-to-digital converter (A/D) peripherals allow automotive microcontrollers to sense and assign digital values to analog input voltages with considerable accuracy. An analog input

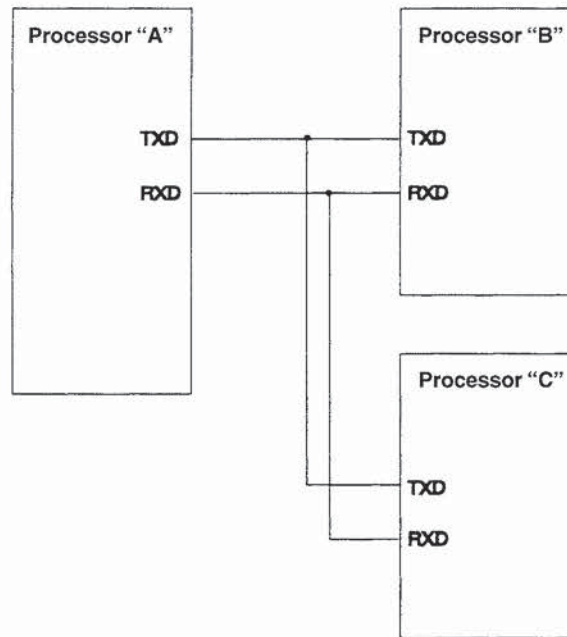


FIGURE 11.45 Asynchronous 9th-bit data frame.

may be defined as a voltage level that varies over a continuous range of values as opposed to the discrete values of digital signals.

11.6.1 Types of A/D Converters

The vast majority of A/D converters available on microcontrollers are of the successive approximation (S/A) type. Other types include flash A/D converters, in which conversions are completed in a parallel fashion and are performed at speeds measuring tens-of-nanoseconds. The drawback is that flash A/D converters require a great deal of die space when integrated on a microcontroller. It is because of their relatively large size that flash A/D converters are seldom offered on microcontrollers. Dual-slope A/D converters offer excellent A/D accuracy but typically take a relatively long period of time to complete a conversion. S/A A/D converters are very popular because they offer a compromise among accuracy, speed, and die-size requirements. The main drawback to successive approximation converters is that implementing the capacitor and resistor ladders takes a considerable amount of die space, although somewhat less than flash A/Ds. These converters are also somewhat susceptible to noise, although there are proven ways to reduce the effects of noise within a given application. The advantage of S/A converters is that they combine the best of other types of converters. They are relatively fast and do not take up excessive die space.

S/A converters typically consist of a resistor ladder, a sample capacitor, an input multiplexer, and a voltage comparator. A typical S/A converter is shown in Fig. 11.46. The resistor ladder is used to produce reference voltages for the input voltage comparison. A sample capacitor is utilized to capture the input voltage during a given period of time known as the sample time. Sample time can be defined as the amount of time that an A/D input voltage is applied to the sample capacitor.

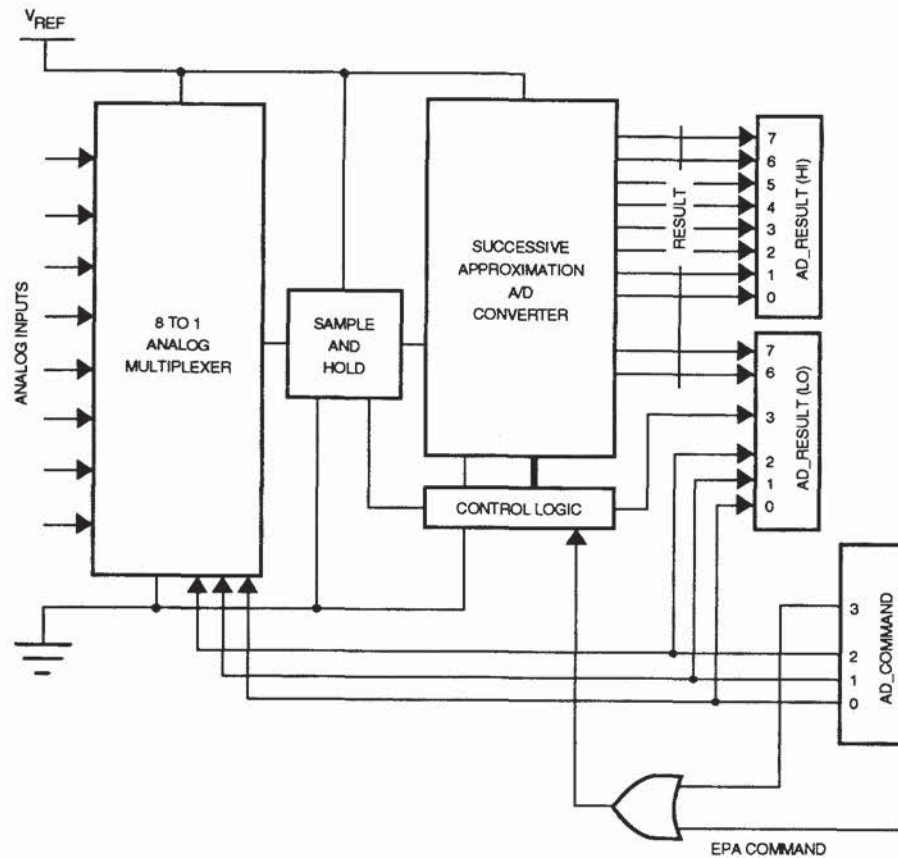


FIGURE 11.46 Typical successive approximation converter.

A successive approximation algorithm is used to perform the A/D conversion. A typical S/A converter consists of a 256-resistor ladder, a comparator, coupling capacitors, and a 10-bit successive approximation register (SAR), along with SFRs and logic to control the process. The resistor ladder provides 20-mV steps (with $V_{ref} = 5.12\text{ V}$), while capacitive coupling creates 5-mV steps within the 20-mV ladder voltages. Therefore, 1024 internal reference voltage levels are available for comparison against the analog input to generate a 10-bit conversion result. Eight-bit conversions use only the resistor ladder, providing 256 levels.

11.6.2 The A/D Conversion Process

The successive approximation conversion compares a reference voltage to the analog input voltage stored in the sampling capacitor. A binary search is performed for the reference voltage that most closely matches the input. The $\frac{1}{2}$ full-scale reference voltage is the first tested. This corresponds to a 10-bit result in which the most significant bit is zero and all other bits are one (0111 1111 11b). If the analog input is less than the test voltage, bit 10 is left at zero and a new test voltage of $\frac{1}{4}$ full scale (0011 1111 11b) is tested. If this test voltage is less than the analog input voltage, bit 9 of the SAR is set and bit 8 is cleared for the next test (0101 1111

11b). This binary search continues until 8 or 10 tests have occurred, at which time the valid 8-bit or 10-bit result resides in the SAR where it can be read by software.

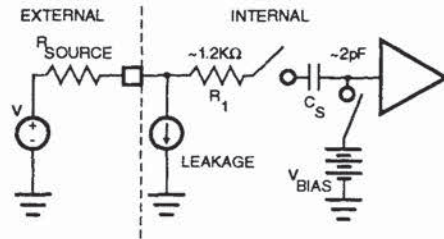


FIGURE 11.47 Idealized interface circuitry.

11.6.3 A/D Interfacing

The external interface circuitry to an analog input is highly dependent upon the application and can impact converter characteristics. Several important factors must be considered in the external interface design: input pin leakage, sample capacitor size, and multiplexer series resistance from the input pin to the sample capacitor. These factors are idealized in Fig. 11.47.

The following example is for a 1- μ s sample time and a 10-bit conversion. The external input circuit must be able to charge a sample capacitor (C_S) through a series resistance (R_1) to an accurate voltage, given a dc leakage (I_L). For purposes of this example, assume C_S of 2 pf, R_1 of 1.2 k Ω , and I_L of 1 μ A.

External circuits with source impedances of 1 k Ω or less can maintain an input voltage within a tolerance of about 0.2 LSB (1.0 k Ω \times 1.0 μ A = 1.0 mV) given the dc leakage. Source impedances above 5 k Ω can result in an external error of at least one LSB due to the voltage drop caused by the 1- μ A leakage. In addition, source impedances above 25 k Ω may degrade converter accuracy because the internal sample capacitor will not charge completely during the sample time.

Typically, leakage is much lower than the maximum specification specified by the microcontroller manufacturer. Given typical leakage, source impedance may be increased substantially before a one-LSB error is apparent. However, a high source impedance may prevent the internal sample capacitor from fully charging during the sample window. This error can be calculated using the following formula:

$$\text{Error (LSBs)} = \left(e^{-\frac{T_{\text{SAM}}}{RC}} \right) \times 1024$$

where T_{SAM} = sample time, μ s
 $R = R_{\text{SOURCE}} + R_1, \Omega$
 $C = C_S, \mu\text{f}$

The effects of this error can be minimized by connecting an external capacitor C_{EXT} from the input pin to ANGND. The external signal will charge C_{EXT} to the source voltage. When the channel is sampled, a small portion of the charge stored in C_{EXT} will be transferred to the internal sample capacitor. The ratio of C_S to C_{EXT} causes the loss in accuracy. If C_{EXT} is .005 μ f or greater, the maximum error will be -0.6 LSB.

Placing an external capacitor on each analog input also reduces the sensitivity to noise because the capacitor combines with series resistance in the external circuit to form a low-pass filter. In practice, one should include a small series resistance prior to the external capacitor on the analog input pin and choose the largest capacitor value practical, given the frequency of the signal being converted. This provides a low-pass filter on the input, while the resistor also limits input current during overvoltage conditions.

11.6.4 Analog References

To achieve maximum noise isolation, on-chip A/D converters typically separate the internal A/D power supply from the rest of the microcontroller's power supply lines. Separate supply

pins, V_{ref} and An_{gnd} , usually supply both the reference and digital voltages for the A/D converter. Keep in mind that V_{ref} and An_{gnd} are the reference for a large resistor ladder on successive approximation converters. Any variation in these supplies will directly affect the reference voltage taps within the ladder, which in turn directly affect A/D conversion accuracy.

If the on-chip A/D converter is not being used, or if accuracy is not a concern, the V_{ref} and An_{gnd} pins can simply be connected to V_{cc} and V_{ss} , respectively. However, since the reference supply levels strongly influence the absolute accuracy of the A/D converter, a precision, well-regulated reference should be used to supply V_{ref} to achieve the highest performance levels. It is also important to use bypass capacitors between V_{ref} and An_{gnd} to minimize any noise that may be present on these supplies. In noise-sensitive applications running at higher frequencies, the use of separate ground planes within the PCB (circuit board) should be considered, possibly as shown in Fig. 11.48. This will help minimize ground loops and provide for a stable A/D reference.

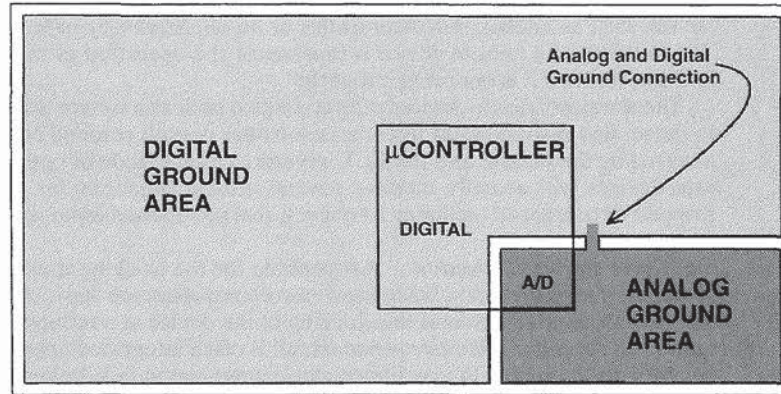


FIGURE 11.48 Example of separate analog and digital ground planes.

11.7 FAILSAFE METHODOLOGIES

The amount and complexity of automotive electronics incorporated into automobiles has increased at an incredible rate over the last decade. This trend has contributed significantly towards the impressive safety record of modern automobiles. Although microcontrollers are extremely reliable electronic devices, it is possible for failures to occur, either elsewhere in the module or within the microcontroller itself. It is critical that these failures be detected and responded to as quickly as possible in safety-related applications such as automotive antilock braking. If proper failsafe methodologies and good programming practices are followed, the chances of a failure going undetected are drastically reduced. The application of *failure mode and effect analysis* (FMEA) is an excellent tool for identifying potential failure modes, detection strategies, and containment methods. Used properly, FMEA will assist the designer in providing a high-quality, reliable automotive module. Although the scope of this chapter does not provide for a discussion on this topic, the author highly encourages the use of FMEA.

11.7.1 Hardware Failsafe Methods

Sometimes a hardware solution is required for detection of and response to certain failure modes. It is difficult for software alone to detect failures external to the device. As an example, consider a case in which electrical overstress (EOS) has damaged a port pin, causing it to

read or drive an incorrect value. In this case, it can be difficult for software to detect because it would base its response on an incorrect value read from a pin.

Watchdog Timers (WDTs). An on-chip hardware watchdog is an excellent method of detecting failures which otherwise may go undetected. An example of this would be a microcontroller fetching either erroneous address or data (due to noise, etc.) and becoming “lost.” WDTs commonly utilize a dedicated 16-bit counter, which provides for a count of 2^{16} (65,536) clocked at a rate of one tick per state time. If users wish to take advantage of this feature, they simply write to a register to enable the count. Once enabled, the user program must periodically clear the watchdog by writing a specific bit pattern to the Watchdog SFR. Clearing the WDT at least every 4.1 ms ($65,535 * 1$ state time at 16 MHz) will prevent the device from being reset. The strategy is that if the WDT initiates a reset, the assumption can be made that a failure has occurred and the microcontroller has become lost.

External Failsafe Devices. It is common for systems to incorporate an external failsafe device, such as another microcontroller or an *application-specific integrated circuit* (ASIC). The function of a failsafe device is to monitor the operation of the primary microcontroller and determine if it is operating properly.

The simplest failsafe devices output a signal such as a square wave for the microcontroller to detect and respond to. If the microcontroller doesn't respond correctly, a reset is typically asserted by the failsafe and the ECU reverts to a safe mode of operation. More complex failsafe devices will actually monitor several critical functions for failures such as low Vcc, stopped or decreased oscillator frequency, shorted/opened input signals, and so forth.

Oscillator Failure Detection. It is possible for the clocking source (typically an oscillator) to fail for various reasons. Since most microcontrollers are static devices, a particularly difficult failure mode to detect is the clocking of the device at a reduced frequency. To detect this failure, an *oscillator failure detection* circuit is often integrated upon the microcontroller. This circuitry will detect if the oscillator clock input signal falls below a specified frequency, in which case an interrupt will be generated or the device will reset itself.

Redundancy/Cross-checking. A common failsafe methodology is achieved by designing a redundant, or backup, processor into the module. In this case, the secondary microcontroller usually executes a subset of the main microcontroller's code. The secondary microcontroller typically processes critical input data and performs cross-checks periodically with the main microcontroller to insure proper operation. A failsafe routine is initiated if data exchanged between the two devices did not correlate.

11.7.2 Software Failsafe Techniques

Failsafe methodologies implemented in software are ideal for detecting failure modes that can interfere with proper program flow. Examples of these types of failures include noise glitches, which are notorious for causing external memory systems to fetch invalid addresses. ROM/EPROM memory corruption could cause an ISR start address to be fetched from an invalid interrupt vector location. Interrupts occurring at a rate faster than anticipated can cause problems such as an overflowing stack. Fortunately, failure modes such as these can be dealt with by implementing software failsafe methods. It is simply good programming practice to anticipate these types of failure modes and provide a failsafe strategy to deal with them. Following are several software strategies commonly used to deal with specific types of failure modes:

Checksum. One possible error that must be accounted for is ROM/EPROM memory corruption. An effective method of detecting these types of failures is through the calculation of

a checksum during the initialization phase of a user's program. A checksum is the final value obtained as the result of performing some arithmetic operation upon every ROM/EPROM memory location. The obtained checksum is then compared against a stored checksum. If the two match, the ROM/EPROM contents are intact. An error routine is called if the two checksums do not match. The most common arithmetic operation used to perform a checksum is addition. The checksum is calculated by adding the contents of all memory locations. When the addition is performed, the carry is ignored which provides for a byte or word checksum. The final result is then used as the checksum.

Unused Interrupt Vectors. It is a rare occasion when all interrupt sources are enabled within an application. If, for some unforeseen reason, the program should vector to an unused interrupt source, some sort of failsafe routine should be implemented to respond to the failure. The failsafe routine could be as simple as vectoring to a reset instruction or it can be as complicated as the programmer wishes.

Unused Memory Locations. A strategy should be in place to detect if, for some unforeseen reason, the program sequence should begin to execute in an unused area of ROM/EPROM. It is uncommon for the user's code to fill the entire ROM/EPROM array of a microcontroller. It is good programming practice to fill any unused locations with the opcode of an instruction such as *Reset*. On the MCS-96 family, executing the opcode FFh (which happens to be the blank state of EPROM) will initiate a reset sequence. Other microcontroller families have similar instructions.

Unimplemented Opcode Interrupt Vectors. Microcontrollers often dedicate one or more interrupt vectors for failsafe purposes. An *unimplemented opcode* interrupt is designed to detect corrupted instruction fetches. The corresponding interrupt service routine is executed whenever an unsupported opcode is fetched for execution. The interrupt service routine contains the user's failsafe routine, which is tailored to address this failure for the specific application.

11.8 FUTURE TRENDS

There are several significant trends developing in automotive electronics as ECU manufacturers strive to meet the challenges of a demanding automotive electronics market. The challenges that are bringing about these trends are: decreasing cost targets, decreasing form-factor goals, increasing performance requirements, and increasing system-to-system communication requirements. As the most significant component of an ECU, microcontrollers are bearing the brunt of these demands. This section will discuss these challenges and provide some insight into some of the ways microcontroller manufacturers are addressing these trends.

11.8.1 Decreasing Cost Targets

Microcontroller manufacturers are approaching cost reduction in two ways: indirectly and directly. *Indirect* cost reductions are achieved by integrating features onto the microcontroller which allow the system designer to reduce cost elsewhere in the system. The key to this approach being successful is in the microcontroller manufacturer's ability to integrate the feature cheaper than the cost of providing an external solution. Integration is not always the cheaper solution, therefore each feature must be evaluated individually to determine the feasibility of integration. An example of an indirect cost reduction would be the integration of watchdog and failsafe functions onto the microcontroller. This would eliminate the need for external watchdog components and thus reduce cost.

Another example would be through the integration of communications protocols such as CAN (Controller Area Network) or J1850 onto the same piece of silicon as the microcontroller. This will reduce the system chip count (and thus cost) by at least one integrated circuit device (the CAN chip) and several interfacing components. In most cases, a reduced chip count will translate into a PCB size decrease and a cost savings.

By *directly* addressing decreasing cost targets, microcontroller manufacturers actually reduce the manufacturing cost of the microcontroller itself. An example of this would be utilizing smaller geometry processes for manufacturing. Process geometry refers to the transistor channel width that is implanted onto a piece of silicon for a given fabrication process. Smaller processes allow for a higher transistor density on an integrated circuit. Higher densities allow for smaller die sizes which relate to lower costs. Most automotive microcontrollers manufactured today are fabricated with a 1.0-micron, or larger, process. As technology advances, future automotive microcontrollers will be manufactured upon submicron processes, such as 0.6 micron.

11.8.2 Increasing Performance Requirements

Automotive applications, such as ABS and engine control, require the processing of a substantial amount of data within a limited period of time. Higher-performance microcontrollers are required as system complexity increases and new features, such as traction control and vehicle dynamics, are incorporated into the ECU.

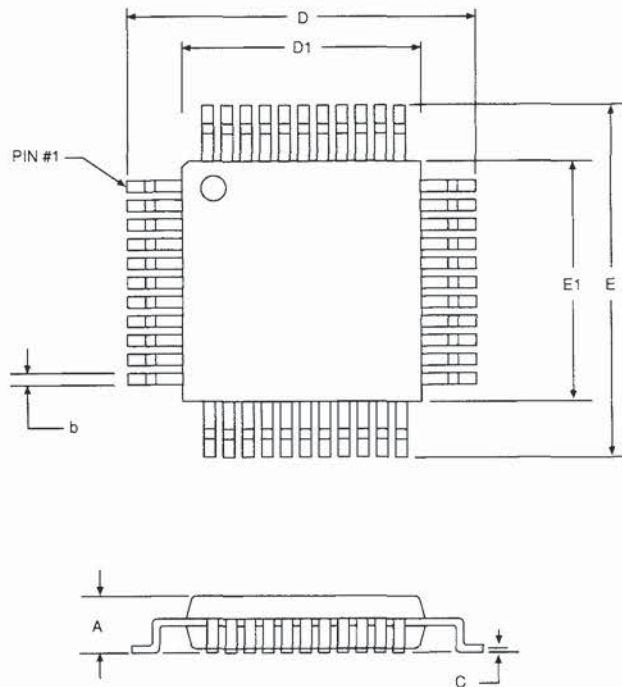
Microcontroller performance can be directly related to speed. Therefore, a rather straightforward approach to increased performance is through increasing clock speed. Today, most automotive microcontrollers have the capability to operate at frequencies of 16 MHz with speeds up to 20 MHz becoming common. Future microcontrollers will have the ability to be operated at frequencies of 24 or even 32 MHz. This allows more code to be executed in the same amount of time, and thus improves performance.

The method of increasing performance is not limited to just increasing the clock frequency. Microcontrollers can also achieve higher performance by enhancing existing peripherals for more efficient operation. This may be in the form of improved data handling or new features which suit the needs of a specific automotive application.

11.8.3 Increasing System-to-System Communication Requirements

The increasing complexity of automotive electronics requires that an increasing amount of information (diagnostics, etc.) be shared between various ECUs within an automobile. To fulfill this need, high-speed data links are utilized to transfer messages between multiple ECUs utilizing protocols such as Bosch's Controller Area Network (CAN) and SAE's J1850. To provide further size and cost savings, it is becoming more and more common to see these protocols supported or integrated onto automotive microcontrollers as opposed to separate integrated circuits.

The theory of centralized body computing is also receiving a closer look due to increased government regulations concerning fuel economy and diagnostics. A centralized body computer would link all ECUs (ABS and traction control, engine, transmission, suspension, instrumentation, etc.) together over a high-speed, in-vehicle serial network. One common scenario would have the central computer (possibly a microprocessor as opposed to a microcontroller) performing the more intense data-crunching tasks, while peripheral microcontrollers located in each individual ECU would perform system I/O functions. These communication protocols provide for efficient two-wire, high-speed serial communications between multiple ECUs utilizing protocols such as CAN and J1850. Supporting these protocols places additional loading upon the microcontroller. Increased microcontroller performance is necessary to manage this loading.



| SHRINK QUAD FLATPACK | | | | |
|----------------------|--------------------|-------|-------|-------|
| SYMBOL | DESCRIPTION | MIN. | NOM. | MAX. |
| N | Lead Count | 80 | | |
| A | Overall Height | | | 1.66 |
| A1 | Stand Off | 0.00 | | |
| b | Lead Width | 0.14 | 0.20 | 0.26 |
| c | Lead Thickness | 0.117 | 0.127 | 0.177 |
| D | Terminal Dimension | 13.70 | 14.00 | 14.30 |
| D1 | Package Body | | 12.0 | |
| E | Terminal Dimension | 13.70 | 14.00 | 14.30 |
| E1 | Package Body | | 12.0 | |
| e1 | Lead Pitch | 0.40 | 0.50 | 0.60 |
| L1 | Foot Length | 0.35 | 0.50 | 0.70 |
| T | Lead Angle | 0.0° | | 10.0° |
| Y | Coplanarity | | | 0.10 |

FIGURE 11.49 Shrink quad flat pack (SQFP) package.

11.8.4 Decreasing Form Factor Goals

Automobile manufacturers striving to build compact, more fuel efficient automobiles are putting pressure upon ECU suppliers to build smaller, lighter modules.

ECU size is directly affected by PCB size. The easiest way to achieve a smaller PCB is through integration and utilization of smaller integrated circuit packages. To support this demand, automotive microcontroller manufacturers are beginning to offer smaller, fine-pitch packages. A package commonly used today is the 68-lead plastic leaded chip carrier (PLCC) which has its pins placed on 1.27-mm centers and a body that is 24.3 mm². An example of a possible automotive package solution for the future would be the 80-lead shrink quad flat pack (SQFP, Fig. 11.49) which has pins on 0.50-mm centers and a body that is 12.0 mm². It is relatively easy to see that the SQFP package offers 12 additional pins in a package that is half the size of the PLCC. This high pin density, fine-pitch packaging allows for a smaller package to be utilized for the same size microcontroller die.

Another technology that is quickly becoming popular for automotive applications is referred to as *multichip modules* (MCMs). An MCM is a collection of unpackaged integrated circuit die (from various manufacturers) which are mounted upon a common substrate and packaged together. The advantage of MCMs is that they require much less PCB space than if the ICs were packaged separately.

GLOSSARY

Accumulator A register within a microcontroller that holds data, particularly data on which arithmetic or logic operations are to be performed.

Arithmetic logic unit (ALU) The part of a microcontroller that performs arithmetic and logic operations.

Analog-to-digital converter An electronic device that produces a digital result that is proportional to the analog input voltage.

Assembly language A low-level symbolic programming language closely resembling machine language.

Central processing unit (CPU) The portion of a computer system or microcontroller that controls the interpretation and execution of instructions and includes arithmetic capability.

EPROM Erasable and programmable read-only memory.

High-speed input/output unit (HSIO) A microcontroller peripheral which has the capability to either capture the time at which a certain input event occurs or create an output event at a predetermined time, both relative to a common clock. HSIO events are configured by the programmer to occur automatically.

Interrupt service routine (ISR) A predefined portion of a computer program which is executed in response to a specific event.

Low-speed input/output The input/output of a digital signal by “manually” reading or writing a register location in software.

Machine language A set of symbols, characters, or signs used to communicate with a computer in a form directly usable by the computer without translation.

Program counter (PC) A microcontroller register which holds the address of the next instruction to be executed.

Program status word (PSW) A microcontroller register that contains a set of boolean flags which are used to retain information regarding the state of the user's program.

Pulse-width modulation (PWM) The precise and timely creation of negative and positive waveform edges to achieve a waveform with a specific frequency and duty cycle.

Random access memory (RAM) A memory device which has both read and write capabilities so that the stored information (write) can be retrieved (reread) and be changed by applying new information to the inputs.

Read-only memory (ROM) A memory that can only be read and not written to. Data is either entered during the manufacturing process or by later programming; once entered, it is unalterable.

Register/arithmetic logic unit (RALU) A component of register-direct microcontroller architectures that allows the ALU to operate directly upon the entire register file.

Serial input/output (SIO) A method of digital communication in which a group of data bits is transferred one at a time, sequentially over a single data line.

Special function register (SFR) A microcontroller RAM register which has a specific, dedicated function assigned to it.

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CHAPTER 12

ENGINE CONTROL

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12.1 OBJECTIVES OF ELECTRONIC ENGINE CONTROL SYSTEMS

The electronic engine control system consists of sensing devices which continuously measure the operating conditions of the engine, an electronic control unit (ECU) which evaluates the sensor inputs using data tables and calculations and determines the output to the actuating devices, and actuating devices which are commanded by the ECU to perform an action in response to the sensor inputs.

The motive for using an electronic engine control system is to provide the needed accuracy and adaptability in order to minimize exhaust emissions and fuel consumption, provide optimal driveability for all operating conditions, minimize evaporative emissions, and provide system diagnosis when malfunctions occur.

In order for the control system to meet these objectives, considerable development time is required for each engine and vehicle application. A substantial amount of development must occur with an engine installed on an engine dynamometer under controlled conditions. Information gathered is used to develop the ECU data tables. A considerable amount of development effort is also required with the engine installed in the vehicle. Final determination of the data tables occurs during vehicle testing.

12.1.1 Exhaust Emissions

Exhaust Components. The engine exhaust consists of products from the combustion of the air and fuel mixture. Fuel is a mixture of chemical compounds, termed hydrocarbons (HC). The various fuel compounds are a combination of hydrogen and carbon. Under perfect combustion conditions, the hydrocarbons would combine in a thermal reaction with the oxygen in the air to form carbon dioxide (CO₂) and water (H₂O). Unfortunately, perfect combustion does not occur and in addition to CO₂ and H₂O, carbon monoxide (CO), oxides of nitrogen (NO_x), and hydrocarbons (HC) occur in the exhaust as a result of the combustion reaction. Additives and impurities in the fuel also contribute minute quantities of pollutants such as lead oxides, lead halogenides, and sulfur oxides. In compression ignition (diesel) engines, there is also an appreciable amount of soot (particulates) created. Federal statutes regulate the allowable amount of HC, NO_x, and CO emitted in a vehicle's exhaust. On diesel engines, the amount of particulates emitted is also regulated.

12.1

Spark Ignition Engines

Air/fuel Ratio. The greatest effect on the combustion process, and therefore on the exhaust emissions, is the mass ratio of air to fuel. The air/fuel mixture ratio must lie within a certain range for optimal ignition and combustion. For a spark ignition engine, the mass ratio for complete fuel combustion is 14.7:1; i.e., 14.7 kg of air to 1 kg of fuel. This ratio is known as the stoichiometric ratio. In terms of volume, approximately 10,000 liters of air would be required for 1 liter of fuel. The air/fuel ratio is often described in terms of the excess-air factor known as lambda (λ). Lambda indicates the deviation of the actual air/fuel ratio from the theoretically required ratio:

$$\lambda = \frac{\text{quantity of air supplied}}{\text{theoretical requirement (14.7 for gasoline)}}$$

At stoichiometry: $\lambda = 1$

For a mixture with excess air (lean): $\lambda > 1$

For a mixture with deficient air (rich): $\lambda < 1$

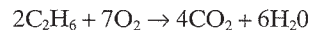
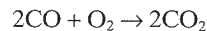
Effect of Air/Fuel Ratio on Emissions

CO emissions. In the rich operating range ($\lambda < 1$), CO emissions increase almost linearly with an increasing amount of fuel. In the lean range ($\lambda > 1$), CO emissions are at their lowest. With an engine operating at ($\lambda = 1$), the CO emissions can be influenced by the cylinder distribution. If some cylinders are operating rich and others lean with the summation achieving $\lambda = 1$, the average CO emissions will be higher than if all cylinders were operating at $\lambda = 1$.

HC emissions. As with CO emissions, HC emissions increase with an increasing amount of fuel. The minimum HC emissions occur at $\lambda = 1.1 \dots 1.2$. At very lean air/fuel ratios, the HC emissions again increase due to less than optimal combustion conditions resulting in unburned fuel.

NO_x emissions. The effect of the air/fuel ratio on NO_x emissions is the opposite of HC and CO on the rich side of stoichiometry. As the air content increases, the oxygen content increases and the result is more NO_x. On the lean side of stoichiometry, NO_x emissions decrease with increasing air because the decreasing density lowers the combustion chamber temperature. The maximum NO_x emissions occur at $\lambda = 1.05 \dots 1.1$.

Catalytic Converters. To reduce the exhaust gas emission concentration, a catalytic converter is installed in the exhaust system. Chemical reactions occur in the converter that transform the exhaust emissions to less harmful chemical compounds. The most commonly used converter for a spark ignition engine is the three-way converter (TWC). As the name implies, it simultaneously reduces the concentration of all three regulated exhaust gases: HC, CO, and NO_x. The catalyst promotes reactions that oxidize HC and CO, converting them into CO₂ and H₂O, while reducing NO_x emissions into N₂. The actual chemical reactions that occur are:



In order for the catalytic converter to operate at the highest efficiency for conversion for all three gases (HC, CO, NO_x), the average air/fuel ratio must be maintained within less than 1 percent of stoichiometry. This small operating range is known as the *lambda window* or *catalytic converter window*. Figure 12.1 is a graph of lambda (λ) versus the exhaust emissions both before and after the catalytic converter. Up to 90 percent of the exhaust gases are converted to less harmful compounds by the catalytic converter.

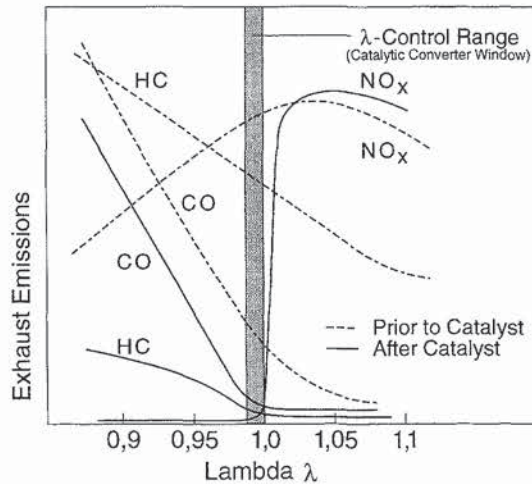


FIGURE 12.1 Lambda effect on exhaust emissions prior to and after catalyst treatment.

To remain within the catalytic converter window, the air/fuel ratio is controlled by the lambda closed-loop fuel control system, which is part of the electronic engine control system. The key component in this system is the lambda sensor. This sensor is installed in the exhaust system upstream of the catalytic converter and responds to the oxygen content in the exhaust gas. The oxygen content is a measure of the excess air (or deficiency of air) in the exhaust gases. A detailed discussion of the lambda closed-loop control system occurs in Sec. 12.2.1.

Ignition Timing. The ignition timing is defined as the crankshaft angle before top dead center (TDC) at which the ignition spark occurs. The ignition timing of the air/fuel mixture has a decisive influence on the exhaust emissions.

Effect of ignition timing on exhaust emissions.

- CO emissions are almost completely independent of the ignition timing and are primarily a function of the air/fuel ratio.
- In general, the more the ignition is advanced, the higher the emissions of HCs. Reactions initiated in the combustion chamber continue to occur after the exhaust valve opens, which depletes the remaining HCs. With advanced timing due to lower exhaust temperatures, these postreactions do not readily occur.
- With increased timing advance, the combustion chamber temperatures increase. The temperature increase causes an increase in NO_x emissions regardless of air/fuel ratio.

To provide the optimal ignition timing for exhaust emissions, precise control of the ignition timing is required. It is imperative that the ignition timing be coordinated with the air/fuel ratio since they have a combined effect on exhaust emissions as well as fuel consumption and driveability. Ignition timing is generally controlled by the ECU. Ignition timing control is discussed in detail in Sec. 12.2.1.

Exhaust Gas Recirculation (EGR). Exhaust gas recirculation (EGR) is a method of reducing emissions of oxides of nitrogen. A portion of the exhaust gas is recirculated back to the combustion chamber. Exhaust gas is an inert gas and, in the combustion chamber, it lowers the peak combustion temperature. Depending on the amount of EGR, NO_x emissions can be reduced by up to 60 percent, although an increase in HC emissions would occur at such high levels of EGR.

Some internal EGR occurs due to the overlap of the exhaust and intake valves. Additional quantities are supplied by a separate system linking the exhaust manifold to the intake mani-

fold. The quantity of EGR flow to the intake system is metered by a pneumatic or electronic valve. The EGR valve is controlled by the ECU. The maximum flow of EGR is limited by an increase in HC emissions, fuel consumption, and engine roughness. EGR control is discussed in detail in Sec. 12.2.1.

Compression Ignition (Diesel) Engines. There are some key distinctions between an SI engine and a CI engine. The CI engine uses high pressure and temperature instead of a spark to ignite the combustible air/fuel mixture. To achieve this, the CI engine compression ratio is in the range of 21:1, as opposed to roughly 10:1 for an SI engine. In a CI engine, the fuel is injected directly into the cylinder near the top of the compression stroke. Mixing of the fuel and air, therefore, occurs directly in the cylinder.

Air/fuel ratio. Diesel engines always operate with excess air ($\lambda > 1$). Where:

$$\lambda = \frac{\text{quantity of air supplied}}{\text{theoretical requirement}}$$

The excess air ($\lambda = 1.1 \dots 1.2$) reduces the amount of soot (particulates), HC, and CO emissions.

Catalytic Converters. An oxidizing catalyst is used that converts CO and HC to CO₂ and H₂O. The NO_x reduction that occurs for an SI engine three-way catalyst (TWC) is not possible with a diesel because the diesel operates with excess air. The optimal conversion of NO_x requires a stoichiometric ratio ($\lambda = 1$) or a deficiency of air ($\lambda < 1$).

Injection Timing. In a compression ignition engine, the start of combustion is determined by the start of fuel injection. In general, retarding the injection timing decreases NO_x emissions, while overretarding results in an increase in HC emissions. A 1° (crankshaft angle) deviation in injection timing can increase NO_x emissions by 5 percent and HC emissions by as much as 15 percent. Precise control of injection timing is critical. Injection timing on some systems is controlled by the ECU. Feedback on injection timing can be provided by a sensor installed on the injector nozzle. Further discussion on injection timing occurs in Sec. 12.3.1.

Exhaust Gas Recirculation (EGR). As with an SI engine, exhaust gas can be recirculated to the combustion chamber to significantly reduce NO_x emissions. The quantity of EGR allowed to enter the intake is metered by the EGR valve. If the quantity is too high, HC emissions, CO emissions, and soot (particulates) increase as a result of an insufficient quantity of air. The EGR valve is controlled by the ECU, which determines how much EGR is tolerable under the current engine operating conditions.

12.1.2 Fuel Consumption

Federal statutes are currently in effect that require each automobile manufacturer to achieve a certain average fuel economy for all their models produced in one model year. The requirement is known as *corporate average fuel economy* or CAFE. The fuel economy for each vehicle type is determined during the federal test procedure, the same as for exhaust emissions determination, conducted on a chassis dynamometer. Because of the CAFE requirement, it is critical that fuel consumption be minimized for every vehicle type produced.

The electronic engine control system provides the fuel metering and ignition timing precision required to minimize fuel consumption. Optimum fuel economy occurs near $\lambda = 1.1$. However, as discussed previously, lean engine operation affects exhaust emissions and NO_x is at its maximum at $\lambda = 1.1$.

During coasting and braking, fuel consumption can be further reduced by shutting off the fuel until the engine speed decreases to slightly higher than the set idle speed. The ECU determines when fuel shutoff can occur by evaluating the throttle position, engine RPM, and vehicle speed.

The influence of ignition timing on fuel consumption is the opposite of its influence on exhaust emissions. As the air/fuel mixture becomes leaner, the ignition timing must be advanced to compensate for a slower combustion speed. However, as discussed previously,

advancing the ignition timing increases the emissions of HC and NO_x. A sophisticated ignition control strategy permitting optimization of the ignition at each operating point is necessary to reach the compromise between fuel consumption and exhaust emissions. The electronic engine control system can provide this sophisticated strategy.

12.1.3 Driveability

Another requirement of the electronic engine control system is to provide acceptable driveability under all operating conditions. No stalls, hesitations, or other objectionable roughness should occur during vehicle operation. Driveability is influenced by almost every operation of the engine control system and, unlike exhaust emissions or fuel economy, is not easily measured. A significant contribution to driveability is determined by the fuel metering and ignition timing. When determining the best fuel and ignition compromises for fuel consumption and exhaust emissions, it is important to evaluate the driveability. Other factors that influence driveability are the idle speed control, EGR control, and evaporative emissions control.

12.1.4 Evaporative Emissions

Hydrocarbon (HC) emissions in the form of fuel vapors escaping from the vehicle are closely regulated by federal statutes. The prime source of these emissions is the fuel tank. Due to ambient heating of the fuel and the return of unused hot fuel from the engine, fuel vapor is generated in the tank. The evaporative emissions control system (EECS) is used to control the evaporative HC emissions. The fuel vapors are routed to the intake manifold via the EECS and they are burned in the combustion process. The quantity of fuel vapors delivered to the intake manifold must be metered such that exhaust emissions and driveability are not adversely affected. The metering is provided by a purge control valve whose function is controlled by the ECU. Further discussion on the operation of the evaporative emissions control system occurs in Sec. 12.2.1.

12.1.5 System Diagnostics

The purpose of system diagnostics is to provide a warning to the driver when the control system determines a malfunction of a component or system and to assist the service technician in identifying and correcting the failure (see Chap. 22). To the driver, the engine may appear to be operating correctly, but excessive amounts of pollutants may be emitted. The ECU determines a malfunction has occurred when a sensor signal received during normal engine operation or during a system test indicates there is a problem. For critical operations such as fuel metering and ignition control, if a required sensor input is faulty, a substitute value may be used by the ECU so that the engine will continue to operate.

When a failure occurs, the malfunction indicator light (MIL), visible to the driver, is illuminated. Information on the failure is stored in the ECU. A service technician can retrieve the information on the failure from the ECU and correct the problem. Detailed examples of system diagnostics are discussed in Sec. 12.2.3.

12.2 SPARK IGNITION ENGINES

12.2.1 Engine Control Functions

Fuel Control. For the purpose of discussing fuel control strategies, a multipoint pulsed fuel injection system is assumed. Additional discussions of fuel control for different types of fuel

systems such as carbureters, single-point injection, and multipoint continuous injection appear in Sec. 12.2.4 (Fuel Delivery Systems).

In order for the fuel metering system to provide the appropriate amount of fuel for the engine operating conditions, the mass flow rate of incoming air, known as the air charge, must be determined.

$$F_m = \frac{A_m}{\text{requested air-fuel ratio}}$$

where F_m = fuel mass flow rate
 A_m = air mass flow rate

The air mass flow rate can be calculated from:

$$A_m = A_v A_d$$

where A_v = volume flow rate of intake air
 A_d = air density

There are three methods commonly used for determining the air charge: speed density, air flow measurement, and air mass measurement. In the speed density method, the air charge is calculated by the engine electronic control unit based on the measurement of air inlet temperature, intake manifold pressure, and engine RPM. The temperature and pressure are used to determine the air density and the RPM is used to determine the volume flow rate. The engine acts as an air pump during the intake stroke. The calculated volume flow rate can be determined as follows:

$$A_{\text{RPM}} = \frac{\text{RPM}}{60} \times \frac{D}{2} \times V_E$$

where RPM = engine speed
 D = engine displacement
 V_E = volumetric efficiency

In an engine using exhaust gas recirculation (EGR), the volume flow rate of EGR must be subtracted from the calculated volume flow rate.

$$A_v = A_{\text{RPM}} - A_{\text{EGR}}$$

The volume flow rate of EGR can be determined empirically based on the EGR valve flow rate and the EGR control strategy being used.

In the air flow measurement method, the air flow is measured using a vane type meter and air density changes are compensated for by an air inlet temperature sensor. The vane meter uses the force of the incoming air to move a flap through a defined angle. This angular movement is converted by a potentiometer to a voltage ratio. Because only the fresh air charge is measured, no compensation is required for EGR.

In the air mass measurement method, the air charge is measured directly using a hot-wire or hot-film air mass flow sensor. The inlet air passes a heated element, either wire or film. The element is part of a bridge circuit that keeps the element at a constant temperature above the inlet air temperature. By measuring the heating current required by the bridge circuit and converting this to a voltage via a resistor, the air mass flow passing the element can be determined. Again, because only the fresh air charge is measured, no compensation for EGR is required. However, sensing errors may occur due to strong intake manifold reversion pulses, which occur under certain operating conditions. In such cases, a correction factor must be determined and applied.

Calculation of Injector Pulse Width. The base pulse width is determined from the required fuel mass flow rate (F_m) and an empirical injector constant. The injector constant is determined by the design of the injector and is a function of the energized time versus the flow volume. This constant is normally determined with a constant differential pressure across the injector (from fuel rail to intake manifold). When the pressure across the injector does not remain constant (i.e., there is no pressure regulator intake manifold vacuum reference), an entire map of injector constants for different manifold pressures may be required.

The effective injector pulse width is a modification of the base pulse width. The base pulse width is adjusted by a number of correction factors depending on operating conditions. For example, a battery voltage correction is required to compensate for the electromechanical characteristics of the fuel injectors. Injector opening and closing rates differ depending on the voltage applied to the injector, which affects the amount of fuel injected for a given pulse width. Other common correction factors may include hot restart, cold operation, and transient operation corrections. Figure 12.2 is a flowchart of a typical injector effective pulse-width calculation method.

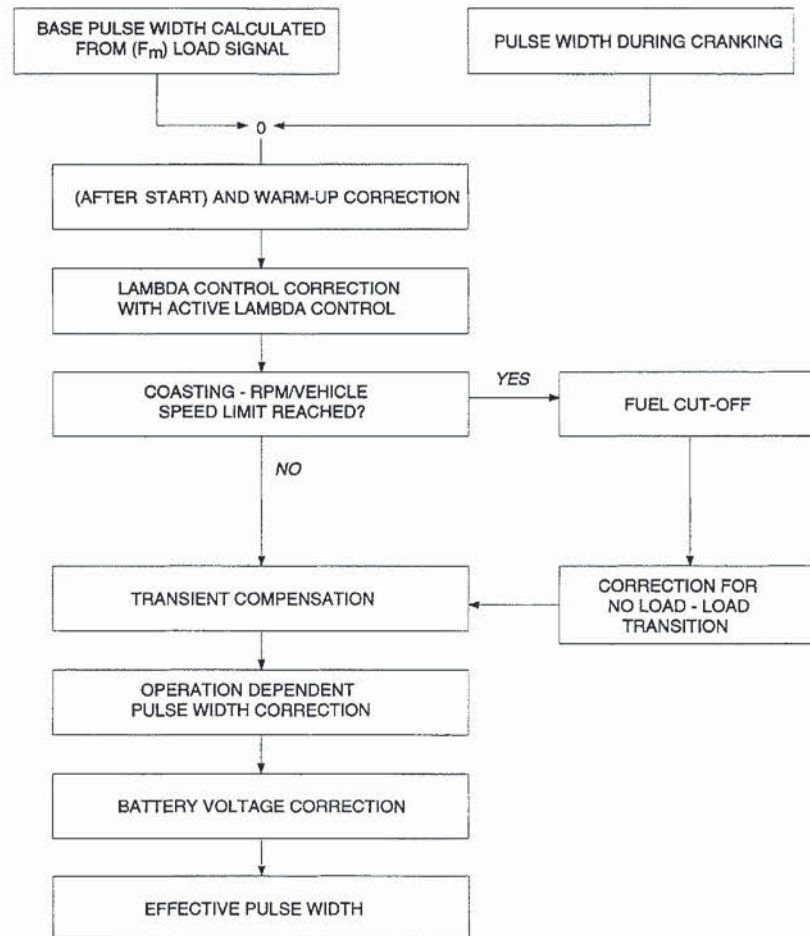


FIGURE 12.2 Determination of effective injector pulse width.

Injection Strategies. There are three commonly used fuel injection strategies for multi-point fuel metering systems: simultaneous injection, group injection, and sequential injection. Figure 12.3 is a diagram of the different strategies. Some engines use simultaneous injection during crank and switch over to sequential after the engine is running. This allows for shorter starting times since no synchronization with the camshaft is necessary before fuel injection begins. A description of each strategy follows.

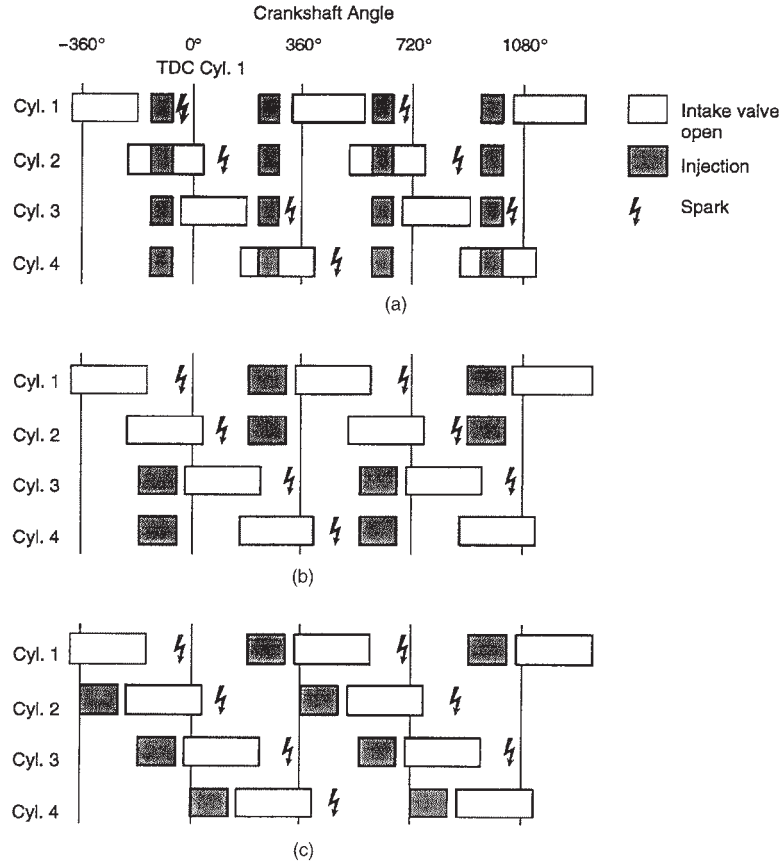


FIGURE 12.3 Fuel injection strategies: (a) simultaneous injection, (b) group injection, and (c) sequential injection.

Simultaneous injection. Injection of fuel occurs at the same time for all cylinders every revolution of the crankshaft. Therefore, fuel is injected twice within each four-stroke cycle. The injection timing is fixed with respect to crank/camshaft position.

Group injection. The injectors are divided into two groups that are controlled separately. Each group injects once per four-stroke cycle. The offset between the groups is one crankshaft revolution. This arrangement allows for injection timing selection that eliminates spraying fuel into an open intake valve.

Sequential injection. Each injector is controlled separately. Injection timing, both with reference to crank/camshaft position and pulse width, can be optimized for each individual cylinder.

Lambda Control. A subsystem of the fuel control system is lambda closed-loop control. Lambda (λ) is defined as the excess-air factor that indicates the deviation of the actual air/fuel ratio from the theoretically required ratio:

$$\lambda = \frac{\text{quantity of air supplied}}{\text{theoretical requirement (14.7 for gasoline)}}$$

The lambda sensor, or exhaust gas oxygen sensor, is installed in the engine exhaust stream upstream of the catalytic converter. The sensor responds to the oxygen content of the exhaust gas. The signal from the lambda sensor serves as feedback to the fuel control system. This provides the fine-tuning needed to remain within the limited catalytic converter window for optimal catalyst performance. (See Sec. 12.1.1 for more discussion on the catalytic converter window.) For a lean mixture ($\lambda > 1$), sensor voltage is approximately 100 mV. For a rich mixture ($\lambda < 1$), the sensor voltage is approximately 800 mV. At roughly $\lambda = 1$ (a stoichiometric mixture), the sensor switches rapidly between the two voltages. The input from the lambda sensor is used to modify the base pulse width to achieve $\lambda = 1$.

Lambda closed-loop control requires an operationally ready lambda sensor, typically one which has reached an operating temperature threshold. Sensor output is monitored by the ECU to determine when the sensor is supplying usable information. An active sensor signal, along with other requirements, such as engine temperature, must be achieved before lambda closed-loop control will be activated.

Under steady state conditions, the lambda control system oscillates between rich and lean around the lambda window. As the lambda sensor switches, the injector pulse width is adjusted by the amount determined by a control factor until the lambda sensor switches again to the opposite condition. The control factor can be defined as the allowable increase or decrease in the commanded fuel injector pulse width. The frequency of oscillation is determined by the gas transport time and the magnitude of the control factor. The gas transport time is defined as the time from air/fuel mixture formation to lambda sensor measurement.

Under transient conditions, the gas transport time results in a delay before the lambda sensor can indicate that the operating conditions have changed. Using only the lambda sensor for closed-loop fuel control would result in poor driveability and exhaust emissions because of this delay. Therefore, the engine control unit uses an anticipatory control strategy that uses engine load and RPM to determine the approximate fuel requirement. The engine load information is provided by the manifold pressure sensor for speed density systems and by the air meter for air flow and air mass measurement systems and by the throttle valve position sensor. The engine control unit contains data tables for combinations of load and RPM. This allows for rapid response to changes in operating conditions. The lambda sensor still provides the feedback correction for each load/RPM point. The data used for these data tables are largely developed from system modeling and engine development testing.

Due to production variations in engines, variations in fuel and changes due to wear and aging, the control system must be able to adapt to function properly for every engine over the engine's life. Therefore, the electronic control unit has a feature for adapting changes in the fuel required for the load/RPM points. At each load/RPM point, the lambda sensor continuously provides information that allows the system to adjust the fuel to the commanded A/F ratio. The corrected information is stored in RAM (random access memory) so that the next time the engine reaches that operating point (load/RPM), the anticipatory value will require less correction. These values remain stored in the electronic control unit even after the engine is shut off. Only if power to the electronic control unit is disrupted (i.e., due to a dead battery), will the correction be lost. In that case, the electronic control unit will revert back to the original production values that are written in ROM (read-only memory).

Lambda sensors do not switch symmetrically from lean to rich and rich to lean. Because of this, the control strategy is modified to account for the asymmetry. This can be accomplished either by delaying the modification by the control factor after the sensor switches or by using control factors of different magnitudes for rich-to-lean and lean-to-rich switching.

Ignition Timing Control. The goal of the engine control system for ignition timing is to provide spark advance which optimizes engine torque, exhaust emissions, fuel economy, and driveability, and which minimizes engine knock. Data tables with the base ignition timing, depending on engine load and RPM, are stored in ROM in the electronic control unit. The values in these tables are optimized for fuel economy, exhaust emissions, and engine torque. They are developed through engine experimentation, usually with an engine dynamometer. Corrections to the base timing values are needed for temperature effects, EGR, hot restart, barometric pressure, and engine knock. In addition, some systems use ignition timing to vary the engine torque for improvement in automatic transmission shift quality or for idle speed control. Figure 12.4 is a flowchart of a typical ignition timing calculation method.

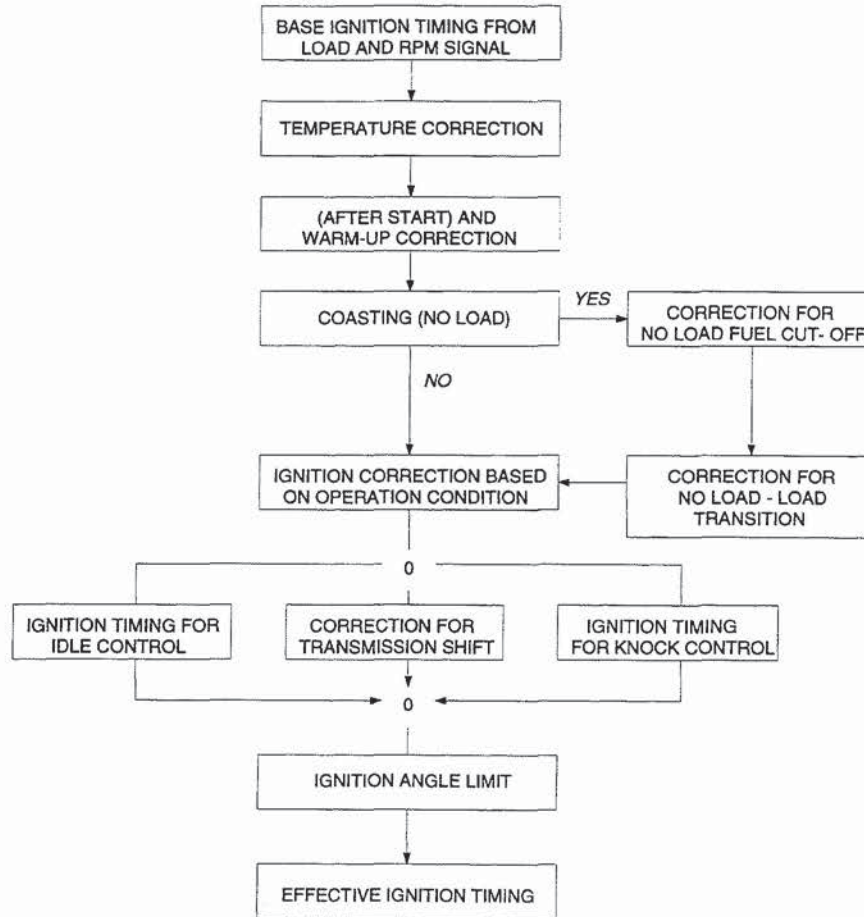


FIGURE 12.4 Determination of effective ignition timing.

Dwell Angle Control. The dwell angle performance map stored in the electronic control unit controls the charging time of the ignition coil, depending on RPM and battery voltage. The dwell angle is controlled so that the desired primary current is reached at the end of the charging time just prior to the ignition point. This assures the necessary primary current, even with quick transients in RPM. A limit on the charge time in the upper RPM ranges allows for the necessary spark duration.

Knock Control. The ignition timing for optimization of torque, fuel economy, and exhaust emissions is in close proximity to the ignition timing that results in engine knock. Engine knock occurs when the ignition timing is advanced too far for the engine operating conditions and causes uncontrolled combustion that can lead to engine damage, depending on the severity and frequency. If a factor of safety was used when developing the base timing map for all conditions that contribute to knock, such as fuel quality and variations in compression ratio, the ignition timing would be significantly retarded from the optimum level, resulting in a significant loss in torque and fuel economy. To avoid this, a knock sensor (one or more) is installed on the engine to detect knocking (see Chap. 8). Knock sensors are usually acceleration sensors that provide an electric signal to the electronic control unit. From this signal, the engine control unit algorithm determines which cylinder or cylinders are knocking. Ignition timing is modified (retarded) for those cylinders until the knock is no longer detected. The ignition timing is then advanced again until knock is detected. (See Fig. 12.5.) Information on the amount of spark retard required to eliminate the knock for each cylinder under each load/RPM condition is saved in the electronic control unit RAM. This allows for quick access to the appropriate “learned” ignition timing for each condition. With this control system, the base timing can be more advanced for improved fuel economy and torque.

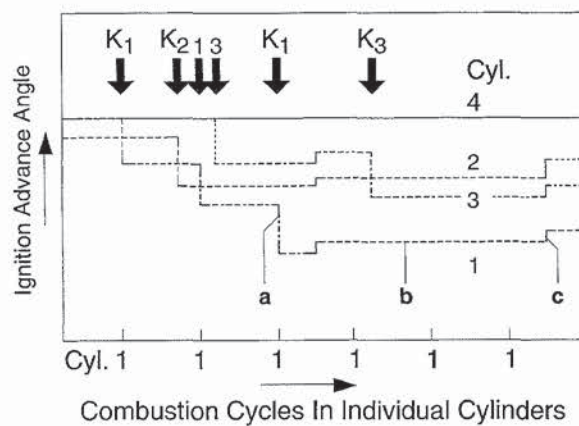


FIGURE 12.5 Knock control. Control algorithm for ignition adjustments for a four-cylinder engine. $K_{1, \dots, 3}$ (knock in cylinders 1 . . . 3), cylinder number four (no knock), (a) (ignition retard), (b) (delay before return to original point), (c) (spark advance).

Evaporative Emissions Control. Hydrocarbon (HC) emissions in the form of fuel vapors escaping from the vehicle, primarily from the fuel tank, are closely regulated by federal statutes. There are two principal causes of fuel vapor in the fuel tank: increasing ambient temperature and return of unused hot fuel from the engine. In order to control the release of these emissions to the atmosphere, the evaporative emissions control system was developed.

Evaporative Emissions Control System. A vapor ventilation line exits the fuel tank and enters the fuel vapor canister. The canister consists of an active charcoal element which absorbs the vapor and allows only air to escape to the atmosphere. Only a certain volume of fuel vapor can be contained by the canister. The vapors in the canister must therefore be purged from and burned by the engine so that the canister can continue to store vapors as they are generated. To accomplish this, another line leads from the charcoal canister to the intake manifold. Included in this line is the canister purge solenoid valve. Figure 12.6 shows a layout of a typical evaporative emissions control system.

During engine operation, vacuum in the intake manifold causes flow through the charcoal canister because the canister vent opening, at the charcoal filter end, is at atmospheric pres-

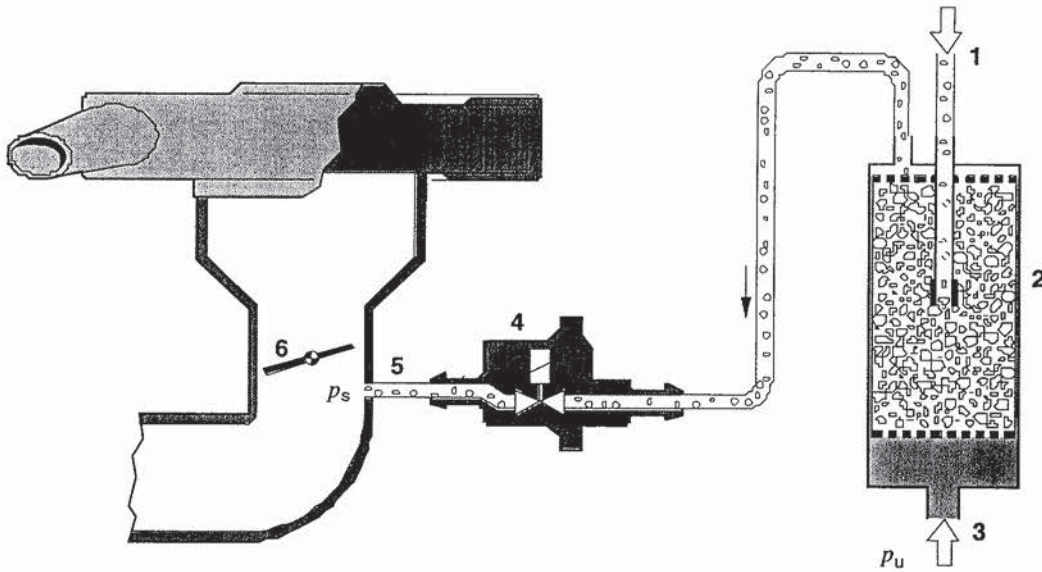


FIGURE 12.6 Evaporative emission control system: fuel vapor from fuel tank (1), charcoal canister (2), canister purge control valve (4), purge line to intake manifold (5), throttle valve (6), p_s is intake manifold vacuum, and p_u is atmospheric pressure.

sure. The canister purge valve meters the amount of flow from the canister. The amount of fuel vapor in the canister and, therefore, contained in the flow stream, is not known. Therefore, it is critical that the lambda control system is operating and adjusting the fuel requirement as the vapors are being purged. Purge vapors could otherwise result in up to a 30 percent increase in air/fuel mixture richness in the engine.

Purge Valve Control. Control of the purge valve must allow for two criteria:

- There must be enough vapor flow so that the charcoal canister does not become saturated and leak fuel vapors to the atmosphere
- Purge flow must generally occur under lambda closed-loop control so that the effect of the purge vapors on A/F ratio can be detected and the fuel metering corrected

When the electronic control unit commands the purge valve to meter vapor from the canister, it requests a duty cycle (ratio of ON time to total ON and OFF time). This allows the amount of vapor flow to be regulated depending on the engine operating conditions. When lambda control is not operating, only low duty cycles and, therefore, small amounts of purge vapors, are allowed. Under deceleration fuel cutoff, the purge valve is closed entirely to minimize the possibility of unburned HCs in the exhaust.

Turbocharger Boost Pressure Control. The exhaust turbocharger consists of a compressor and an exhaust turbine arranged on a common shaft. Energy from the exhaust gas is converted to rotational energy by the exhaust turbine, which then drives the compressor. The compressed air leaves the compressor and passes through the air cooler (optional), throttle valve, intake manifold, and into the cylinders. In order to achieve near-constant air charge pressure over a wide RPM range, the turbocharger uses a circuit that allows for the bypass of the exhaust gases away from the exhaust turbine. The valve that regulates the bypass opens at a specified air charge pressure and is known as the wastegate.

Engines that have turbochargers benefit significantly from electronic boost pressure control. If only a pneumatic-mechanical wastegate is used, only one boost pressure point for the entire operating range is used to divert the exhaust gas. This creates a compromise for part-load conditions, which results in increased exhaust backpressure, more turbocharger work, more residual exhaust gas in the cylinders, and higher-charge air temperatures.

By controlling the wastegate with a pulse-width modulated solenoid valve, different wastegate opening pressures can be specified, depending on the engine operating conditions (Fig. 12.7). Therefore, only the level of air charge pressure required is developed. The electronic control unit uses information on engine load from either manifold pressure or the air meter and RPM and throttle position. From this information, a data table is referenced and the proper boost pressure (actually a duty cycle of the control valve) is determined. On systems using manifold pressure sensors, a closed-loop control system can be developed to compare the specified value with the measured value.

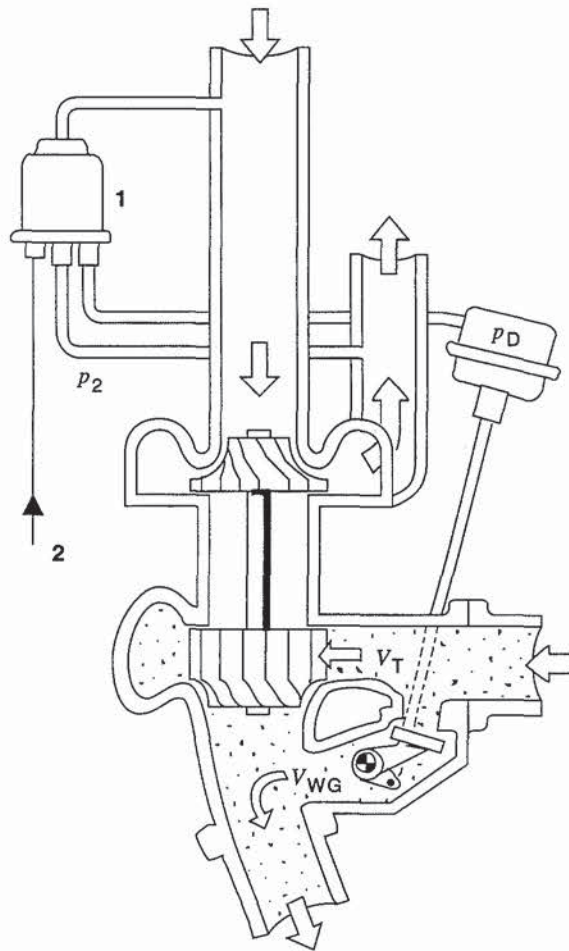


FIGURE 12.7 Electronic turbocharger boost control: solenoid valve (1), control signal from ECU (2), boost pressure (p_D), volume flow through turbine (V_T), volume flow through wastegate (V_{WG}).

The boost pressure control system is usually used in combination with knock control for turbocharged engines. When the ignition timing is retarded due to knock, an increase in already high exhaust temperatures for turbocharged engines occurs. To counteract the temperature increase, the boost pressure is reduced when the ignition timing is retarded past a predetermined threshold.

Engine/Vehicle Speed Control. Using the inputs of engine RPM and vehicle speed to the electronic control unit, thresholds can be established for limiting these variables with fuel cut-off. When the maximum speed is achieved, the fuel injectors are shut off. When the speed decreases below the threshold, fuel injection resumes.

EGR Control. By mixing a portion of the exhaust gas with the fresh intake air/fuel mixture, oxides of nitrogen (NO_x) can be reduced by lowering the peak combustion temperatures. However, the addition of exhaust gas can degrade driveability by causing combustion instability, especially at idle and low speeds and with a cold engine. The ECU references an engine RPM/load table of optimal EGR valve openings. The data table is developed on the engine dynamometer by analyzing the exhaust emissions. With increasing EGR, a point is reached where hydrocarbon (HC) emissions begin to increase. The optimal percent of EGR is just prior to that point.

The electronic control unit regulates a pneumatic- or solenoid-type valve to meter a certain quantity of exhaust gas back to the intake manifold. Typically, an engine coolant temperature threshold is also required before EGR is activated to avoid poor driveability. Under acceleration and at idle, EGR is deactivated.

Camshaft Control. There are two types of camshaft controls: phasing (i.e., overlap or intake/exhaust valve opening point) and valve lift and opening duration.

Camshaft Phasing Control. Valve overlap is a function of the rotation of the intake camshaft with respect to the exhaust camshaft. Overlap can be controlled by an electrohydraulic actuator. At idle and at high RPM, it is desirable to have the intake valves open and close later, which reduces the overlap. For idle, this reduces the residual exhaust gases that return with the fresh charge air and improves idle stability. At high RPM, late closing of the intake valve provides the best condition for maximum cylinder filling and, therefore, maximum output. For partial loads, a large valve overlap, where the intake opens early, is desirable. This allows for an increase in residual exhaust gas for improved exhaust emissions (Fig. 12.8).

Valve Lift and Opening Duration Control. Control of the valve lift and opening duration is accomplished by switching between two camshaft profiles. An initial cam specifies the optimal lift and duration for the low to middle RPM range. A second cam profile controls a higher valve lift and duration for high-RPM operation. By monitoring engine load and RPM, the ECU actuates the electrohydraulic device that switches from one cam profile to the other (Fig. 12.9).

Variable Intake Manifold Control. The goal of the engine design is to achieve the highest possible torque at low engine RPM as well as high output at high engine RPM. The torque curve of an engine is proportional to the air charge at any given engine speed. Therefore, a primary influence on the torque is the intake manifold geometric design. The simplest type of air charging uses the dynamics of the drawn-in air. The standard intake manifolds for multipoint engines consist of several intake runners and collectors converging at the throttle valve.

In general, short intake runners result in a high output at high RPM with a simultaneous loss of torque at low RPM. Long intake runners have the opposite effect. Due to intake valve and piston dynamics, pressure waves occur that oscillate within the intake manifold. Proper selection of runner lengths and collector sizes can result in the pressure waves arriving at the intake valves just before they are closing. This has a supercharging effect. The limitation of this method is that, for a given intake manifold configuration, the tuning peak can only occur at one operating point.

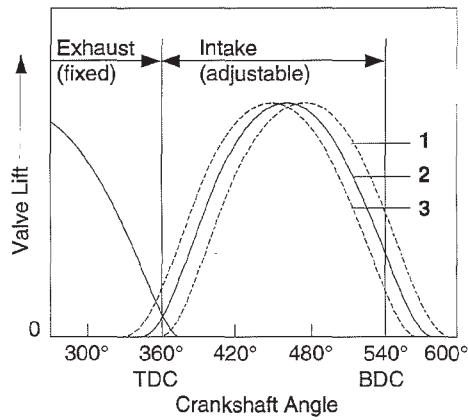


FIGURE 12.8 Adjustment angle for intake camshaft: retard (1), standard (2), advance (3).

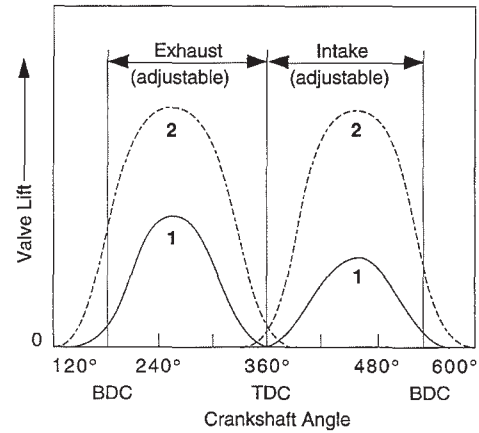


FIGURE 12.9 Selective camshaft lobe actuation: base cam lobe (1), auxiliary cam lobe (2).

Variable Intake Systems. To optimize the benefits of intake manifold charging, several systems have been developed that allow for changes in runner length and collector volume, depending on engine operating conditions. This allows for tuning peaks at more than one operating point. One method developed uses electronically controlled valves to close off areas of the intake manifold (Fig. 12.10). Inputs of engine load, RPM, and throttle angle determine the position of the valves.

12.2.2 Engine Control Modes

Engine Crank and Start. During engine cranking, the goal is to get the engine started with the minimal amount of delay. To accomplish this, fuel must be delivered that meets the requirements for starting for any combination of engine coolant and ambient temperatures. For a cold engine, an increase in the commanded air/fuel ratio is required due to poor fuel vaporization and “wall wetting,” which decreases the amount of usable fuel. Wall wetting is the condensation of some of the vaporized fuel on the cold metal surfaces in the intake port and combustion chamber. It is critical that the fuel does not wet the spark plugs, which can reduce the effectiveness of the spark plug and prevent the plug from firing. Should plug wetting occur, it may be impossible to start the engine.

Fuel Requirement. Within the ECU ROM there are specific data tables to establish cold-start fuel based on engine coolant temperature. For two reasons, the lambda sensor output cannot be used during crank: the lambda sensor is below its minimum operating temperature and the air/fuel ratio required is outside the lambda sensor control window.

Many starting sequences use a front-loading strategy for fueling whereby the quantity of fuel is reduced after a speed threshold (RPM) is achieved, after a certain number of revolutions or at a defined time after the initial crank. Some systems also switch over from simultaneous injection to sequential injection after a speed threshold is achieved. For cold temperature starting, the fuel mixture may remain richer than $\lambda = 1$ after starting, due to the continuing poor mixture formation in the cold induction system.

Ignition Timing Requirement. Ignition timing is controlled by the ECU during crank and is determined by engine coolant temperature and cranking speed. For a cold engine with low cranking speeds, ideal timing is near TDC. For higher cranking speeds, a slightly more advanced timing is optimal. Timing advance must be limited during cranking to avoid igniting

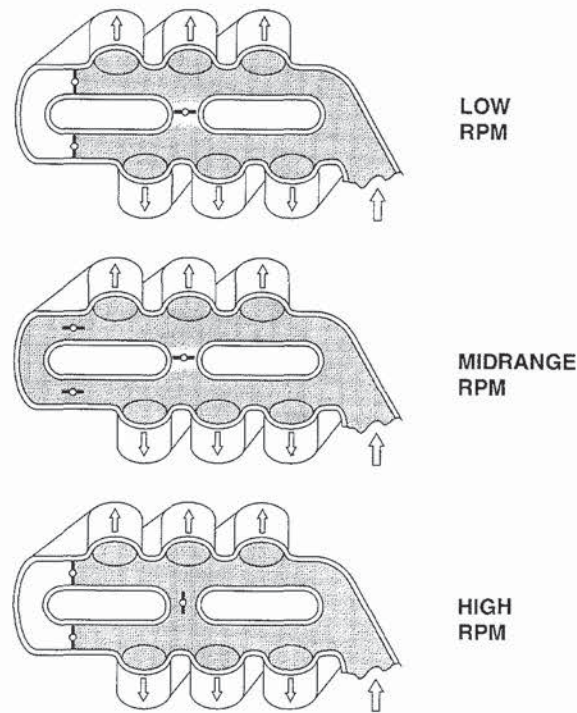


FIGURE 12.10 Variable configuration intake manifold.

the air/fuel mixture before the crankshaft reaches top dead center (TDC). A damaging torque reversal could occur that would damage the starter. After the engine starts, ignition timing is advanced to improve cold engine running as well as to reduce the need for fuel enrichment.

Engine Warm-Up. During the warm-up phase, there are three conflicting objectives: keep the engine operating smoothly (i.e., no stalls or driveability problems), increase exhaust temperature to quickly achieve operational temperature for catalyst (light-off) and lambda sensor so that closed-loop fuel control can begin operating, and keep exhaust emissions and fuel consumption to a minimum. The best method for achieving these objectives is very dependent on the specific engine application.

If the engine is still cold, fuel enrichment will be required to keep the engine running smoothly due, again, to poor fuel vaporization and wall wetting effects. The amount of enrichment is dependent on engine temperature and is a correction factor to the injector pulse width. This enrichment, combined with secondary air injection, also helps achieve the desired increase in catalyst temperature. To provide secondary air injection, an external air pump delivers fresh air downstream of the exhaust valves for a short time after start. The excess air causes oxidation (burning) of the excess HC and CO from the rich mixture in the exhaust manifold, which rapidly increases the temperature of the catalytic converter. The oxidation also removes harmful pollutants from the exhaust stream.

It is possible to increase the exhaust temperature by increasing the idle speed during warm-up. The increased idle speed may also be combined with a slightly retarded ignition timing, which increases temperatures in the exhaust, thereby promoting rapid warm-up of the catalyst.

Transient Compensation. During transitions such as acceleration or deceleration, the objective of the engine control system is to provide a smooth transition from one engine operating condition to another (i.e., no hesitations, stalls, bumps, or other objectionable driveability concerns), and keep exhaust emissions and fuel consumption to a minimum.

Acceleration Enrichment. When an increase in engine load and throttle angle occurs, a corresponding increase in fuel mixture richness is required to compensate for the increased wall wetting. The sudden increase in air results in a lean mixture that must be corrected swiftly to obtain good transitional response. The rate of change of engine load and throttle angle are used to determine the quantity of fuel during acceleration enrichment. The amount of fuel must be enough to provide the desired performance, but not so much as to degrade exhaust emissions and fuel economy.

During acceleration enrichment, the ignition timing is set for maximum torque without knocking. Additionally, when a large change in engine load occurs, some systems delay the ignition timing advance briefly to prevent engine knock, which may arise from a momentary lean mixture or from transient ignition timing errors.

Deceleration Enleanment. During deceleration modes, such as coasting or braking, there is no torque requirement. Therefore, the fuel may be shut off until either an increase in throttle angle is detected or the engine speed falls to a speed slightly above the idle RPM. Fuel shut-off or cutoff can decrease exhaust emissions by eliminating unburned HC and CO and may also improve fuel consumption. Fuel cutoff is also used to protect the catalytic converter from extreme high temperatures during extended overrun conditions. During transition to fuel cutoff, the ignition timing is retarded from its current setting to reduce engine torque and to assist in engine braking. The fuel is then shut off. During the transition, the throttle bypass valve or the main throttle valve may remain open for a short period to allow fresh air to oxidize the remaining unburned HC and CO to further reduce exhaust emissions. During development of the fuel cutoff strategy, the advantage of reduced emission effects and catalyst temperature control must be balanced against driveability requirements. The use of fuel cutoff may change the perceived amount of engine braking felt by the driver. In addition, care must be taken to avoid a “bump” feel when entering the fuel cutoff mode, due to the change in torque.

Full Load. Under steady state full-load conditions, such as for climbing a grade, it is desirable to control the air/fuel mixture and ignition timing to obtain maximum power and to also limit engine and exhaust temperatures. The best engine torque is typically delivered at about $\lambda = 0.9$ to 0.95 . When the ECU determines the engine is operating at full load via the throttle valve sensor (at WOT), the commanded air/fuel mixture, if required, can be enriched. The lambda sensor signal cannot be used to provide correction to the air/fuel mixture because the rich operating point lies outside the lambda control window.

The ignition timing at full load is set to achieve the maximum torque without knocking. This initial value is determined through engine dynamometer testing. With a knock control system (see Sec. 12.2.1), the ignition timing is modified (retarded) when engine knock occurs. The modification required to eliminate the knock may be saved in the ECU so that the next time that engine RPM/load point occurs, less knocking will occur and less correction will be required.

Idle Speed Control. The objectives of the engine control system during idle are:

- Provide a balance between the engine torque produced and the changing engine loads, thus achieving a consistent idle speed even with various load changes due to accessories (i.e., air conditioning, power steering, and electrical loads) being turned on and off and during engagement of the automatic transmission. In addition, the idle speed control must be able to compensate for long-term changes in engine load, such as the reduction in engine friction that occurs with engine break-in.
- Provide the lowest idle speed that allows smooth running to achieve the lowest exhaust emissions and fuel consumption (up to 30 percent of a vehicle’s fuel consumption in city driving occurs during idling).

To control the idle speed, the ECU uses inputs from the throttle position sensor, air conditioning, automatic transmission, power steering, charging system, engine RPM, and vehicle speed. There are currently two strategies used to control idle speed: air control and ignition control.

Air Control. The amount of air entering the intake manifold is controlled either by a bypass valve or by an actuator acting directly on the throttle valve. The bypass valve uses, for example, an electronically controlled motor controlled by the ECU that opens or closes a fixed amount. For large throttle valves, it may be desirable to use a bypass valve because a small change in throttle angle may result in a large change in air flow and, therefore, idle speed may be difficult to control. Using engine RPM feedback input, the ECU adjusts the air flow to increase or decrease the idle speed. A disadvantage to air control is that the response to load changes is relatively slow. To overcome this, air control is often combined with ignition timing control to provide acceptable idle speed control. The fuel quantity required at idle is determined by engine load and RPM. During closed-loop operation, this value is optimized by the lambda sensor closed-loop control.

Ignition Timing Control. Engine torque may be increased or decreased by advancing or retarding the ignition timing within an established window. This principle can be employed to help control idle speed. Ignition timing control is particularly desirable for responding to idle load changes because engine torque output changes more rapidly in response to a change in ignition timing than to a change in air valve position. Using the same inputs as for air control, the ECU adjusts the spark advance to either raise or lower the idle speed.

Anticipating Accessory Loads. Specific electric inputs to the ECU, such as a pressure switch located in the power steering system, are used to anticipate accessory loads so that the idle control system can compensate more quickly. This “feed forward” strategy allows better idle control than a strictly feedback system which does not respond until the idle speed begins to fall. When an accessory can be controlled by the ECU, further improvement in idle speed control is obtained. By delaying the load briefly after it is requested, the compensation sequence can begin before the load is actually applied. Such a load delay strategy is effective for controlling air conditioning compressor loads, for example. In this case, when the air conditioner is requested, the ECU begins to increase the idle speed first and then activates the A/C compressor.

12.2.3 Engine Control Diagnostics

The purpose of system diagnostics is to provide a warning to the driver when the control system determines that a malfunction of a component or system has occurred and to assist the service technician in identifying and correcting the failure (see Chap. 22). In many cases, to the driver, the engine may appear to be operating correctly, but excessive amounts of pollutants may be emitted. The ECU determines that a malfunction has occurred when a sensor signal received during normal engine operation or during a system test indicates there is a problem. For critical operations such as fuel metering and ignition control, if a required sensor input is faulty, a substitute value may be used by the ECU so that the engine will continue to operate, but likely not at optimal performance. It is also possible to apply an emergency measure if the failure of a component may result in engine or emission system damage. For example, if repeated misfires are detected in one cylinder, perhaps due to an ignition failure, the fuel injector feeding that cylinder can be shut off to avoid damage to the catalytic converter. When a failure occurs, the malfunction indicator light (MIL), visible to the driver, is illuminated. Information on the failure is stored in the ECU. A service technician can retrieve the information on the failure from the ECU and correct the problem.

Air Mass Sensor. For air mass measurement systems, the pulse width of the fuel injectors is calculated in the ECU from the air mass sensor input. As a comparison, the pulse width is also calculated from the throttle valve sensor and the engine RPM. If the pulse width values devi-

ate by a predetermined amount, the discrepancy is stored in the ECU. Then, while the vehicle is being driven, plausibility tests determine which input is incorrect. When this has been determined, the appropriate failure code is saved in the ECU.

Misfire Detection. Misfiring is the lack of combustion in the cylinder. Misfiring can be caused by several factors including fouled or worn spark plugs, poor fuel metering, or faulty electrical connections. Even a small number of misfires may result in excessive exhaust emissions due to the unburned mixture. Increased misfire rates can damage the catalytic converter.

To determine if the engine is experiencing a misfire, the crankshaft speed fluctuation is monitored. If a misfire occurs, no torque is created during the power stroke of the cylinder(s) that is misfiring. A small decrease in the rotational speed of the crankshaft occurs. Because the change in speed is very small, highly accurate sensing of the crankshaft speed is required. In addition, a fairly complicated calculation process is required in order to distinguish misfiring from other influences on crankshaft speed. As was mentioned previously, if a cylinder repeatedly misfires, it is possible to shut off the fuel to that cylinder to prevent damage to the catalytic converter.

Catalytic Converter Monitoring. During the useful life of a catalytic converter, its efficiency decreases. If subjected to engine misfire, the decrease in efficiency occurs more rapidly. A loss in efficiency results in an increase in exhaust pollutants. For this reason, the catalytic converter is monitored. A properly operating catalytic converter transforms O_2 , HC, CO, and NO_x into H_2O , CO_2 , and N_2 . The incoming air/fuel ratio oscillates from rich to lean due to the lambda closed-loop control strategy discussed in Sec. 12.2.1. Only a properly functioning catalytic converter is able to dampen these oscillations by storing and converting the incoming components. As the catalyst ages, this storage effect is diminished. To monitor the catalytic converter, an additional lambda sensor is installed downstream of the catalyst. The ECU compares the signal of the lambda sensor upstream with the lambda sensor downstream and determines if the catalytic converter is operating properly. If not, the ECU illuminates the malfunction indicator light (MIL) and stores a failure code.

Lambda Sensor Monitoring. To minimize exhaust emissions, the engine must operate within the catalytic converter window for air/fuel ratio (see Sec. 12.1.1 for a detailed description of the catalytic converter window). Output from the lambda sensor serves as feedback to the ECU to control the fuel within that window. When a lambda sensor is exposed to high heat for a long period of time, it may respond more slowly to changes in the air/fuel mixture. This can cause a deviation in the air/fuel mixture from the window, which would affect the exhaust emissions.

If the upstream lambda sensor operation is determined to be too slow, which can be detected by the system operation frequency, the ECU illuminates the malfunction indicator light (MIL) and a failure code is stored. Additionally, the ECU compares the output signal of the additional lambda sensor downstream of the catalytic converter with the lambda sensor signal upstream. With this, the ECU is able to detect deviations of the average value in air/fuel ratio.

For heated lambda sensors, the electric current and voltage of the heater circuit is monitored. To accomplish this, the heater is directly controlled by the ECU, not through a relay.

Fuel System Monitoring. To provide the correct air/fuel ratio, the ECU uses a preset data map with the optimal fuel required for each load and RPM point. The lambda closed-loop control system (see Sec. 12.2.1) provides feedback to the ECU on the necessary correction to the preset data points. The corrected information is stored in the ECU's RAM so that the next time that operating point is reached, less correction of the air/fuel ratio will be required. If the ECU correction passes a predetermined threshold, it is an indication that some component in the fuel supply system is outside of its operating range. Some examples are defective pressure regulator, defective manifold pressure sensor, intake system leakage, or exhaust system leakage. When the ECU determines a problem exists, the MIL is illuminated and a code is stored in the ECU.

Exhaust Gas Recirculation (EGR) Monitoring. There are currently two methods used to monitor EGR operation. One method confirms that hot exhaust gases are returning to the intake manifold during EGR operation by use of a temperature sensor in the intake manifold. The second method requires the EGR valve to be fully opened during coast operation, where high intake manifold vacuum occurs. The exhaust gas flowing into the manifold causes a measurable increase in pressure. Thus, if a measured increase in pressure does not occur, the EGR system is not operating.

Evaporative Emissions Control System (EECS) Monitoring. In general, a valve will be installed at the atmospheric side of the purge canister. During idle, this valve would close and the purge valve would open. Intake manifold vacuum would occur in the entire EECS. A pressure sensor in the fuel tank would provide a pressure profile during this test to the ECU, which would then determine if a leak existed in the system.

12.2.4 Fuel Delivery Systems

Overview. Fuel management in the spark ignition engine consists of metering the fuel, formation of the air/fuel mixture, transportation of the air/fuel mixture, and distribution of the air/fuel mixture. The driver operates the throttle valve, which determines the quantity of air inducted by the engine. The fuel delivery system must provide the proper quantity of fuel to create a combustible mixture in the engine cylinder. In general, two fuel delivery system configurations exist: *single-point* and *multi-point* (Fig. 12.11).

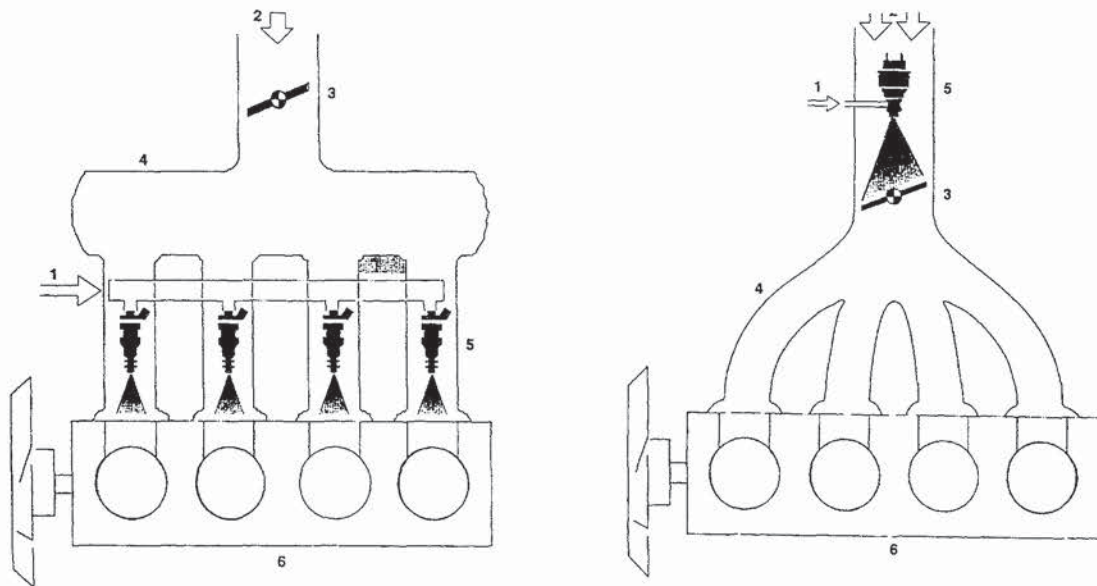


FIGURE 12.11 Air-fuel mixture preparation: right, single-point fuel injection; left, multipoint fuel injection with fuel (1), air (2), throttle valve (3), intake manifold (4), injector(s) (5), and engine (6).

For single-point systems such as carburetors or single-point fuel injection, the fuel is metered in the vicinity of the throttle valve. Mixture formation occurs in the intake manifold. Some of the fuel droplets evaporate to form fuel vapor (desirable) while others condense to form a film on the intake manifold walls (undesirable). Mixture transport and distribution is a function of intake manifold design. Uniform distribution under all operating conditions is difficult to achieve in a single-point system.

For multipoint systems, the fuel is injected near the intake valve. Mixture formation is supplemented by the evaporation of the fuel on the back of the hot intake valve. Mixture transport and distribution occurs only in the vicinity of the intake valve. The influence of the intake manifold design on uniform mixture distribution is minimized. Since mixture transport and distribution is not an issue, the intake manifold design can be optimized for air flow.

Single-Point Injection Systems A single-point injection system uses one or, in some cases, two electronic fuel injectors to inject fuel into the intake air stream. The main component is the fuel injection unit which is located upstream of the intake manifold.

Component Description. An electric fuel pump provides fuel at a medium pressure (typically 0.7 to 1.0 bar) to the electronic fuel injection unit (Fig. 12.12). The fuel injection unit houses the solenoid-operated fuel injector, which is located in the intake air flow above the throttle valve. This allows for homogeneous mixture formation and distribution. The injector spray pattern is designed to allow fuel to pass between the throttle valve and the throttle bore. To prevent vapor lock of the injector, fuel flows through the injector at all times. Fuel not used by the engine is returned to the fuel tank. The injector is activated in relation to the speed of the engine, typically once per ignition event. The length of the pulse width determines the quantity of fuel provided.

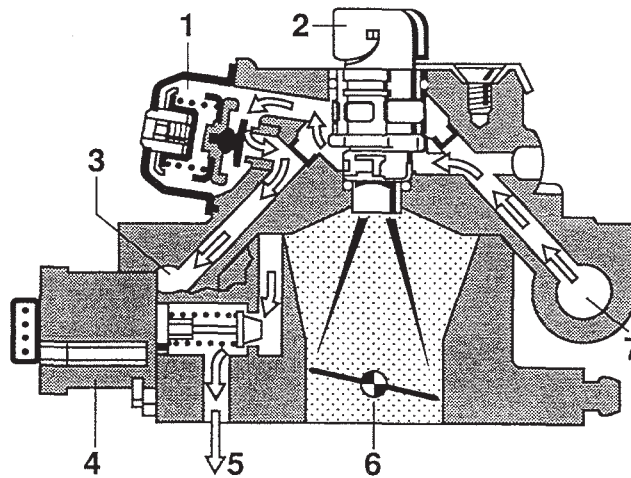


FIGURE 12.12 Single-point injection unit: pressure regulator (1), injector (2), fuel return (3), stepper motor for idle speed control (4), to intake manifold (5), throttle valve (6), and fuel inlet (7).

The electronic injection unit also houses the throttle position sensor and, in some cases, an inlet air temperature sensor which provides operating condition information to the ECU. The throttle valve actuator and fuel pressure regulator are also mounted on the injection unit. In addition, some units contain an air bypass valve for idle speed control. Engine temperature, battery voltage, and engine speed via the ignition system are all inputs to the ECU. The single-

point injection system also uses lambda closed-loop fuel control to optimize fuel metering within the lambda control window (see Sec. 12.2.1).

Adaptation to Operating Conditions. For cold-start and engine warm-up, the ECU uses engine temperature information to determine the correct amount of fuel and commands the fuel injector via a pulse width. Due to wall wetting and poor fuel vaporization when the engine is cold, an increase in mixture richness is required. As the engine warms up to operating temperature, the commanded pulse width is reduced.

During an acceleration transition, the ECU adds a correction factor (an increase) to the commanded injector pulse width. The sudden increase in air results in a lean mixture which must be corrected swiftly to obtain good transitional response. During a deceleration transition, the fuel can be shut off by simply not providing a pulse width signal to the injector to minimize exhaust emissions and fuel consumption.

During full-load operation, the air/fuel mixture can be enriched ($\lambda < 1$) to deliver maximum torque. The ECU determines full-load operation by the throttle position sensor (at or near wide-open throttle) and adds a correction to the injector pulse width to achieve the desired air/fuel mixture richness.

The single-point system can control the idle speed by ECU control of either a throttle valve actuator or a bypass valve. Idle speed is a function of engine operating temperature, whether the transmission is in drive, and what accessories are in use. Fuel metering at idle is determined by engine RPM and load as well as lambda closed-loop control.

Multipoint Fuel Injection Systems. A multipoint fuel injection system supplies fuel to each cylinder individually via a mechanical or solenoid-operated fuel injector located just upstream of the intake valve. Advantages of this system type compared to SPI systems are numerous:

- *Increased fuel economy.* On an SPI engine, due to the intake manifold configuration, mixture formation will differ at each cylinder. To provide adequate fuel for the leanest cylinder, too much fuel must be metered overall. In addition, during engine load changes, a film of fuel is deposited on the intake manifold walls. This leads to further variations in mixture from cylinder to cylinder. Multipoint injection provides the same quantity of fuel to each cylinder.
- *Higher power output.* With the fuel being injected near the intake valve, the rest of the intake manifold can be optimized for maximum air flow. The result is increased torque.
- *Improved throttle response.* Because the fuel is injected onto the intake valves, responses to increases in throttle position are swift. With an SPI system, the increased fuel required must travel the length of the intake manifold before entering the cylinder.
- *Lower exhaust emissions.* As was discussed for fuel economy, mixture variation in an SPI system creates increased exhaust emissions. Metering of the fuel at the intake valve decreases this variation. In addition, the system transport time is reduced, increasing the frequency at which the lambda closed-loop control system can switch air/fuel ratio. Catalytic converter efficiency is increased.

Although there are numerous advantages of the MPI systems over the SPI systems, there is still one important advantage the SPI systems have over the MPI systems. In general, SPI systems have better fuel preparation, similar to a carburetor.

Mechanically Controlled Continuous Injection System. This type of system meters the fuel as a function of the intake air quantity and injects it continuously onto the intake valves. This is accomplished by measuring the air flow as it passes through the air flow meter by means of deflection of a meter plate. The fuel is supplied through a fuel accumulator to the fuel distributor by an electric fuel pump. A primary-pressure regulator in the fuel distributor maintains constant fuel pressure. The fuel distributor, through its interface with the air flow meter and warm-up regulator, meters fuel to the continuously flowing fuel injectors.

Component Description

Mixture control unit. The mixture control unit houses the air flow meter and the fuel distributor. In the air flow meter, the measurement of the intake air serves as the basis for

determining the amount of fuel to be metered to the injectors. The air flow meter is located upstream of the throttle valve so that it measures all the air entering the engine. It consists of an air funnel, in which a sensor plate is free to pivot. Intake air flowing through the funnel causes a deflection of the sensor plate. The sensor plate is mechanically linked to a control plunger and movement of the plate results in movement of the control plunger. The control plunger movement determines the amount of fuel to be injected.

In the fuel distributor, the control plunger moves up and down in a cylindrically shaped device (barrel) with rectangular openings (metering slit), one for each engine cylinder. Increased air flow causes the control plunger to move upward, uncovering a larger area of the metering slit and increasing the fuel metered. Downstream of each metering slit is a differential-pressure valve that maintains a constant pressure drop across the metering slits at different flow rates. Due to the constant pressure, the fuel flow through the slits is directly proportional to the position of the control plunger (Fig. 12.13).

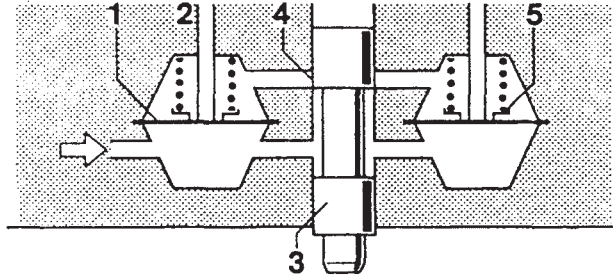


FIGURE 12.13 Fuel distributor for mixture control unit: diaphragm (1), to injector (2), control plunger (3), metering slot (4), differential pressure regulator (5).

Warm-up regulator. The warm-up regulator is used to richen the fuel mixture under cold engine conditions. It consists of a diaphragm valve and an electrically heated bimetallic spring. Under cold conditions, the warm-up regulator lowers the control pressure on the control plunger. The control pressure acts on the opposite end of the plunger from the air flow meter plate. A lower control pressure results in a lower force required to move the meter plate. Therefore, the same air flow causes the meter plate and control plunger to move a greater distance and additional fuel is metered to the injectors.

Fuel injectors. The injectors open at a pressure of approximately 3.6 bar. Atomization of the fuel occurs through oscillation (audible chatter) of the valve needle caused by the fuel flowing through it. The injectors remain open as long as fuel is provided above the opening pressure. Fuel is injected continuously into the intake port. When the intake valve opens, the mixture is drawn into the cylinder.

Auxiliary air valve. The auxiliary air valve provides additional air to the engine by bypassing the throttle valve during cold engine operation. This creates an increase in the idle speed needed during cold operation.

Thermo-time switch. The thermo-time switch controls the cold start valve as a function of time and engine temperature. Fuel enters the intake manifold from the cold start valve and further enriches the mixture to improve cold-starting at low ambient temperatures. When the engine is warm, the contacts in the thermo-time switch open and the cold-start valve is not used in starting the engine.

Lambda sensor. With the addition of a lambda sensor in the exhaust stream, a frequency valve, a modified fuel distributor, and an electronic control unit, the mechanically controlled fuel system can operate under lambda closed-loop control. The lambda sensor sig-

nal is read by the ECU. The ECU outputs electric pulses to an electromagnetic (frequency) valve. The frequency valve modulates the pressure to the lower chambers of the differential-pressure valves in the fuel distributor. This results in a modification of the pressure drop across the metering slits, effectively increasing or decreasing the amount of fuel injected. Figure 12.14 is a schematic of a typical mechanically controlled continuous injection system.

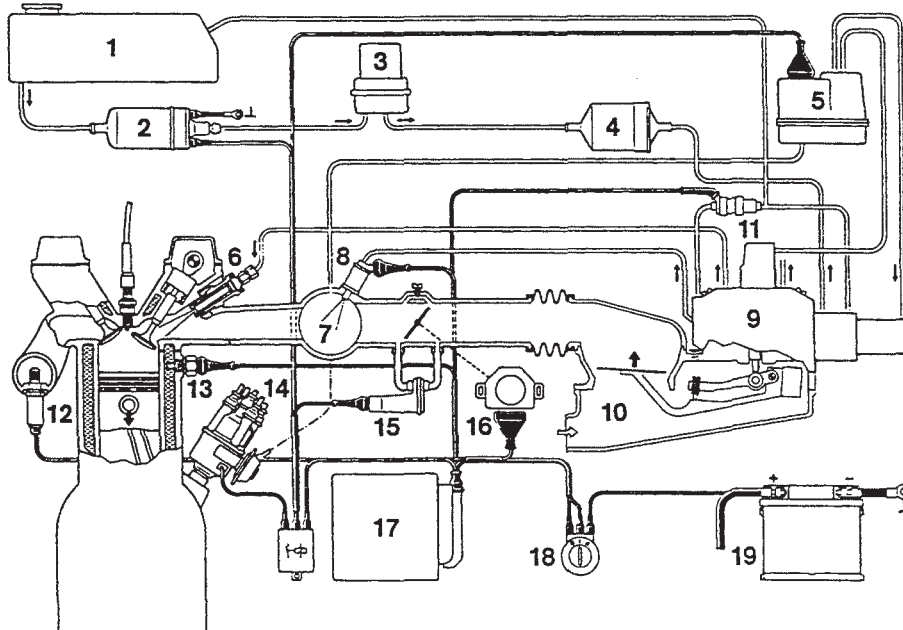


FIGURE 12.14 Schematic of mechanically controlled continuous injection system: fuel tank (1), electric fuel pump (2), fuel accumulator (3), fuel filter (4), warm-up regulator (5), injector (6), intake plenum (7), cold-start valve (8), fuel distributor (9), air flow sensor (10), electrohydraulic pressure actuator (11), lambda sensor (12), thermo-time switch (13), ignition distributor (14), auxiliary air valve (15), throttle switch (16), ECU (17), ignition switch (18), and battery (19).

Depending on the engine temperature, the cold-start valve injects extra fuel into the intake manifold for a limited period during cold start. The injection period is determined by a combination of time and temperature and is controlled by the thermo-time switch. As the engine temperature increases, this additional enrichment is no longer required and the thermo-time switch turns off the cold-start valve. For repeated start attempts or long cranking, the thermo-time switch turns off the cold-start injector after a given time. This minimizes engine flooding when engine start has not occurred.

As the engine continues to warm up, wall wetting and poor fuel vaporization still occur and mixture enrichment is still required until the engine reaches operating temperature. This enrichment is controlled as a function of temperature by the warm-up regulator. As the temperature increases, the warm-up regulator commands less and less additional fuel by increasing the control pressure.

For acceleration response, the air flow sensor “overswings” during quick throttle increases. This causes an additional quantity of fuel to be injected for acceleration enrichment. For full-load enrichment to achieve maximum power, a special warm-up regulator

that uses intake manifold pressure is required. At increased manifold pressures, i.e., during wide-open throttle, the warm-up regulator lowers the control pressure, which results in an increase in fuel delivery. Deceleration fuel shutoff is accomplished by diverting all intake air through an air bypass around the air flow sensor plate. With no air flow past the air flow sensor plate, the fuel pressure to the injectors is decreased below the opening pressure.

Idle speed for the cold-running engine is increased by the auxiliary air valve. The amount of additional air varies with engine temperature until the auxiliary air valve is closed and the idle speed is then controlled only by the air passing the throttle valve.

Electronically Controlled Continuous Injection. The basis of the electronically controlled continuous injection is still the mechanical hydraulic injection system discussed previously. This is supplemented by an electronic control unit (ECU) that allows for an increase in flexibility and the use of additional functions. This system incorporates additional sensors for detecting the engine temperature, the throttle valve position (load signal), and the air flow sensor plate deflection. This information is processed by the ECU, which then commands an electrohydraulic pressure actuator to adapt the injected fuel quantity for the present operating conditions.

In contrast to the mechanical system mentioned previously, the control pressure or counterpressure on the control plunger is not varied by a warm-up regulator. The control pressure remains constant and is the same as the primary pressure. The function of the warm-up regulator is now handled by the ECU and the electrohydraulic pressure actuator. Figure 12.15 is a schematic of a typical electronically controlled continuous injection system.

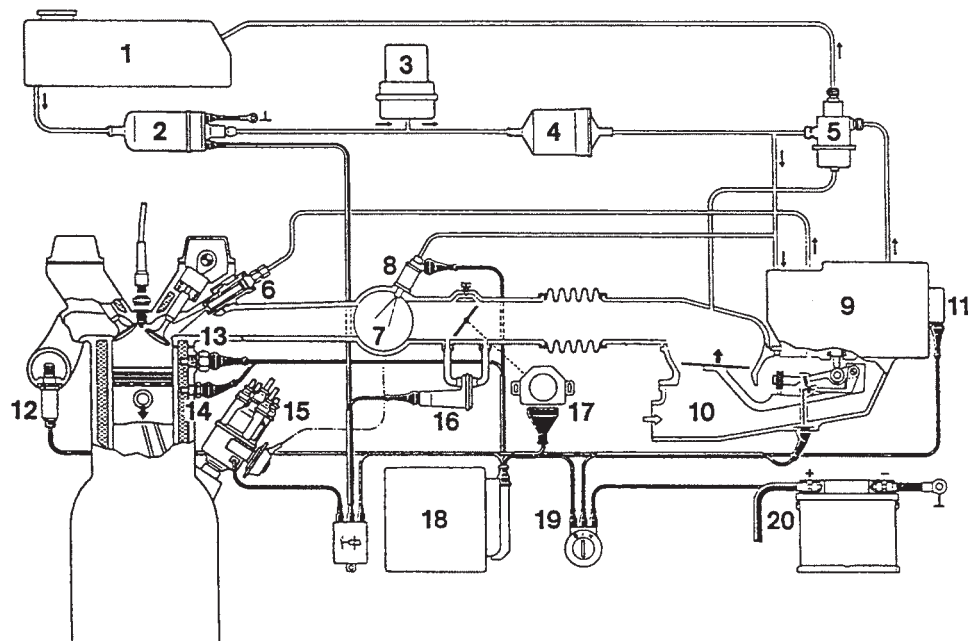


FIGURE 12.15 Schematic of an electronically controlled continuous fuel injection system: fuel tank (1), electric fuel pump (2), fuel accumulator (3), fuel filter (4), fuel pressure regulator (5), injector (6), intake plenum (7), cold-start valve (8), fuel distributor (9), air flow sensor (10), electrohydraulic pressure actuator (11), lambda sensor (12), thermo-time switch (13), coolant temperature sensor (14), ignition distributor (15), auxiliary air valve (16), throttle valve switch (17), ECU (18), ignition switch (19), and battery (20).

Component description—electrohydraulic pressure actuator. The main difference in the componentry between the purely mechanical system and the electronically controlled system is the addition of the electrohydraulic actuator and the elimination of the warm-up regulator. With the addition of the ECU control of fuel metering, the purely mechanical warm-up regulator is no longer required. Depending on the signal received from the ECU, the electrohydraulic pressure actuator varies the pressure in the lower chambers of the differential pressure valves. This changes the amount of fuel delivered to the injectors.

Lambda closed-loop control. As with the mechanical system, the lambda sensor signal is processed by the ECU to determine mixture composition. The difference is that the ECU now commands the electrohydraulic actuator to modify the fuel metered, as opposed to the separate frequency valve, which is no longer necessary.

Adaptation to operating conditions. Depending on the engine temperature, the cold-start valve injects extra fuel into the intake manifold for a limited period during cold-start. The quantity to be injected is controlled by the ECU and is a function of engine temperature (from the engine temperature sensor). The thermo-time switch controls how long the cold-start valve remains active, depending on engine temperature and time.

Acceleration enrichment is controlled by the ECU. Input from the air flow sensor plate position sensor provides the ECU with information on how quickly the engine load has increased. The ECU commands additional enrichment via the electrohydraulic pressure actuator. For full-load enrichment for maximum power, the ECU receives input from the throttle position sensor that the throttle is wide open. The ECU then commands additional enrichment via the electrohydraulic pressure actuator. Deceleration fuel shutoff is also controlled by the ECU when the throttle valve switch indicates the throttle is closed and the engine speed is above idle RPM. The ECU signals the electrohydraulic pressure actuator to interrupt fuel delivery to the injectors.

Idle speed control can be a closed-loop function with the addition of the idle actuator valve. This valve is ECU-controlled and the RPM signal from the ignition, combined with the engine temperature signal, is used to determine its position for the correct idle speed.

Pulsed Fuel Injection Systems. Pulsed fuel injection systems are a further enhancement of the continuous injection systems. Today, most continuous injection systems have been replaced with pulsed fuel injection systems. Instead of injecting fuel continuously and controlling the quantity of fuel by modifying the delivery volume flow rate, the fuel quantity is controlled by the open time of the solenoid-operated injectors. The injectors are controlled directly by the ECU. For most systems, the fuel pressure drop across the injector, from the fuel rail to the intake manifold, is kept constant by using intake manifold air pressure to compensate the fuel pressure regulator. This type of system allows for still greater precision of fuel control and is usually coupled with an equally precise ignition timing control system.

Component description. Several multipoint pulsed injection systems exist in various configurations. The components discussed here serve as a general outline of this system type. Figure 12.16 is a schematic of a typical pulsed fuel injection system.

- *Inlet air sensing.* The inlet air charge can be measured directly using either an air flow meter or a mass air flow meter. The air flow meter is a vane-type meter, which uses the force of the incoming air to move a flap through a defined angle. The angular movement is converted by a potentiometer to a voltage ratio. The air flow meter requires an air inlet temperature sensor to correct for air density changes. The air mass flow meter measures the air mass directly by hot-wire or hot-film element. As the inlet air flow passes the heated element, a bridge circuit keeps the element at a constant temperature above the inlet temperature. The heating current required by the bridge circuit to maintain the element at a constant temperature is measured and converted to an air density value.

The air charge can also be measured indirectly by measuring the inlet air temperature, intake manifold pressure, and engine RPM and then calculating the air charge (see Sec. 12.2.1 for further discussion on the calculation method which is called speed density air measurement).

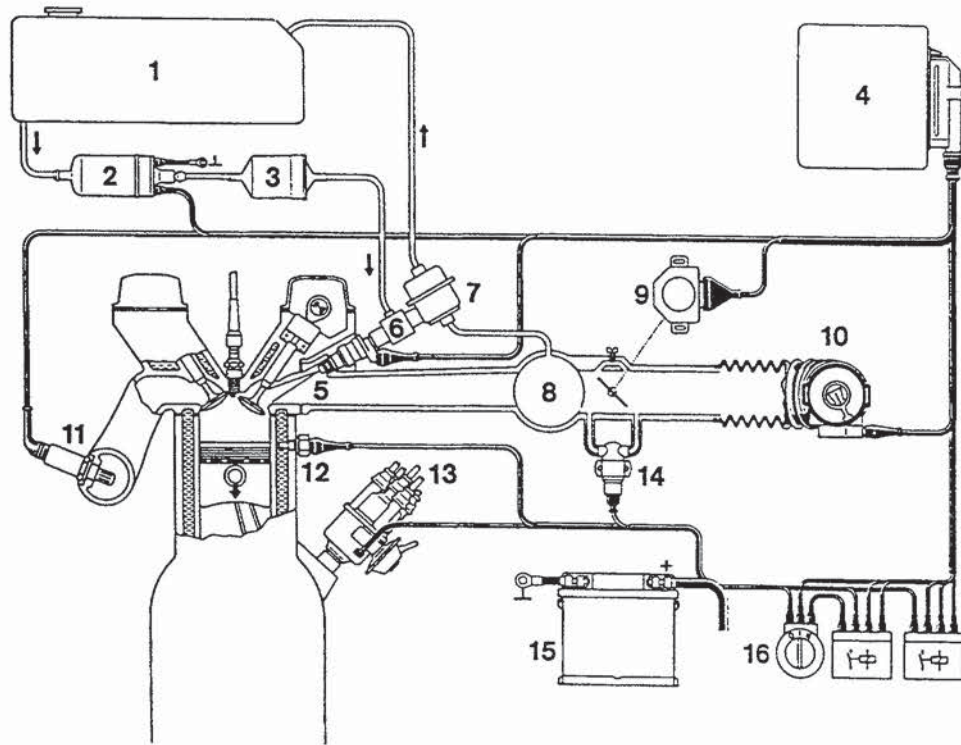


FIGURE 12.16 Schematic of a pulsed fuel injection system: fuel tank (1), electric fuel pump (2), fuel filter (3), ECU (4), injector (5), fuel distributor (6), fuel pressure regulator (7), intake plenum (8), throttle valve switch (9), hot-wire mass air flow sensor (10), lambda sensor (11), coolant temperature sensor (12), ignition distributor (13), idle speed actuator (14), battery (15), and ignition switch (16).

- *Fuel metering.* The fuel supply system includes an electric fuel pump, fuel filter, fuel rail, pressure regulator, and solenoid-operated injectors. The fuel pump provides more fuel than the maximum required by the engine. Fuel not used by the engine is returned to the fuel tank. The fuel rail supplies all injectors with an equal quantity of fuel and ensures the same fuel pressure at all injectors.

The pressure regulator keeps the pressure differential across the injectors constant. It contains a diaphragm that has intake manifold pressure on one side and fuel rail pressure on the other. Normally, it is mounted at the outlet end of the fuel rail. The diaphragm operates a valve which opens at a differential pressure between 2.0 and 3.5 bar and allows excess fuel to return to the fuel tank.

The fuel injectors are solenoid-operated valves that are opened and closed by means of electric pulses from the ECU. The injectors are mounted in the intake manifold and spray onto the back of the intake valves. In general, one injector is used for each cylinder.

In addition, some systems also use a separate cold-start injector mounted in the intake manifold just downstream of the throttle valve. This injector ensures good fuel vaporization during cold-start and supplies the additional enrichment needed to start the cold engine. Control of the cold-start valve is either by the ECU directly or in conjunction with a thermo-time switch.

- *Lambda closed-loop control.* The lambda sensor signal is processed by the ECU. The ECU determines the required injector pulse width to maintain the air/fuel ratio within the lambda control window (see Sec. 12.2.1 for further discussion on lambda closed-loop control).

Adaptation to operating conditions. For cranking, the fuel required is determined by a data table in the ECU with reference to engine temperature. The ECU then commands a pulse width for the fuel injectors. The air/fuel mixture is greatly enriched due to poor fuel vaporization and wall wetting, which reduces the amount of usable fuel. After start, the fuel mixture remains rich due to continuing poor air/fuel mixture formation. The amount of enrichment should be minimized to obtain good emission results. The target is to stay close to lambda (λ) = 1.

For acceleration enrichment, the throttle valve position sensor indicates that the throttle has moved rapidly. The ECU adds a correction factor to increase the pulse width so that a smooth transition occurs. For deceleration, the ECU uses input from the throttle position sensor and engine RPM to indicate that the throttle has closed and the engine speed is above the idle speed. Since no torque is required under this condition, the ECU provides no pulse width to the injectors and they are therefore closed. For full-load enrichment, when necessary, the ECU can provide an injector pulse width that would result in the engine achieving its maximum torque (roughly $\lambda = 0.9$). Fuel metering during idle is primarily controlled by lambda closed-loop control when the engine has reached operating temperature.

12.2.5 Ignition Systems

Overview. The purpose of the ignition system in the spark ignition engine is to initiate combustion of the air/fuel mixture by delivering a spark at precisely the right moment. The spark consists of an electrical arc generated across the electrodes of the spark plug. Two important factors for proper ignition are the energy of the spark and the point in the four-stroke cycle when the spark occurs (ignition timing).

Electrical Energy. The energy required for a spark to ignite an air/fuel mixture at stoichiometry depends on specific engine conditions. If there is insufficient energy available to ignite the air/fuel mixture, misfiring will occur. Misfiring will result in poor engine operation, high exhaust emissions, and possible catalytic converter damage. Therefore, the amount of ignition energy available must always exceed the amount necessary to ensure ignition even under adverse conditions.

Some of the conditions that affect ignitability of the air/fuel mixture are fuel atomization, access of the mixture to the spark, spark duration, and spark physical length. Fuel atomization is controlled by the fuel system and the engine design. Access to the spark depends on combustion chamber and spark plug design. Spark duration is a function of the ignition system. Spark physical length is determined by the spark plug dimensions (gap).

Ignition Timing. The ignition timing must be selected to meet the following objectives: maximize engine performance, limit fuel consumption, minimize engine knock, and minimize exhaust emissions. Unfortunately, all of these objectives cannot be achieved simultaneously under all operating conditions and compromises must be made.

It is desirable in the SI engine to have ignition of the combustible mixture occur prior to the piston reaching TDC on the compression stroke to achieve the best engine performance. The ignition spark must occur early enough to ensure that the peak cylinder combustion pressure occurs at the correct point after top dead center (ADC) under all operating conditions. Figure 12.17 is a graph of ignition angle vs. combustion pressure. The length of the combustion process from initial ignition to final combustion is approximately 2 ms. This combustion time remains relatively constant with respect to engine speed. Therefore, as the engine speed increases, the ignition spark must occur earlier in terms of crankshaft angle to ensure complete combustion.

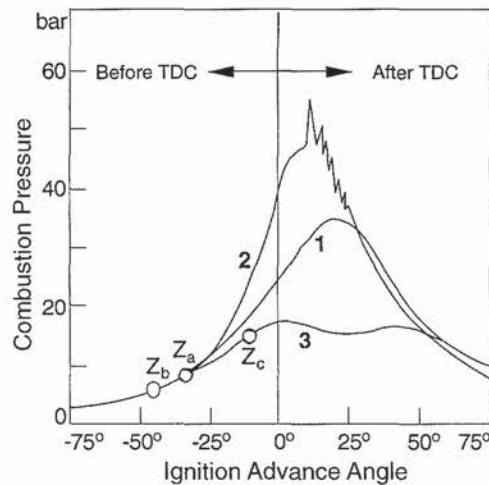


FIGURE 12.17 Combustion pressure curve for various ignition timing points: correct ignition advance Z_a (1), excessive ignition advance Z_b (2), and excessive ignition retard Z_c (3).

At low engine loads, the lower air charge and the residual gas content, due to valve overlap, serve to lengthen the time required for complete combustion. To compensate for this effect, the ignition timing is advanced at low loads to ensure that complete combustion occurs.

Ignition timing influences exhaust emissions and fuel consumption. With more advanced timing, the emission of unburned hydrocarbons (HC) and of oxides of nitrogen (NO_x) increases. Carbon monoxide (CO) emissions are not influenced greatly by ignition timing. To achieve improvements in fuel consumption, the air/fuel mixture must be lean. To ensure complete combustion for a lean mixture, the ignition timing must be advanced. However, as previously stated, advanced timing increases emissions of HC and NO_x .

Spark Ignition Systems. The general configuration of an ignition system consists of the following components: energy storage device, ignition timing mechanism, ignition triggering mechanism, spark distribution system, and spark plugs and high tension wires.

Inductive ignition systems use an ignition coil as the energy storage device. The coil also functions as a transformer, boosting the secondary ignition voltage. A typical turns-ratio of the primary to secondary winding is 1:100. Electrical energy is supplied to the coil's primary winding from the vehicle electrical system. Before the ignition point, the coil is charged during the dwell period to its interruption current. Open- or closed-loop dwell angle control ensures a sufficient interruption current even at high speeds. Sufficient ignition energy at the interruption current is ensured by an adequate coil design. At the ignition point, the primary current will be interrupted. The rapid change of the magnetic field induces the secondary voltage in the secondary winding. A distribution system assigns the high voltage to the corresponding spark plug. After exceeding the arcing over voltage at the spark plug, the coil will be discharged during the spark duration.

The ignition timing mechanism, ignition triggering mechanism, and the spark distribution system differ between ignition systems. Further discussion of these will occur within the discussion of each ignition system type.

The spark plugs provide the ignition energy via the high-tension wires to the air/fuel mixture in the cylinder to initiate combustion. The voltage required at the spark plug can be more

than 30 kV. Because the spark plug extends into the combustion chamber, it is exposed to extreme temperature and pressure conditions. Spark plug design and materials are chosen to ensure long-term operation under tough operating conditions.

A typical spark plug consists of a pair of electrodes, called a center and ground electrode, separated by a gap. The size of the gap is important and is specified for each plug type and engine. The center electrode is electrically connected to the top terminal of the plug which is attached to the high-tension wire. The electrical energy travels through the high-tension wire to the top terminal and down to the center electrode. The ground electrode is part of the threaded portion of the spark plug that is installed in the cylinder head. The ground electrode is at electrical ground potential because the negative terminal of the battery is also connected to the engine. The spark is produced when the high-voltage pulse travels to the center electrode and jumps the gap to the ground electrode.

Ignition System Types. Table 12.1 summarizes the various ignition systems used on SI engines.

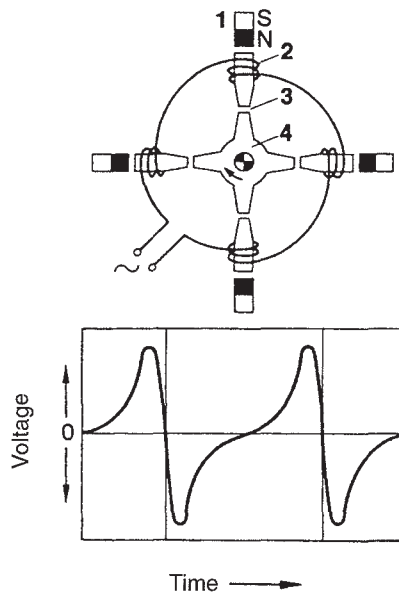


FIGURE 12.18 Induction-type pulse generator: permanent magnet (1), induction winding with core (2), variable air gap (3), trigger wheel (4).

Coil ignition. Breaker-triggered coil ignition systems have been replaced by breakerless transistorized ignition systems and are no longer installed as original equipment.

On breakerless transistorized ignition systems, the contact breaker's function is replaced by a magnetic pulse generator. The pulse generator is installed in the distributor and turns with the distributor shaft. There are commonly two types of pulse generators: induction-type and Hall-type. Induction-type pulse generators consist of a stator and a trigger wheel (Fig. 12.18). The stator consists of a permanent magnet, inductive winding, and core, and remains fixed. The trigger wheel teeth correspond to the number of cylinders, and the trigger wheel turns with the distributor shaft. The operating principle is that as the air gap changes between the stator and the rotor, the magnetic flux changes. The change in magnetic flux induces an ac voltage in the inductive winding. The frequency and magnitude of the alternating current increases with increasing engine speed. The electronic control unit or trigger box uses this information to trigger the ignition timing.

TABLE 12.1 Overview of Various Ignition Systems

| Ignition function | Ignition designation | | | | |
|--|----------------------|----------------------------|----------------------------|------------------------------------|-----------------------------------|
| | Coil system | Transistorized coil system | Capacitor discharge system | Electronic system with distributor | Electronic distributorless system |
| Ignition triggering | Mechanical | Electronic | Electronic | Electronic | Electronic |
| Ignition timing | Mechanical | Mechanical | Electronic | Electronic | Electronic |
| High-voltage generation | Inductive | Inductive | Capacitive | Inductive | Inductive |
| Spark distribution to appropriate cylinder | Mechanical | Mechanical | Mechanical | Mechanical | Electronic |

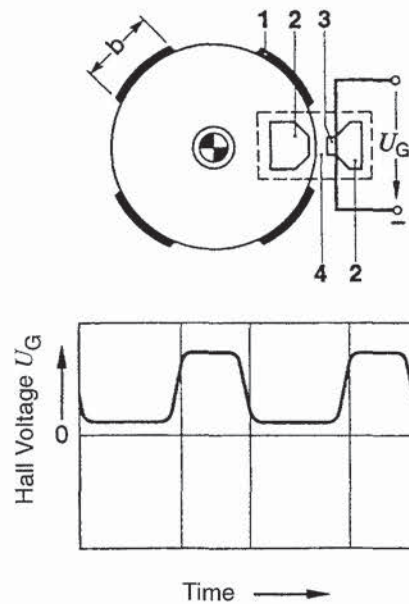


FIGURE 12.19 Hall-type pulse generator: vane (1), soft magnetic conductive elements (2), Hall IC (3), and air gap, U_G -Hall sensor voltage (4).

Hall-type pulse generators utilize the Hall effect (Fig. 12.19). As the distributor shaft turns, the vanes of the rotor move through the air gap of the magnetic barrier. When the vane is not in front of the Hall IC, the sensor is subjected to a magnetic field. The magnetic flux density is high and thus the voltage U_G is at a maximum. As soon as the rotor vane enters the air gap, the magnetic flux runs through the vane area and is largely prevented from reaching the Hall layer. The voltage U_G is at a minimum. The resulting pulses switch the primary current off and on.

The distributor dispurses the ignition pulses to the spark plugs via the high-tension wires in a specific sequence. It also adjusts the ignition timing by means of spark advance mechanisms. The distributor rotor is turned by the engine at one-half the crankshaft speed. The electrical energy is fed to the center of the rotor. While the rotor turns, the rotor electrode aligns with the outer electrodes that are connected to the high-tension wires. One outer electrode and high-tension wire connection exists for each cylinder. When alignment occurs between the center and outer electrode, the spark is distributed to that particular cylinder.

The spark advance mechanisms advance the ignition timing by rotating the distributor plate relative to the distributor shaft. The centrifugal advance increases the spark advance with increasing engine speed. The vacuum advance, using intake manifold vacuum, increases the spark advance at low engine speeds.

Capacitor discharge ignition system. The capacitive discharge system differs from the coil-type ignition systems previously discussed. Ignition energy is stored in the electrical field of a capacitor. Capacitance and charge voltage of the capacitor determine the amount of energy that is stored. The ignition transformer converts the primary voltage discharged from the capacitor to the required high voltage.

Electronic ignition—with distributor. Electronic ignition calculates the ignition timing electronically (Fig. 12.20). This replaces the function of the centrifugal advance and vacuum advance in the distributor discussed on the previous coil ignition systems. Because the ignition timing is not limited by mechanical devices, the optimal timing can be chosen for each engine operating point. Figure 12.21 is a comparison of an ignition map from a mechanical advance system and a map of an electronically optimized system. Also, additional influences such as engine knock detection can be used to modify the ignition timing. The engine speed input and crankshaft position input can be obtained from a sensor mounted near the crankshaft. Precision is improved over using the distributor-mounted trigger. This input is provided to the electronic control unit (ECU) along with the engine temperature and engine load. The ECU references data tables to determine the optimal spark advance for each engine operating condition. Additional corrections to the spark timing, such as for EGR usage or knock sensor detection, are made in the ECU.

Electronic ignition—distributorless. On distributorless ignition systems, the high voltage distribution is accomplished by using either single or double spark ignition coils. Ignition timing is determined by the ECU, as discussed for electronic ignition with distributor. For the double spark ignition coils, one coil exists for two corresponding cylinders. Two high-tension

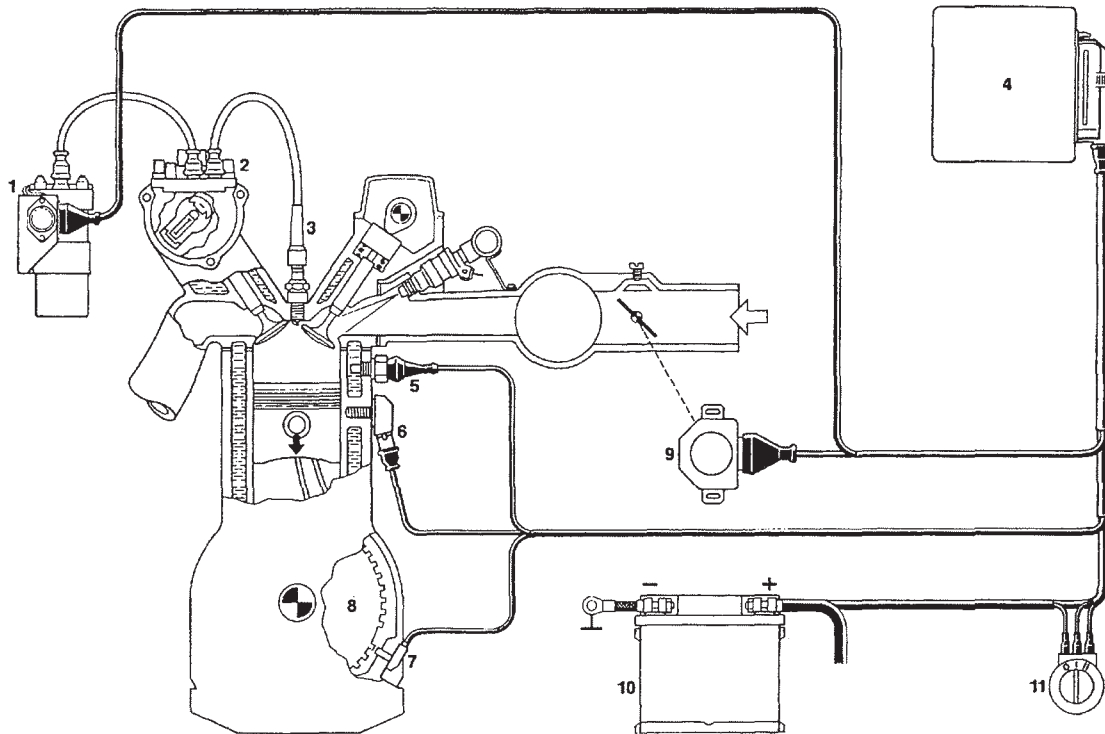


FIGURE 12.20 Schematic of an electronic ignition system with distributor: ignition coil (1), high-voltage distributor (2), spark plug (3), ECU (4), coolant temperature sensor (5), knock sensor (6), engine speed and crankshaft reference sensor (7), sensor wheel (8), throttle valve (9), battery (10), and ignition switch (11).

wires are routed from each coil to two cylinders, which are 360° out of phase. When the coil output stage is triggered via the ECU, a spark is delivered to both cylinders. One cylinder will be on the compression stroke, the other on the exhaust stroke. Because both cylinders are fired together, for a given crankshaft rotation, one will always be on the compression stroke and the other on the exhaust stroke. Therefore, there is no need to know which cylinder is compressing the ignitable mixture.

On single spark ignition coils, one coil exists for each cylinder. Each coil triggers only once during the four-stroke cycle. Because of this, it must be known which cylinder is on the compression stroke. Synchronization with the camshaft must occur. The information needed on camshaft position is supplied by a phase sensor mounted on the camshaft.

12.3 COMPRESSION IGNITION ENGINES

12.3.1 Engine Control Functions

Electronic engine controls are now being used on compression ignition (diesel) engines. These controls offer greater precision and control of fuel injection quantity and timing, engine speed, EGR, turbocharger boost pressure, and auxiliary starting devices. The following inputs

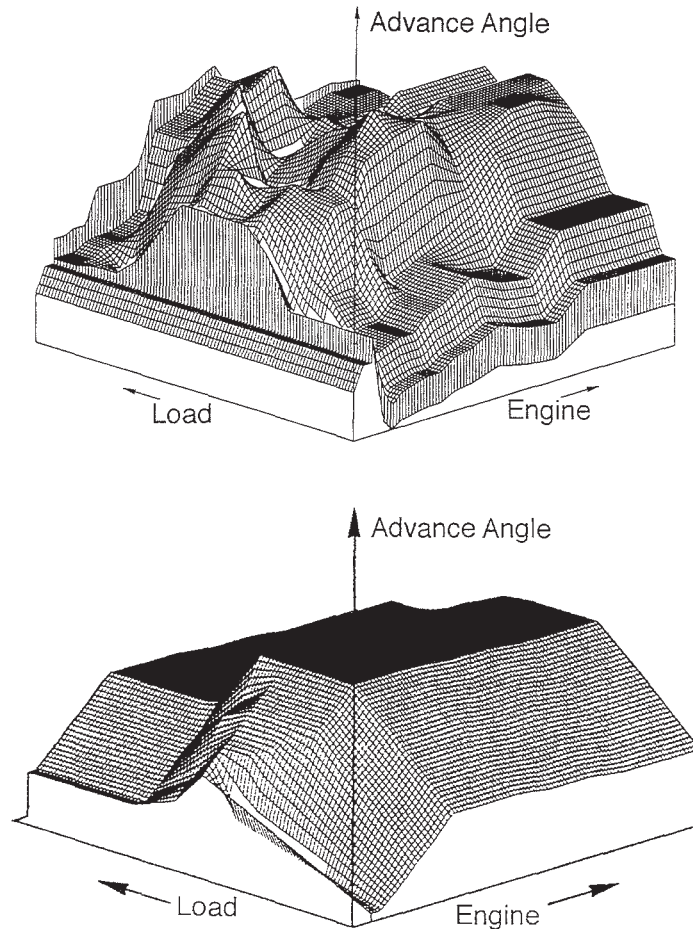


FIGURE 12.21 Ignition timing maps: electronically optimized (*above*) and mechanical advance system (*below*).

are used to provide the ECU with information on current engine operating conditions: engine speed; accelerator position; engine coolant, fuel, and inlet air temperatures; turbocharger boost pressure, vehicle speed, control rack, or control collar position (for control of fuel quantity); and atmospheric pressure. Figure 12.22 is a schematic of an electronic engine control system on an in-line diesel fuel injection pump application.

Fuel Quantity and Timing. The fuel quantity alone controls a compression ignition engine's speed and load. The intake air is not throttled as in a spark ignition engine. The quantity of fuel to be delivered is changed by increasing or decreasing the length of fuel delivery time per injection. On the injection pump, the delivery time is controlled by the position of the control rack on in-line pumps and the position of the control collar on distributor-type pumps. An ECU-controlled actuator is used to move the control rack or the collar to increase or decrease the fuel delivery time. The ECU determines the correct length of delivery time (expressed as a function of control rack or collar position) using performance maps based on engine speed and calculated fuel quantity. Corrections and/or limitations as functions of

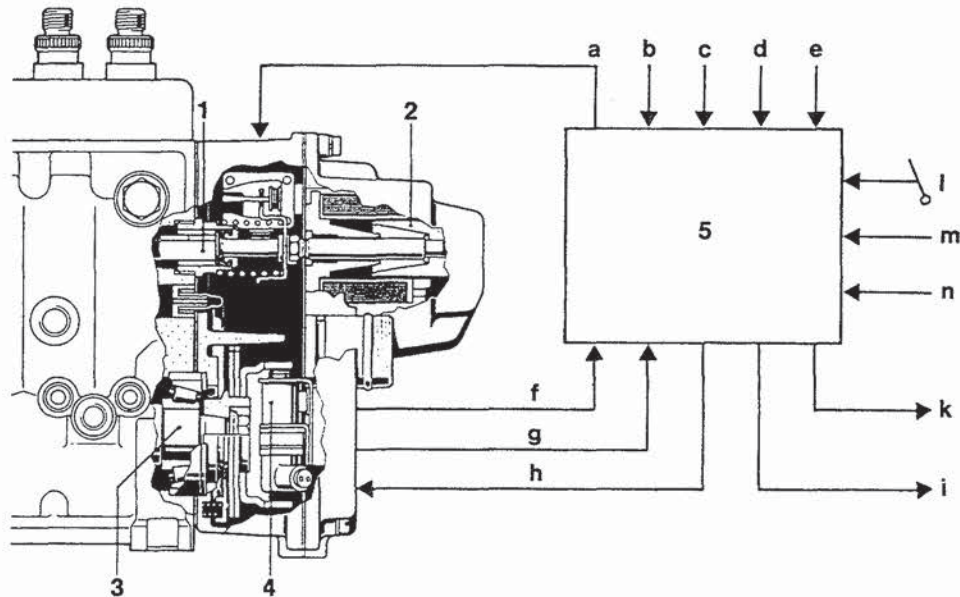


FIGURE 12.22 Electronic engine control system for an in-line injection pump: control rack (1), actuator (2), camshaft (3), engine speed sensor (4), ECU (5). Input/output: redundant fuel shutoff (a), boost pressure (b), vehicle speed (c), temperature—water, air, fuel (d), intervention in injection fuel quantity (e), speed (f), control rack position (g), solenoid position (h), fuel consumption and engine speed display (i), system diagnosis information (k), accelerator position (l), preset speed (m), and clutch, brakes, engine brake (n).

engine speed, temperature, and turbocharger boost pressure are used to modify the delivery time. In addition, the control rack or collar actuator contains a position sensor that provides feedback to the ECU on controller position. If the requested position differs from the commanded position, the ECU continues to move the controller via the actuator until the commanded and actual position are the same.

The start of injection time of the fuel at the cylinder is a function of the wave propagation speed (i.e., the speed of sound) of the fuel from the fuel injection pump to the injector. Because this time remains a constant, at increasing engine speed the delivery of fuel at the cylinder would be delayed with reference to crankshaft angle. Therefore, the timing at the injection pump must be advanced with increasing engine speed so that the start of injection occurs at the same crankshaft angle at higher engine speeds. Selection of injection timing has a large impact on exhaust emissions and engine noise. Delaying the start of injection reduces NO_x emissions, but excessive delay increases HCs in the exhaust. A 1° deviation in injection timing can increase NO_x emissions by 5 percent and HC emissions by as much as 15 percent. Therefore, precise control of the start of injection is essential.

Although many systems use mechanical devices to control injection timing, electronic control of injection timing is being used on some pump types. The advantage of electronic control is that a sophisticated timing data map can be used that provides the best injection timing for exhaust emissions under various operating conditions. On electronic control systems, the start of injection is monitored at the injector nozzle by a needle-motion sensor. The ECU uses this information to determine and control the injection timing. The timing is then modified by control of a pulse-width modulated solenoid valve. The valve varies the pressure exerted on the spring-loaded timing device plunger. The plunger rotates the pump's collar ring (for distributor type pumps) in the opposite direction of the pump's rotation which advances the timing.

Speed Control. As was mentioned previously, for a CI engine, fuel quantity alone controls the engine's speed and load. Therefore, presuming adequate injected fuel quantity, an unloaded CI engine can speed up out of control and destroy itself. Because of this, a governor is required to limit the engine's maximum speed. In addition, governors are also used for low idle and cruise control to maintain a constant engine or vehicle speed and meter the correct fuel for cold-starting. Fuel is also controlled as a function of speed and boost pressure to limit smoke levels, engine torque, and exhaust gas temperatures. On an electronically controlled CI engine, the governor's functions are controlled by the fuel delivery system described previously. Engine speed is provided by an RPM sensor that monitors the periods of angular segments between the reference marks on the engine's flywheel or in the in-line injection pump.

EGR Control. Rerouting of exhaust gases into the intake air stream is known as exhaust gas recirculation (EGR). EGR reduces the amount of oxygen in the fresh intake charge while increasing its specific heat. This lowers combustion temperatures and results in lower NO_x emissions. However, excessive amounts of EGR result in higher emissions of soot (particulates), CO, and HCs all due to insufficient air. Also, the introduction of EGR can have an adverse affect on driveability during cold-engine operation, full-load operation, and at idle. It is best, therefore, to control the EGR valve with the ECU. Both pneumatically controlled and solenoid-controlled EGR valves are in use. The ECU determines when and how much EGR will occur based on engine temperature and accelerator position.

Turbocharger Boost Pressure Control. Engines that have turbochargers benefit significantly from electronic boost pressure control. If only a pneumatic-mechanical wastegate is used, only one boost pressure point for the entire operating range is used to divert the exhaust gas away from the turbine side of the turbocharger. This creates a compromise for part-load conditions because all the exhaust gases must pass the turbine. The result is increased exhaust backpressure, more turbocharger work, more residual exhaust gas in the cylinders, and higher charge air temperatures.

By controlling the wastegate with a pulse-width-modulated solenoid valve, the wastegate can be opened at different pressures depending on the engine operating conditions. Therefore, only the level of air charge pressure required is developed. The electronic control unit uses information on engine speed and accelerator position to reference a data table and the proper boost pressure (actually, duty cycle of the control valve) is determined. On systems using intake manifold pressure sensors, a closed-loop control system can be developed to compare the specified value with the measured value.

Glow Plug Control. Electronic control of the glow plug duration can be handled by the ECU or a separate control unit. Input for determining glow time is from an engine coolant temperature sensor. At the end of the specified glow period, the controller turns out the start indicator light to signal the driver that the engine can be started. The glow plugs remain energized while the starter is engaged. An engine load monitor is used to switch off the glow process after start. To limit the loads on the battery and the glow plugs, a safety override is also used.

12.3.2 Fuel Delivery Systems

The diesel fuel delivery system comprises a low- and high-pressure side. On the low-pressure side is the fuel tank, fuel filter, fuel supply pump, overflow valve, and fuel supply lines. The high-pressure side is initiated in the plunger and barrel assembly and continues through the delivery valve, high-pressure injection lines, and injection nozzle.

The fuel injection pump must deliver fuel at a pressure between 350 and 1200 bar, depending on the engine's combustion configuration. The quantity and timing of injection must be precisely controlled to achieve good mixture quality and to minimize exhaust emissions.

Fuel Injection Process. An engine-driven camshaft (in-line pump) or cam plate (distributor pump) drives the injection pump's plunger in the supply direction, creating pressure in the high-pressure gallery. The delivery valve responds to the increase in pressure by opening. This sends a pressure wave to the injection nozzle at the speed of sound. The needle valve in the nozzle overcomes the spring force of the injection nozzle spring and lifts from its seat when the opening pressure is reached. Fuel is then injected from the spray orifices into the engine's combustion chamber. The injection process ends with the opening of the spill port in the plunger and barrel assembly. This causes the pressure in the pump chamber to collapse, which then causes the delivery valve to close. Due to the action of the delivery valve relief collar, the pressure in the injection line is reduced to the "stand-by pressure." The stand-by pressure is determined to ensure that the injector nozzle closes quickly to eliminate fuel dribble, and the residual pressure waves in the lines prevent the nozzles from reopening.

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CHAPTER 13

TRANSMISSION CONTROL

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13.1 INTRODUCTION

In North America and Japan, 80 to 90 percent of all passenger cars sold have automatic transmissions (ATs), but in Europe only 10 to 15 percent of passenger cars sold have ATs. There are two main reasons for the difference. In Europe, drivers tend to view ATs, compared to manual transmissions, as detrimental to driveability and responsible for a somewhat higher fuel consumption. But implementation of electronic control concepts has invalidated both of those arguments.

Since the introduction of electronic transmission controls units (TCUs) in the early 1980s by Renault and BMW (together with a four-speed transmission from Zahnradfabrik Friedrichshafen, or ZF), the acceptance of the AT rose steeply, even in Europe. For this reason, all new ATs are designed with electronic control. The market for ATs is divided into stepped and continuously variable transmissions (CVTs). For both types the driver gets many advantages. In stepped transmissions, the smooth shifts can be optimized by the reduction of engine torque during gear shift, combined with the correctly matched oil pressure for the friction elements (clutches, brake bands). The reduction of shift shocks to a very low or even to an unnoticeable level has allowed the design of five-speed ATs where a slightly higher number of gear shifts occur. In today's standard systems, the driver can choose between sport and economic drive programs by operating a selector switch. In highly sophisticated newer systems, the selection can be replaced by the self-adaptation of shift strategies. This leads not only to better driveability but also to a significant reduction in fuel consumption. Additionally, a well-matched electronic control of the torque converter lockup helps to improve the yield of the overall system. Both automotive and transmission manufacturers benefit from the reduced expense resulting from the application of different car/engine combinations. Different shift characteristics are easy to implement in software, and much adaptation can be achieved by data change, leaving the transmission hardware and TCU unchanged. The reduction of power losses in friction elements increases the life expectancy and enables the optimization of transmission hardware design.

With the CVT, one of the biggest obstacles to the potential reduction in fuel consumption by operating the engine at its optimal working point is the power loss from the transmission's oil pump. Only with electronic control is it possible to achieve the required yield by matching the oil mass-stream and oil pressure for the pulleys to the actual working conditions.

To guarantee the overall economic solution for an electronically controlled transmission, either stepped or CVT, the availability of precision electrohydraulic actuators is imperative.

13.1

13.2 SYSTEM COMPONENTS

The components of an electronic transmission control system are a transmission which is adapted to the electronic control requirements and an electronic control unit with corresponding inputs and outputs and attached sensor elements.

13.2.1 Transmission

The greatest share of electronically controlled transmissions currently on the market consists of four- or five-speed units with a torque converter lockup clutch, commanded by the control unit. Market share for five-speed transmissions is continuously increasing. With electronically controlled transmissions there are numerous possibilities to substitute mechanical and hydraulic components with electromechanical or electrohydraulic components. One basic method is to substitute only the shift point control. In a conventional pure hydraulic AT, the gear shifts are carried out by mechanical and hydraulic components. These are controlled by a centrifugal governor that detects the vehicle speed, and a wire cable connected to the throttle plate lever. With an electronic shift point control, on the other hand, an electronic control unit detects and controls the relevant components. In the transmission's hydraulic control unit, mechanical and hydraulic components are replaced by electrohydraulic controlling elements, usually in the form of electrohydraulic on/off solenoids. This way the number of solenoids, as well as the control logic, can be varied over a wide range. For example, for each gear, one specific solenoid can operate the relevant clutch for this gear shift. Alternatively, there can be one solenoid for each gear change, which is switched corresponding to the shift command. In this way, only three solenoids are required in a four-speed transmission. In some current designs, the gears are controlled by a logical combination of solenoid states. This design needs only two gear-controlling solenoids for a four-speed transmission. For five-speed applications, accordingly, three solenoids are required (Table 13.1)

TABLE 13.1 Example of a Gear-Solenoid Combination for a Five-Speed Transmission Application

| | Solenoid 1 | Solenoid 2 | Solenoid 3 |
|----------|------------|------------|------------|
| 1st gear | on | on | on |
| 2nd gear | on | on | off |
| 3rd gear | on | off | off |
| 4th gear | off | off | off |
| 5th gear | off | on | off |

The hydraulic pressure is controlled in this basic application by a hydraulic proportional valve which is, in turn, controlled by a wire cable connected to the throttle plate lever. With this design, the shift points can be determined by the electronic TCU, resulting in a wide range of freely selectable driving behaviors regarding the shift points. It is also possible to use different shift maps according to switch or sensor signals. The influence on driving comfort during gear shifting in this electronic transmission control application has important restrictions. The only possible way to control shift smoothness is with an interface to the electronic engine management. This way, the engine output torque is influenced during gear shifting. A systematic wide-range control of the hydraulic pressure during and after the gear shift necessitates the replacement of the hydraulic pressure governor with an electronically controlled hydraulic solenoid. This design allows the use of either a pulse-width-modulated (PWM) solenoid or a pressure regulator. The choice of which type of pressure control solenoid to use results from the requirements concerning shift comfort under all driving conditions. For

present-day designs with high requirements for shift comfort during the entire life of the transmission, at all temperatures, and with varying oil quality, the analog pressure control solenoid is superior to the usual PWM solenoid, providing there is no pressure sensor in operation as a guideline for pressure regulation. This application usually uses one central controlling element in the transmission for the pressure regulation to control the shift quality.

In other transmission developments, the shift quality is further increased using electronically controllable brake elements (brake bands) for some specific gear changes. In this case, the flywheel effect of the revolving elements is limited by an electronic control of a brake band according to an algorithm or special timing conditions.

The most sophisticated transmission application to date is so designed that overrunning clutches are eliminated and gear changes are exclusively controlled by the electronic control unit with pressure regulator solenoids.¹ This application is characterized by extremely high demands on the electronic TCU concerning real-time behavior and data handling. The relationship between weight, transmission outline, and transferrable torque has reached a high level. Compared to transmissions with overrun clutches, the necessary fitting dimensions are reduced.

Present electronically controlled ATs usually have an electronically commanded torque converter clutch, which can lock up the torque converter between the engine output and the transmission input. The torque converter clutch is activated under certain driving conditions by a solenoid controlled by the electronic TCU. The solenoid design, depending on the requirements of TCC functions and shift comfort, can either be an on/off solenoid, a PWM solenoid, or a pressure regulator. Locking up the torque converter eliminates the slip of the converter, and the efficiency of the transmission system is increased. This results in an even lower fuel consumption for cars equipped with AT.

13.2.2 Electronic Control Unit

Another important component in electronic transmission control is the electronic control unit, which is designed according to the requirements of the transmission and the car environments. The electronic control unit can be divided into two main parts: the hardware and the corresponding software.

Hardware. The hardware of the electronic control unit consists of the housing, the plug, the carrier for the electronic devices, and the devices themselves. The housing, according to the requirements, is available as an unsealed design for applications inside the passenger compartment or within the luggage compartment. It is also possible to have sealed variants for mounting conditions inside the engine compartment or at the bulkhead. The materials for the housing can be either various plastics or metals. There are many different nonstandardized housings on the market. The various outlines and plug configurations differ, depending upon the manufacturer of the electronic unit. The plug configuration, i.e., the number of pins and the shape, depends on the functions and the requirements of the automotive manufacturer. The number of pins is usually less than 100. Some control unit manufacturers try to standardize their plugs and housings throughout all their electronic control units, such as engine management, ABS, traction control, and others. This is important to simplify and to standardize the unit production and the tests during manufacturing.

The carrier for the electronic devices is usually a conventional printed circuit board (PCB). The number of layers on the PCB depends on the application. For units with a complex device structure and high demands for electromagnetic compatibility, multilayer applications are in use. In special cases, it is possible to use ceramics as a carrier. There are usually some parts of the electronic circuit, resistors for example, designed as a thick-film circuit on the hybrid. In this case the electronic unit is manufactured as a solder hybrid or as a bond hybrid with direct-bonded integrated circuit devices. Some single applications exist with a flex-foil as a carrier for the electronic devices. These applications are limited to very special requirements.

The transmission control area requires some specially designed electronic devices, in particular, the output stages for the actuators of pressure regulation and torque converter clutch control. These actuators for pressure control have extremely high demands regarding accuracy of the actuator current over the whole temperature range and under all conditions independent of battery voltage and over the entire lifetime. There are some known applications of customer-specific integrated circuits or devices. Here, special attention paid to quality and reliability over the entire lifetime is necessary to meet the continuously increasing quality requirements of the automotive market. Currently, there is an increasing spread of surface-mounted devices in transmission control applications. This is why the unit size is continuously decreasing despite an increasing number of functions.

On the functional side, the hardware configuration can be divided into power supply, input signal transfer circuits, output stages, and microcontroller, including peripheral components and monitoring and safety circuits (Fig. 13.1). The power supply converts the vehicle battery voltage into a constant voltage required by the electronic devices inside the control unit. Accordingly, special attention must be paid to the protection of the internal devices against destruction by transients from the vehicle electrical system such as load dump, reverse battery polarity, and voltage peaks. Particular attention is also necessary in the design of the elec-

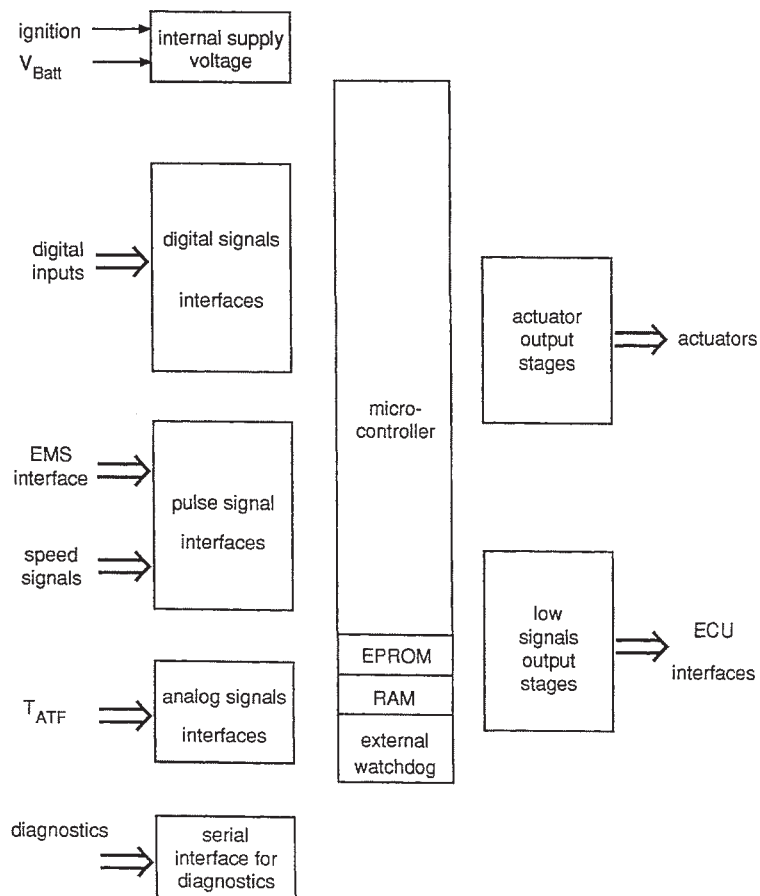


FIGURE 13.1 Overview of hardware parts.

tronic ground concept for the control unit, especially where the electromagnetic compatibility and RF interference is concerned. This is very important to prevent undesired gear shifting that may be troublesome for drivers. One part of the input circuit is the preparation of the digital signals, such as position switch, program selector, and kickdown switch. A second part is the transfer of the analog signals like ATF temperature and voltages according to potentiometer states. The third part is the interface to other electronic control units, especially to the engine management system. Here the single signal lines between the control units will be increasingly substituted by bus systems like CAN. The fourth part is the preparation of the transmission-specific signals from the speed sensors inside the transmission.

The calculators inside the control units are usually microcontrollers. The real-time requirements and the directly addressable program storage size of the selected microcontrollers are determined by the functions of the transmission control and the car environment. In present applications, either 8-bit or 16-bit microcontrollers are in use. There are systems with 32-bit microcontrollers in development for new, highly sophisticated control systems with increasing functional and extreme real-time requirements originating from the transmission concept. The memory devices for program and data are usually EPROMS. Their storage capacity is, in present applications, up to 64 Kbytes. Future applications will necessitate storage sizes up to 128 Kbytes. The failure storages for diagnostics and the storage for adaptive data are in conventional applications, battery voltage-supplied RAMs. These are increasingly being replaced by EEPROMs.

There are usually watchdog circuits in various configurations in use regarding safety and monitoring. These can be either a second, low-performance microcontroller, a customer-specific circuit, or a circuit with common available devices. The output stages can be divided into high-power stages for the transmission actuator control and low-power stages like lamp drivers or interfaces to other electronic control units. The low-power output stages are mostly conventional output drivers either in single or in multiple applications, which are mainly protected against short circuits and voltage overloads.

For the transmission solenoid control, special output stages are necessary, and they are specialized for operation with inductive actuators. The pressure regulation during shifting in some applications requires high accuracy and current-regulated output stages are needed. These are mainly designed as customer-specific devices. The type and number of solenoid output stages depend on the control philosophy of the transmission: they are generally of a special design for specific transmission applications. During the preparation of the speed sensor signals, attention must be paid to the electromagnetic compatibility and radio frequency interference conditions.

Software. The software within the electronic transmission control system is gaining increasing importance due to the increasing number of functions which, in turn, requires increasing software volume. The software for the control unit can be divided into two parts: the program and the data. The program structure is defined by the functions. The data are specific for the relevant program parts and have to be fixed during the calibration stage. The most difficult software requirements result from the real-time conditions coming from the transmission design. This is also the main criterion for the selection of the microcontroller (Fig. 13.2).

The program is generally made up in several parts:

- Software according to the special microcontroller hardware; e.g., I/O preparation and filter, driver functions, initialization of the microcontroller and the control unit, internal services for the controller peripheral devices, and internal software services like operating systems.
- Software coming from the defined functions, originating from specific transmission and car functions.
- Parts concerning safety functions like output switch-off, substitute values for the input signals, and safety states of the microcontroller environment in case of failures. Depending on the requirements, there can be a software watchdog or a hardware-configured watchdog circuit in use. The watchdog instruction is also part of the security software.

The second software part, data, can be divided into fixed data, which is related to fixed attributes of the system; e.g., the number of actuators, and calibration data for system tuning. The calibration data can be adapted to changing parameters of the system such as the engine, vehicle, and transmission characteristics. The fixing of calibration data takes place during the tuning stage of the vehicle and has to be redetermined for each type of vehicle and transmission. With some applications, the calibration data are added to a basic program during the vehicle production according to different types of cars by the so-called end-of-line programming. This means that the units can be programmed with the calibration data with closed housings by a special interface. The share of software development in relation to the total development time is increasing continuously. The requirements for real-time behavior and memory size are rising in accordance with the considerably increasing demands for shift comfort and self-learning functions. This requires an ingenious structure of the software and an event-related distribution of software models, especially during gear shifting. The rising software complexity with simultaneously increasing quality requirements causes higher demands for software quality control.

13.2.3 Actuators

Electrohydraulic actuators are important components of the electronic transmission control systems.² Continuously operating actuators are used to modulate pressure, while switching actuators function as supply and discharge valves for shift-point control. Figure 13.3 provides a basic overview of these types of solenoids.

Important qualities for the use of actuators in ATs are low hydraulic resistance to achieve high flow rates, operation temperature range from -40 to $+150$ °C, small power loss, minimized heat dissipation in the ECU's output stages, small size and low weight, highest reliability in heavily contaminated oils, maximum accuracy and repeatability over lifetime, short reaction times, pressure range up to 2000 kPa, maximum vibration acceleration of 300 m/s², and high number of switch operations.

A very important aspect is that the hardware and software of the ECU be developed, taking into account the electrical specifications of the solenoid to obtain an optimized complete system concerning performance and cost.^{6,7} For further details in design and application, refer to Sec. 10.3.5.

It should be noted that these characteristics can be varied over a wide range and that many other types of solenoids exist or are in development for the special requirements of new applications.

13.3 SYSTEM FUNCTIONS

Functions can be designated as systems functions if the individual components of the total electronic transmission control system cooperate efficiently to provide a desired behavior of the transmission and the vehicle. There are different stages of functionality which have different effects on driving behavior and shift characteristics (Fig. 13.4). In general, there is an increasing complexity of the system relating to all components to improve the translation of driver behavior into transmission action. That means that the expense of actuators, sensors, and links to other control units is increasing, as is the expense of the TCU software and hardware in the case of high-level requirements regarding driveability and shift comfort. Figure 13.4 shows three main areas. These will be discussed in detail in the following material.

13.3.1 Basic Functions

The basic functions of the transmission control are the shift point control, the lockup control, engine torque control during shifting, related safety functions, and diagnostic functions for

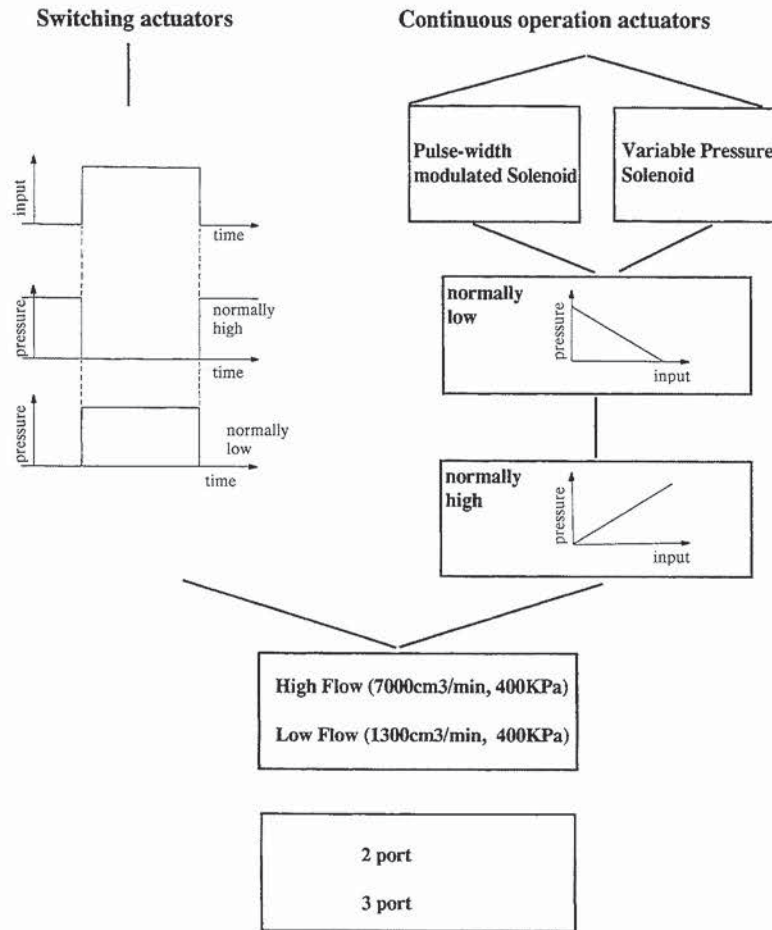


FIGURE 13.3 Electrohydraulic actuators for automatic transmissions.

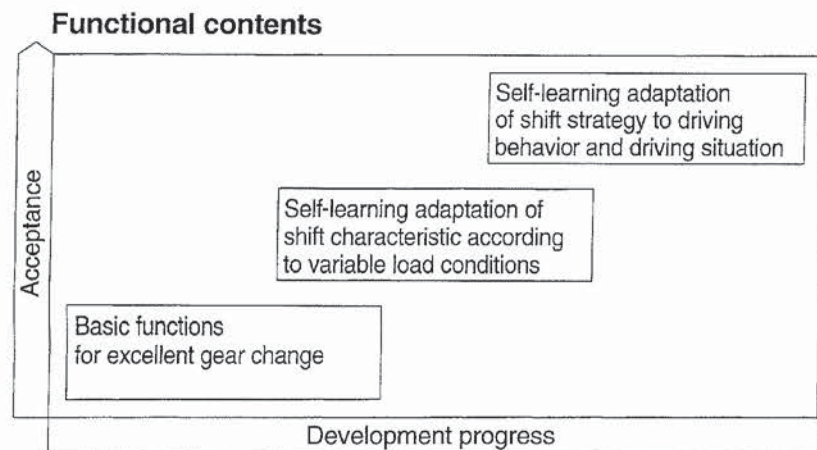


FIGURE 13.4 Relationship between driving characteristic and function complexity.

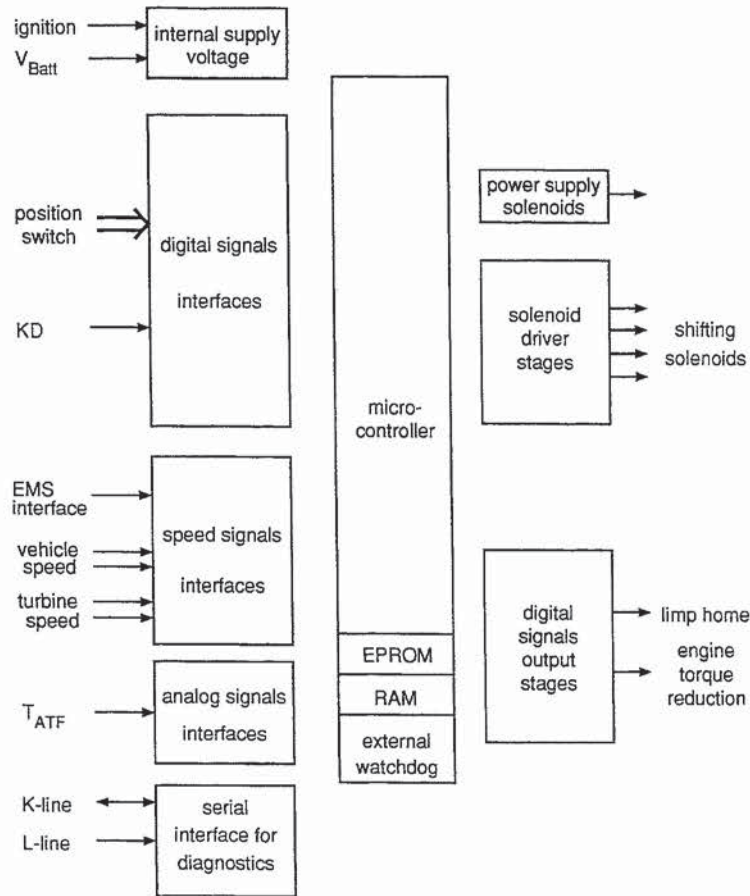


FIGURE 13.5 Structure of a basic transmission electronic control unit.

vehicle service. The pressure control in transmission systems with electrical operating possibilities for the pressure during and outside shifting can also be considered as a basic function. Figure 13.5 shows the necessary inputs and outputs as well as the block diagram of an electronic TCU suitable for the basic functions.

Shift Point Control. The basic shift point control uses shift maps, which are defined in data in the unit memory. These shift maps are selectable over a wide range. The shift point limitations are made, on the one hand, by the highest admissible engine speed for each application and, on the other hand, by the lowest engine speed that is practical for driving comfort and noise emission. The inputs of the shift point determination are the throttle position, the accelerator pedal position, and the vehicle speed (determined by the transmission output speed). Figure 13.6 shows a typical shift map application of a four-speed transmission.

To prevent overly frequent shifting between two gears, a hysteresis between the upshift and the downshift characteristic is incorporated. The hysteresis is determined by the desired shifting habit of the transmission and, alternatively, the car behavior. In the event that the particular shift characteristic is crossed by one of either of the two input valves, the electronic ECU releases the shift by activating the related actuators. This can be a direct shift into the

E-Program (Economy)

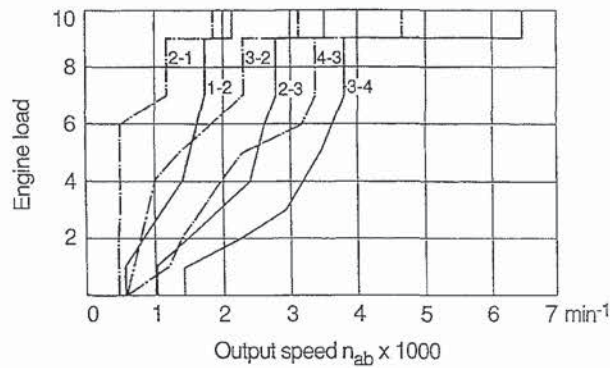


FIGURE 13.6 Shift characteristics of a four-speed application.

target gear or by a serial activation of specific actuators in a fixed sequence to the target gear, depending on the transmission hardware design.

Lockup Control/Torque Converter Clutch.⁸ The torque converter clutch connects both functional components of the hydraulic converter, the pump and the turbine. The lockup of the clutch reduces the power losses coming from the torque converter slip. This is a permanent slip because it is necessary in principle to have a slip between the pumpwheel and the turbine to translate torque from the engine output to the transmission input. To increase the efficiency of the lockup, it is necessary to close the clutch as often as possible. On the other hand, the torque converter is an important component to prevent vibrations of the powertrain. The activation of the lockup is, therefore, a compromise between low fuel consumption and high driving comfort. The shift points of the lockup are determined in the same way as the determination of the shift point in the gear shift point control. Usually there is one separate characteristic curve for the lockup for each gear. To prevent powertrain vibrations, it is advisable to open the lockup during coasting to use the damping effect of the torque converter. In the case of a high positive gradient of the accelerator pedal with low engine speed, the converter clutch has to open to use the torque gain of the converter for better acceleration of the car. In some applications, the lockup is opened during shifting for improved shift comfort. After shifting, the lockup can be closed again. When driving in first gear, the lockup is usually open, because the time spent in first gear is usually very low and, therefore, the frequency of lockup shifting versus gear shifting becomes very high. This may result in decreased driving comfort. A second reason is the improved acceleration of the car in first gear when using the converter gain for wheel torque.

Engine Torque Control During Shifting.⁸ The engine torque control requires an interface to an electronic engine management system. The target of the engine torque control, torque reduction during shifting, is to support the synchronization of the transmission and to prevent shift shocks.

In conventional applications, the engine torque reduction originates from an ignition angle control. The timing and absolute value of the ignition control depends on the operating conditions concerning actual engine torque and shifting type.

Upshift. The upshift occurs without an interruption of the tractive power. The engine torque reduction may be activated if the clutch of the target gear stays with the translation of torque. The beginning of the engine torque reduction is determined by the course of engine or transmission input speed. There it is important to detect a decreasing speed. The start of the

torque reduction is characterized by a specific speed difference. The end of the torque reduction is activated at an applicable speed lead before reaching the synchronous speed of the new gear.

The power losses, which have to be picked up by the clutches, are dependent on the engine torque and the slipping time

$$Q = f \times (M_{\text{eng}} \times t_s + Q_{\text{kin}}) \quad (13.1)$$

where Q = power losses

M_{eng} = engine torque

t_s = slipping time

Q_{kin} = kinetic energy of revolving elements

It is possible to reduce the temperature stress to the clutches by reducing the engine torque and, consequently, by increasing the slipping time at a fixed possible maximum power loss Q [Eq. (13.1)]. Figure 13.7 shows a typical upshift characteristic.

Shift Quality Comparison

Upshift

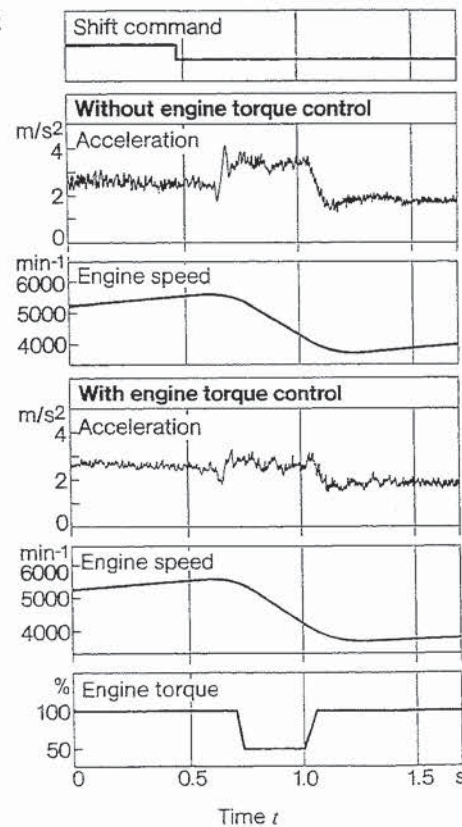


FIGURE 13.7 Timing of engine torque reduction during upshift.

Downshift. Downshift under driving conditions results in a short interruption of the tractive power. At the synchronous point, the tractive power is in operation. The higher revolving energy, on the other hand, results in undesired vibrations of the powertrain. To prevent such

vibrations, it is necessary to reduce the engine output torque before reaching the synchronous point of the new gear. When the transmission input speed reaches the synchronous speed of the new gear, the engine torque has to increase to the nominal value. The increase is usually applied as a torque ramp. Figure 13.8 shows a typical characteristic of a downshift. The values and timing of the engine torque reduction are generally part of the special calibration data for each combination of vehicle, engine, and transmission.

Shift Quality Comparison

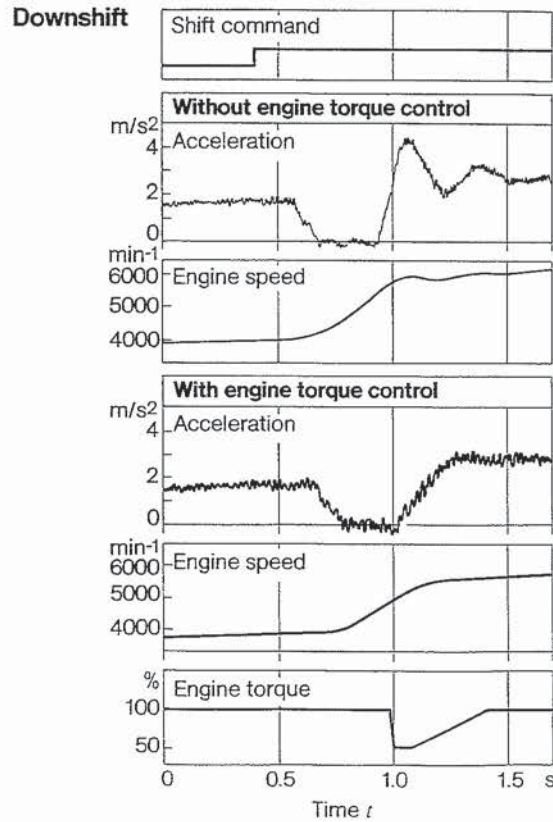


FIGURE 13.8 Timing of engine torque reduction during downshift.

Pressure Control.⁸ The timing and absolute values of the pressure, which is responsible for the torque translation of the friction elements, is, aside from the engine torque reduction, the most important influence to shift comfort. The electronic TCU offers additional possibilities for better function than a conventional hydraulic system.

The pressure values during and outside shifting can be calculated by different algorithms or can be determined by characteristic maps. The inputs for a pressure calculation are engine torque, transmission input speed, turbine torque, throttle position, and so on. The inputs depend on the special signal availability in different systems as well as the requirement concerning shift comfort. The variable pressure components are usually added to a constant pressure value according to the different transmission designs. Equation (13.2) gives a typical algorithm for a pressure calculation.

$$P_{\text{mod}} = P_{\text{const}} + k_n \times P_n + k_{\text{tor}} \times P_{\text{tor}} + k_s \times P_s \quad (13.2)$$

where P_{mod} = pressure

P_{const} = constant pressure value

k_n = adaptation factor for input speed

P_n = pressure component dependent on the revolution signal

k_{tor} = adaptation factor for engine torque

P_{tor} = pressure component dependent on torque

k_s = adaptation factor for vehicle speed

P_s = pressure component dependent on vehicle speed

During applications, the factors must be defined in the calibration phase. In general, the determination of these factors requires many vehicle tests, because the dynamic characteristic of the total system has an important influence on shift comfort. Another possibility for the pressure determination is to use characteristic maps which have to be defined during the calibration phase. This kind of pressure determination allows an improved selection of the optimum pressure at various extreme points independent of an algorithm.

Safety and Diagnostic Functions. The functions, which are usually known as diagnostic functions of the electronic TCU, can be divided into real safety functions to prevent critical driving conditions and diagnostic functions which affect an increasing availability of the car and a better failure detection for servicing. The boundary between safety and diagnostic functions depends on the philosophy of the automotive manufacturer. In the category of real safety functions belong all security functions that prevent uncontrollable shifting, especially unintended downshifting. One section is the monitoring of the microcontroller and its related peripheral devices. The monitoring of the transmission, like gear ratio detection, is also a part of this functional block, as are the actuator and speed sensor monitoring. The microcontroller monitor is usually a watchdog circuit. One possibility is to use the controller internal watchdog. In common applications, it is necessary to use an external watchdog circuit for safety reasons. This can be done with a second, low-performance microcontroller or by a separate hardware watchdog designed as an ASIC or as a conventional circuit device. Usually there is a safety logic circuit connected to the watchdog, which, in the case of a microcontroller breakdown, activates the failure signal and switches the outputs for the transmission actuators to a safety condition.

For the detection of the watchdog, it is necessary to test the watchdog function after each power-on during the electronic initialization. The monitoring of the controller peripheral components, in general EPROM, RAM, and chip-select circuits, works continuously with specific algorithms; e.g., by writing fixed data values to the storage cells and following comparison with the read value or by checksum comparison with fixed sum values. The actuator monitoring includes detection of short circuit to supply voltage and ground, as well as open-load conditions.

In case of actuator malfunction, the limp home mode is selected. This means that the transmission runs in a fixed, safe gear, depending on the driving conditions. The safe state of the actuators is the noncurrent condition, which is secured by the electronic control unit. The control unit can put the output stages into the noncurrent stage separate for each output or by a common supply switch, usually a relay or a transistor. There are some applications that use a combination of both the watchdog and safety circuits.

The monitoring of the transmission-specific sensors, such as input speed, output speed, and oil temperature, works as a plausibility check. For example the transmission input speed can be calculated as a combination of the transmission output speed and the gear ratio. In case of a detected speed sensor malfunction, the limp home mode is generally required. With a temperature sensor failure, the TCU usually works with a substitute value.

The diagnostic functions, which facilitate the finding of failures in the service station, contain the failure storage and the communication to the service tester, which allow the stored

failures of the electronic TCU to be read. The communication between the control unit and the service tester is mainly car manufacturer-specific and must be defined by the car manufacturer before going into series production. The communication runs on a bidirectional, separate communication link.

The failure storage takes place in a nonvolatile memory device; e.g., in a permanent supplied RAM or in an EEPROM. It is also possible to store sporadic failures to detect such problems during the next service. The failure codes, number of stored failures, the handling of the failure storage, as well as the reaction of the TCU in case of a particular failure, is manufacturer-specific and is part of the unit specification. The real safety functions are part of the basic functions of an electronic TCU. The diagnostic functions concerning service tester and communication protocols are, over a wide range, manufacturer-specific. These range from a simple blink code up to a real self-test of the electronic unit, including all peripheral components.

13.3.2 Improvement of Shift Control

In a second development stage, the basic functions can be revised by a modification of the software functions and by adding new parts to the basic functions. This action results in a significant enhancement of the driving and shifting comfort. By a revision of the basic safety and diagnostic functions with so-called substitute functions, it is possible to increase the availability of the vehicle with AT as well as the driveability in case of a malfunction.

Shift Point Control. The basic function can be improved significantly by adding a software function, the so-called adaptive shift point control.⁸ This function requires only signals which are available in an electronic TCU with basic functions. The adaptive shift point control is able to prevent an often-criticized attribute, the tendency for shift hunting especially when hill climbing and under heavy load conditions.

The adaptive function calculates the vehicle acceleration from the transmission output speed over time. The value of the actual acceleration in relation to a set value of the acceleration is the input for the shift point correction. The set value is given by the traction resistance characteristic. For a certain difference between set and actual value, the adaptation of the shift point occurs. The dimension of the shift point correction can be determined by calibration data and depends in general also on the actual vehicle speed and the engine load.

The shift point correction leads to higher hysteresis between upshift and downshift characteristics. With a high difference between set and actual values, it is also possible to forbid certain gears. The return to the basic shift point control is organized by software and can be fixed by calibration data. Usually, in the case of power-on, the adaptive shift point control is reset (Figs. 13.9 and 13.10).

In addition to these functions, different shift maps can be implemented into the data field of the TCU. For example, it is possible to have one shift map for low fuel consumption, which has shift points in the range of the best efficiency of the engine, and additionally to have another map for power operation, where the shift points are placed at points of highest engine output power. The character and number of different shift maps can be selected over a wide range. The choice of the different shift maps can be done by a selector push button or switch commanded by the driver. In further applications, the changing of the different shift programs is possible by self-learning strategies. It is also possible to implement a manual program in which fixed gears are specific to predetermined positions of the selector lever.

Lockup Control. There are some additional functions which can improve considerably the shift comfort of the lockup. In a first step, it is possible to replace the on/off control of the lockup actuator by a pulse control during opening and closing. This can be achieved using conventional hardware only by a software modification. In a further step, the on/off solenoid is replaced by a pressure regulator or a PWM solenoid.

By coordinating intelligent control strategies and corresponding output stages within the electronic TCU, a considerable improvement of the shift behavior of the lockup results. Here

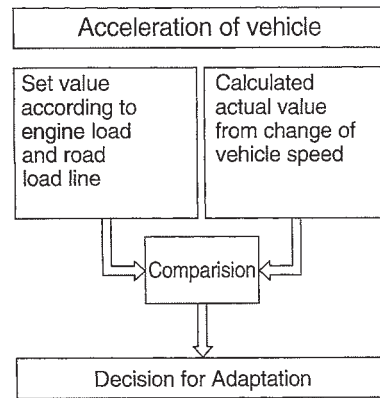


FIGURE 13.9 Basic principle of adaptive shift point control.

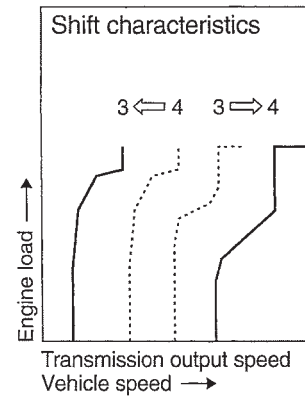


FIGURE 13.10 Shift characteristics before (---) and after (—) adaptation.

it is possible to close the lockup at low engine speed and low engine load with good shift comfort, resulting in decreased fuel consumption.

Engine Torque Reduction During Gear Shifting. By an improved interface design to the engine management system, it is possible to extend the engine torque reduction function. It is necessary to use a PWM signal with related fixed values or a bus interface. The engine torque reduction is controlled directly by the TCU. The advantage of such an interface is an independent calibration of the TCU data over a wide range without changing the engine management data. A further advantage is the improved possibility for the coordination of the engine torque reduction and the pressure control within the TCU. The improvement of this interface can be extended up to a real torque interface, especially when using a bus communication link.

Pressure Control.⁸ The pressure control can be improved in a similar way as the shift point control with an adaptive software strategy. The required inputs for the adaptive pressure control are calculated from available signals in the transmission control. The main reasons for the implementation of the adaptive pressure control are the variations of the attributes of the transmission components like clutch surfaces and oil quality as well as the changing engine output torque over the lifetime of the car.

The principle of adaptive pressure control is a comparison of a set value for the shift time with an actual value, measured by the transmission input speed course. At a specific difference of the set value to the actual value, the pressure value is corrected by a certain increment in the positive or negative direction. The original adaptation time and the pressure value increment were fixed during the calibration phase. For safety reasons, the total deviation of the pressure value from a given value is limited, depending on the particular application. Usually the correction values are stored in the nonvolatile memory to have the correct values available after power-on of the electronic TCU.

Safety and Diagnostic Functions. The safety functions extend over better monitoring of the selector lever and functions concerning misuse by the driver. With a corresponding transmission hardware design, the implementation of a reverse gear inhibit function is possible; i.e., above a certain vehicle speed, the position R is blocked hydraulically by a single solenoid or by a particular solenoid combination commanded by the electronic TCU. This function pre-

vents the destruction of the transmission in the event of an unintentional shift to the reverse gear. Downshift prevention is part of the safety function, especially during manual shifting by the driver. Here the synchronous speed of the new gear is calculated and compared with the admissible maximum engine speed. In the case of a calculated synchronous speed above the maximum engine speed, the downshift is prohibited by the TCU. This function can be supported by an overrun safeguard which releases the limp home mode in case of exceeding the admissible maximum engine speed.

All of those functions can be extended and have to be defined during the development stage by the automobile transmission and electronic TCU manufacturers. To increase availability of the AT system, even with the failure of certain signals, it is possible to provide a substitute operation with better drivability than in the limp home mode. This can be done by substitute functions. The electronic TCU falls back on substitute values or signals in the case of a breakdown of certain interfaces. There is, for example, the possibility to run with a programmable fixed throttle value with a breakdown of the throttle position signal. This results in a reduction of the shift characteristics to shift points. Shifting into all gears is possible, however, with reduced shift comfort. A further method is to use secondary signals in case the original signals break down. For example, the calculation of vehicle speed can be from wheel speed during breakdown of the transmission output speed signal. This technique usually requires a connection between ABS and transmission control. The third variant is the canceling of certain functions if the necessary input signals are missed. For example, in the case of a kickdown switch failure, the kickdown function is canceled. This results in no downshift after operation of the kickdown. Downshifts are nevertheless still possible via the full-throttle opening point according to the full-load shift characteristic.

The availability and driveability of automobiles equipped with electronic TCU in case of system failures can be improved significantly with the implementation of substitute functions. This results in a considerable increase in acceptance by the drivers of automobiles with electronic transmission control.

13.3.3 Adaptation to Driver's Behavior and Traffic Situations

In certain driving conditions, some disadvantages of the conventional AT can be prevented by using self-learning strategies.⁹ This is especially valid when improving the compromise in the shift characteristics regarding gear selection under particular driving conditions and under difficult environmental conditions. The intention of the self-learning functions is to provide the appropriate shift characteristic suitable to the driver under all driving conditions. Additionally, the behavior of the car under special conditions can be improved by suitable functions. Available input signals of the car, provided by the related electronic TCUs from interfaces and communication links, are processed by the TCU with specific algorithms. The self-learning functions can be divided into a long respectively medium term adaptation for driver's style detection and into a short-term adaptation which reacts to the present driving situation, such as hills or curves.

The core of the adaptive strategies is the driver's style detection. The driver's style can be detected by monitoring of the accelerator pedal movements. The inputs are operation speed, operation frequency, and the rating position of the accelerator pedal. These inputs are processed depending on priorities with special algorithms related to the desired driving behavior of the car. The calculated driver style is related to certain shift maps. There is a large choice of shift maps available. With the currently known applications, there are mostly four different shift maps ranging from fuel economic to extremely sporty vehicle behavior. The calculated driver's style can also depend on the actual vehicle speed and the share of constant driving conditions during a certain driving cycle. These self-learning functions can be calibrated by the car manufacturer, depending on his philosophy and target market. In this way, the number of shift maps and the speed of the adaptation have the main influence. A further possibility to match the driver's style is by rating the accelerator pedal operation during vehicle start, for example, after a red light stop. In this way the operation speed and frequency of the accelera-

tor pedal below a certain vehicle speed can be interpreted and calculated as part of the driver's style rating. In the event of kickdown, the shift maps of the driver's style rating are shut down by a priority command. The driver has the usual behavior of the car during kickdown, generally a downshift, providing no other safety function is in operation.

To prevent shift hunting, the self-learning functions are carried out over a long respectively medium term adaptation with the adaptation timer ranging from several seconds up to one minute. The second part of the self-learning functions is the driving condition detection. There is a correlation between the input signals of the transmission control and the driving condition.

One of the main disadvantages of a conventional electronic transmission control is the upshifting at constant vehicle speed by crossing the upshift characteristic with a reduction of the accelerator pedal angle. This results in an unintended gear shift, especially when cornering and when approaching a crossing or an obstacle. To prevent these gear shifts it is possible to use so-called upshift prevention. Cornering can be detected by the acceleration of the car along the driving direction related to the vehicle speed. The vehicle speed is calculated from the transmission output speed. The acceleration can be detected by an acceleration sensor or by the difference between the nondriven wheel speeds. In this way it is possible to prevent the upshift when cornering, resulting in a considerable improvement in vehicle stability.

The detection of a crossing or obstacle approach is possible by the detection of a fast off condition of the accelerator pedal. At a certain gradient of the pedal position, the upshift is prevented. This is a considerable advantage especially when overtaking low-speed vehicles. With this strategy the correct gear is available without a shift delay.

Another part of the driving situation detection is the recognition of uphill driving and full-load conditions. This is possible by adding special functions to the adaptive gear shift control. When driving downhill, it makes sense to support the engine braking effect for a better deceleration of the car. Downhill driving can be detected by a comparison of throttle position and vehicle speed gradient. An upshift is prevented and, in some special cases, a downshift is activated by the electronic TCU.

A further section of the self-learning functions is the environmental monitoring with related shift strategies. A special application can be a self-learning winter program. The wheel slip of the driven wheels is compared with a set value of a combination of given wheel torque and vehicle speed. When exceeding a set limit of wheel slip, a special shift strategy is chosen. For example, the vehicle starts off in second gear or an upshift takes place at lower engine speeds.

The development of adaptive shift strategies started a few years ago and is currently one of the main areas in electronic transmission development. The efficiency of the self-learning functions has led to a wide acceptance of AT-equipped vehicles. The future development concerning new adaptive functions and an improvement of the already known functions is an important area in control development. This can be supported by an increasing share of electronic units and interfaces for the communication between units. With multiple use of sensors providing the necessary input signals, the total system gains increased functionality, especially with bus systems.

At present, an increasing share of manual programs with an AT can be registered. The driver instructs the AT to shift via a switch or a push button. In this manner, the driver can operate the AT like a manual gearbox independently of other shift maps, with only the safety functions in operation. This has led to a broad acceptance, especially in the sports car market. These functions can all be calibrated and applied by the car manufacturer with data relating to his philosophy and to the target market. The result is the prevention of the known disadvantages of the conventional AT control without canceling the advantages in driving comfort and safety.

13.4 COMMUNICATIONS WITH OTHER ELECTRONIC CONTROL UNITS

With the existence of electronic control units for various applications in vehicles, many opportunities exist to link these ECUs and to establish communications between them. The main partner of the TCU is the engine management system. Due to the coupling of engine and

transmission within the vehicle powertrain, it is necessary to have an interface between these ECUs for a functional coupling and an interchange of signals. It is essential for the pressure control inside the transmission control to sensor the engine load, the engine speed, and the throttle position. The engine torque reduction during shifting is also important to establish a good shift comfort and a satisfactory lifetime for the clutches. By handing over certain signals like position lever state, lockup condition, or shift commands to the engine management, the driving comfort of the vehicle can be improved significantly. An interface to ABS and traction control is useful for some self-learning functions in the transmission control when using the wheel speeds.

It is possible to implement certain shift strategies in the transmission control as an active support for ABS and traction control. A link to the electronic throttle control or cruise control makes it possible to optimize certain functions for the total vehicle. By interfaces between the ECUs, a reduction of the sensor expense results by a multiple use via communications. Suitable links include, especially, PWM or bus configurations for trouble-free communication. Bus systems in particular have the advantage of the link-up of additional ECUs without changing their existing hardware. Additional coupling requires only a software change. The interchange of required supplementary signals for new functions is possible without any problems. An example of powertrain management by coupling the powertrain ECUs to achieve lower fuel consumption, simultaneously improving the driveability, is described as follows.

13.5 OPTIMIZATION OF THE DRIVETRAIN

The newest generation of transmission controllers has overcome the former disadvantage regarding fuel efficiency. Adaptive functions in cooperation with carefully designed torque converter clutch control,⁸ which allows the clutch to be closed even at low gears, have improved fuel consumption significantly. Based on the driver's behavior, together with an adaptive shift strategy as previously described, part of the TCU's adaptive program software may select an economy or even super-economy shift strategy whenever possible. There is, however, still more potential for fuel economy by optimization of the drivetrain.

The concept called Mastershift¹⁰ is shown in Fig. 13.11. The basic idea is to interpret the accelerator pedal position as an acceleration request. That acceleration request, or a request for wheel torque, has to be converted by operating the engine at high torque, i.e., open throttle and low rpm values. In order to realize this, it is necessary to use an electronic throttle control system. The communication between the electronic throttle, the engine, and transmission is shown in Fig. 13.12.

Mastershift, concept for drivetrain optimization

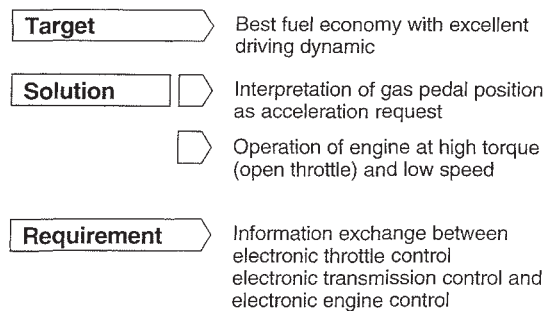


FIGURE 13.11 Drivetrain operation.

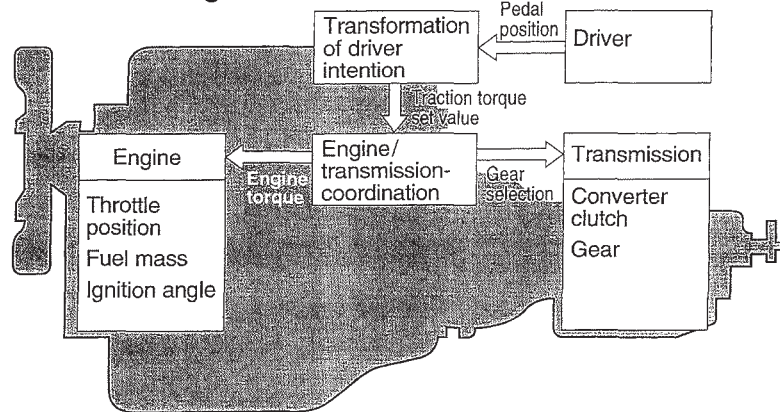
Mastershift – logical structure

FIGURE 13.12 Mastershift: logical structure and communication between different control systems.

In such a system, a well-defined coordination between the engine torque, mainly given by throttle position (air mass), fuel mass, and ignition angle on one side and selection of the appropriate gear including torque converter clutch on the other side, is imperative. Depending on the type of engine, fuel consumption can be reduced further by 5 to 10 percent with this optimized Mastershift concept. Because the average engine operation is at higher torque levels compared to standard systems, a greater number of gear shifts may occur. This is important to guarantee optimal shift comfort. Figure 13.13 shows how that can be accomplished by using the additional degree of freedom given by the electronic throttle control. It is possible to operate the throttle angle during the gear shift in such a way as to achieve constant wheel torque before and after downshifts.

13.6 FUTURE DEVELOPMENTS

In future years, development work will be concentrated on redesign of hardware components for cost reduction, improvement of yield to reduce fuel consumption, and improvement of driveability. A good approach to meet cost targets on the electronic hardware side would be to integrate two or more individual control modules into a common housing. Regarding the electronic components, one could continue using two separate microcontrollers. This would have the advantage that the software development and application could be done individually for two different systems, for example engine and transmission controllers. Another approach could be to mount the TCU on the transmission housing itself. This could lead to a significant reduction in the expense for the wiring harness. Here, however, the problem of hostile ambient temperatures on electronic components has to be solved. Today's stand-alone actuators could be integrated into a common housing similar to the solution shown by Chrysler Corp. in its A 604 transmission.

The improvement of the yield is a main topic for designers of ATs. Oil pumps and torque converters are a major source of energy losses. A significant improvement of yield will be possible as soon as torque converter clutches are available with the capability for continuous slip operation. The torque converter clutch can then be operated in low gears and at low engine speeds without facing problems from drivetrain oscillations and/or noise emission.

The driveability is the most important feature for the drivers' acceptance of ATs. In addition to the self-adaptive functions described, the implementation of shift strategies benefiting from control algorithms using fuzzy theory may further improve driveability.

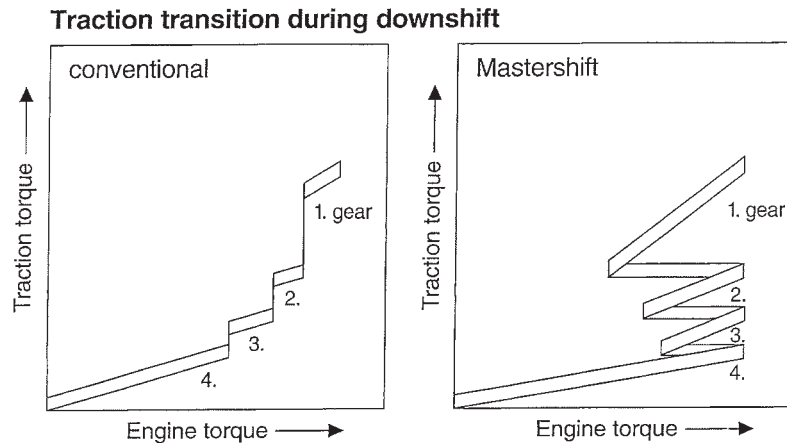


FIGURE 13.13 Constant traction torque by operation of throttle opening during gear shift.

GLOSSARY

- ASIC** Application-specific integrated circuit.
- AT** Automatic transmission.
- ATF** Automatic transmission fluid.
- CAN** Controller area network.
- CVT** Continuously variable transmission.
- EEPROM** Electrically erasable and programmable read-only memory.
- EMC** Electromagnetic compatibility.
- EPROM** Erasable programmable read-only memory.
- PWM** Pulse-width modulation.
- RAM** Random access memory.
- RFI** Radio frequency interference.
- TCC** Torque converter clutch.
- TCU** Transmission control unit.

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CHAPTER 14

CRUISE CONTROL

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Motorola Inc.

14.1 CRUISE CONTROL SYSTEM

A vehicle speed control system can range from a simple throttle latching device to a sophisticated digital controller that constantly maintains a set speed under varying driving conditions. The next generation of electronic speed control systems will probably still use a separate module (black box), the same as present-day systems, but will share data from the engine, ABS, and transmission control systems. Futuristic cruise control systems that include radar sensors to measure the rate of closure to other vehicles and adjust the speed to maintain a constant distance are possible but need significant cost reductions for widespread private vehicle usage.

The objective of an automatic vehicle cruise control is to sustain a steady speed under varying road conditions, thus allowing the vehicle operator to relax from constant foot throttle manipulation. In some cases, the cruise control system may actually improve the vehicle's fuel efficiency value by limiting throttle excursions to small steps. By using the power and speed of a microcontroller device and fuzzy logic software design, an excellent cruise control system can be designed.

14.1.1 Functional Elements

The cruise control system is a closed-loop speed control as shown in Fig. 14.1. The key input signals are the driver's speed setpoint and the vehicle's actual speed. Other important inputs are the faster-accel/slower-coast driver adjustments, resume, on/off, brake switch, and engine control messages. The key output signals are the throttle control servo actuator values. Additional output signals include cruise ON and service indicators, plus messages to the engine and/or transmission control system and possibly data for diagnostics.

14.1.2 Performance Expectations

The ideal cruise system features would include the following specifications:

- *Speed performance:* ± 0.5 m/h control at less than 5 percent grade, and ± 1 m/h control or vehicle limit over 5 percent grade.
- *Reliability:* Circuit designed to withstand overvoltage transients, reverse voltages, and power dissipation of components kept to minimum.

14.1

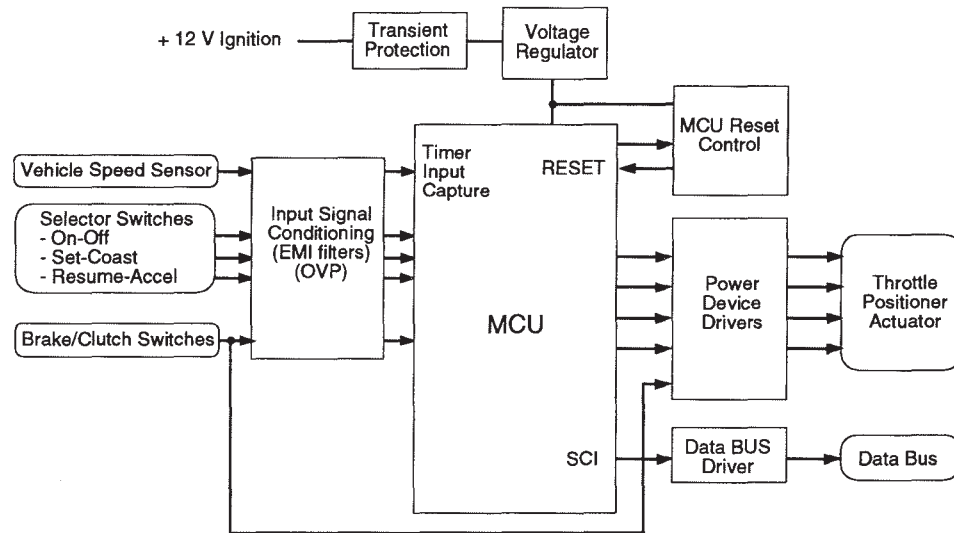


FIGURE 14.1 Cruise control system.

- *Application options:* By changing EEPROM via a simple serial data interface or over the MUX network, the cruise software can be upgraded and optimized for specific vehicle types. These provisions allow for various sensors, servos, and speed ranges.
- *Driver adaptability:* The response time of the cruise control can be adjusted to match the driver's preferences within the constraints of the vehicle's performance.
- *Favorable price-to-performance ratio:* The use of integrated actuator drivers and a high-functionality MCU reduce component counts, increase reliability, and decrease the cruise control module's footprint.

14.1.3 Safety Considerations (Failsafe)

Several safety factors need to be considered for a vehicle speed control design. The most basic is a method designed into the throttle control circuit to insure a failsafe mode of operation in the event that the microcontroller or actuator drivers should fail. This electronic failsafe circuit shuts off the control servos so that the throttle linkage will be released when the brake switch or cruise off switch is activated, no matter the condition of the MCU or servo actuator control transistors. (This assumes the actuators are mechanically in good shape and will release.)

Other safety-related items include program code to detect abnormal operating conditions and preserving into memory the data points associated with the abnormal condition for later diagnostics. Abnormal conditions, for example, could be an intermittent vehicle speed sensor, or erratic driver switch signals. A test could also be made during the initial ignition "key on time" plus any time the cruise is activated to verify the integrity of the cruise system, with any faults resulting in a warning indicator to the driver. Obviously, the most serious fault to avoid is runaway acceleration. Continuous monitoring of the MCU and key control elements will help minimize the potential for this type of fault.

14.2 MICROCONTROLLER REQUIREMENTS FOR CRUISE CONTROL

The MCU for cruise control applications requires high functionality. The MCU would include the following:

- a precise internal timebase for the speed measurement calculations
- A/D inputs
- PWM outputs
- timer input capture
- timer output compares
- serial data port (MUX port)
- internal watchdog
- EEPROM
- low-power CMOS technology

14.2.1 Input Signals

The speed sensor is one of the most critical parts in the system, because the microcontroller calculates the vehicle speed from the speed sensor's signal to within $\frac{1}{2}$ m/h. Any speedometer cable whip or oscillation can cause errors to be introduced into the speed calculation. An averaging routine in the speed calculations can minimize this effect. The speedometer sensor drives the microcontroller's timer input capture line or the external interrupt line. The MCU then calculates the vehicle's speed from the frequency of the sensor signals and the MCU internal timebase. The vehicle's speed value is continually updated and stored into RAM for use by the basic speed control program. Speed sensors traditionally have been a simple ac generator located in the transmission or speedometer cable. The ac generator produces an ac voltage waveform with its frequency proportional to the sensor's rpm and vehicle speed. Optical sensors in the speedometer head can also be incorporated. Usually the speed sensor produces a number of pulses or cycles per km or mile. With the increasing ABS system usage, a backup speed sensor value could be obtained from the ABS wheel speed sensors. The ABS speed data could be obtained by way of a MUX network.

The user command switch signals could either be single MCU input lines to each switch contact or a more complex analog resistor divider type to an A/D input line. Other input signals of interest to the cruise system program would be throttle position, transmission or clutch status, A/C status, actuator diagnostics, engine status, etc., which could be obtained over the MUX data network.

14.2.2 Program Flow

The microcontroller is programmed to measure the rate of vehicle speed and note how much, and in which direction, the vehicle speed is drifting. The standard PI (proportional-integral) method produces one output signal p that is proportional to the difference between the set-speed and actual vehicle speed (the error value) by a proportional gain block K_p . Another signal i is generated that ramps up or down at a rate set by the error signal magnitude. The gains of both K_i and K_p are chosen to provide a quick response, but with little instability. In effect, the PI system adds up the error rate over time, and, therefore, if an underspeed condition occurs as in a long uphill grade, the error signal integral will begin to greatly increase to try to compensate. Under level driving conditions, the integral control block K_i will tend toward zero

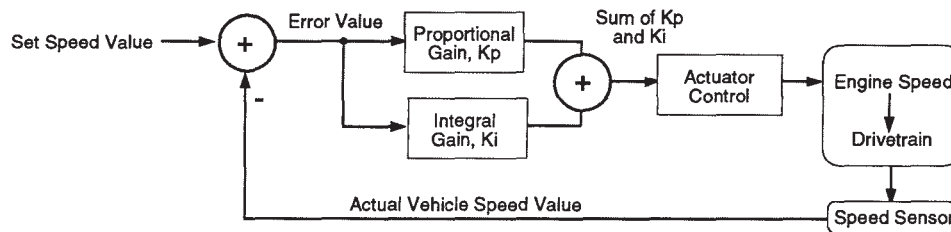


FIGURE 14.2 PI speed error control.

because there is less error over time. The vehicle's weight, engine performance, and rolling resistance all factor in to determine the PI gain constants. In summary, the PI method allows fast response to abrupt grades or mountains and stable operation under light grades or hills. Figure 14.2 shows the traditional PI cruise control diagram.

14.2.3 Output Controls

When the error signal has been computed, an output signal to the servo actuators is generated to increase, hold, or decrease the throttle position. The servo is updated at a rate that is within the servo's mechanical operating specifications, which could be several milliseconds. The error signal can be computed at a much faster rate and, therefore, gives extra time for some averaging of the vehicle speed sensor signal.

Throttle positioning is traditionally either a vacuum type servo or motor. The vacuum supply to the vacuum servo/actuator is discharged as a failsafe measure whenever the brake system is engaged in addition to the normal turn-off of the actuator driver coils. Electric servo type motors require more complex drive electronics and some type of mechanical failsafe linked backed to the brake system.

14.3 CRUISE CONTROL SOFTWARE

The cruise error calculation algorithm can be designed around traditional math models such as PI or fuzzy logic.

14.3.1 Fuzzy Logic Examples

Fuzzy logic allows somewhat easier implementation of the speed error calculation because its design syntax uses simple linguistics. For example: IF speed difference negative and small, THEN increase throttle slightly.

The output is then adjusted to slightly increase the throttle. The throttle position update rate is determined by another fuzzy program which looks for the driver's cruise performance request (slow, medium, or fast reaction), the application type (small, medium, or large engine size), and other cruise system factory preset parameters. Figure 14.3 shows one part of a fuzzy logic design for computing normal throttle position. Other parts would compute the effects of other inputs, such as resume, driver habits, engine type, and the like.

Other program design requirements include verification that the input signals fall within expected boundaries. For example, a broken or intermittent speed sensor could be detected.

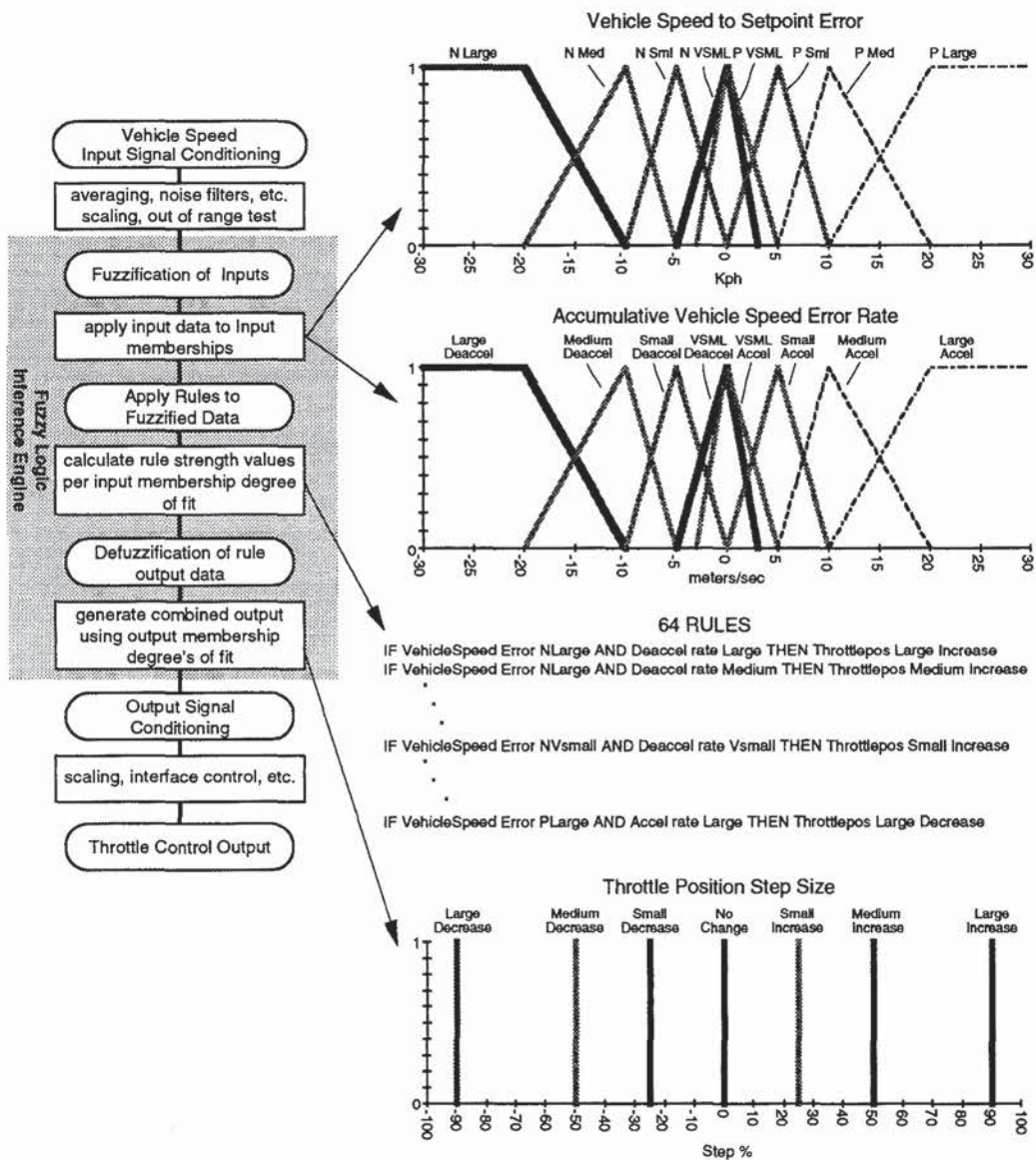


FIGURE 14.3 Fuzzy speed error program flow.

A heavily loaded vehicle with a small engine may not be able to maintain a high setpoint speed up a steep grade, and the cruise control needs to be disengaged to protect the engine from sustained full-throttle operation under a heavy load. This could be preset to occur 20 percent below the setpoint speed. Another program can test the vehicle speed to resume setpoint speed and prevent unsafe acceleration under certain conditions. For example, if a high-performance vehicle (>200-kW or 268-hp engine) has a setpoint speed of 125 km/h (78 mi/h), and drives from the freeway into heavy city traffic doing 48 km/h (30 mi/h) and the vehicle's

driver fortuitously hits the cruise resume switch at this low speed, the cruise control invokes a near full-throttle action, and an accident is likely. A fuzzy design can limit the acceleration upon resume using simple rules such as IF resume and big speed error, THEN increase throttle slightly.

14.3.2 Adaptive Programming

The response time and gain of the cruise system can be adjusted to match individual drivers. For example, some drivers may prefer to allow the vehicle to slow down somewhat when climbing a grade and then respond quickly to maintain a setspeed; other drivers may prefer a constant speed at all times, while still other drivers may prefer a very slow responding cruise system to maximize fuel efficiency. The cruise system can be adapted either by a user selection switch (slow, medium, fast) or by analyzing the driver's acceleration/deacceleration habits during noncruise operation. Once these habits are analyzed, they can be grouped into the three previously mentioned categories. One drawback of a totally automatic adaptive cruise system is when various drivers with vastly different driving preferences operate the vehicle on the same trip. The cruise system would have to be "retrained" for each driver.

14.4 CRUISE CONTROL DESIGN

Many of the required elements of a cruise control can be integrated into one single-chip MCU device. For example, the actuator drivers can be designed in the MCU if their power requirements are on the low side.

14.4.1 Automatic Cruise System

Figure 14.4 shows an experimental system design for a cruise control based upon a semicustom 8 or 16-bit single-chip MCU that incorporates special high-power output driver elements and a built-in voltage regulator.

14.4.2 Safety Backup Examples

The design of a cruise control system should include many safeguards:

- A test to determine vehicle speed conditions or command inputs that do not fall within the normal conditions for operation of the cruise control function.
- A test to determine if the vehicle speed has decreased below what the cruise routine can compensate for.
- Speed setpoint minimums and maximums (30 km/h min to 125 km/h max, for example) are checked and, if exceeded, will cause the cruise function to turn off.
- Speedometer cable failure is detected by checking for speed sensor electrical output pulses over a 100-ms time period and, if these pulses are absent, the system is disengaged.
- Software program traps should also be scattered throughout the program and, if memory permits, at the end of each program loop. These will catch an out-of-control program and initiate a vector restart.

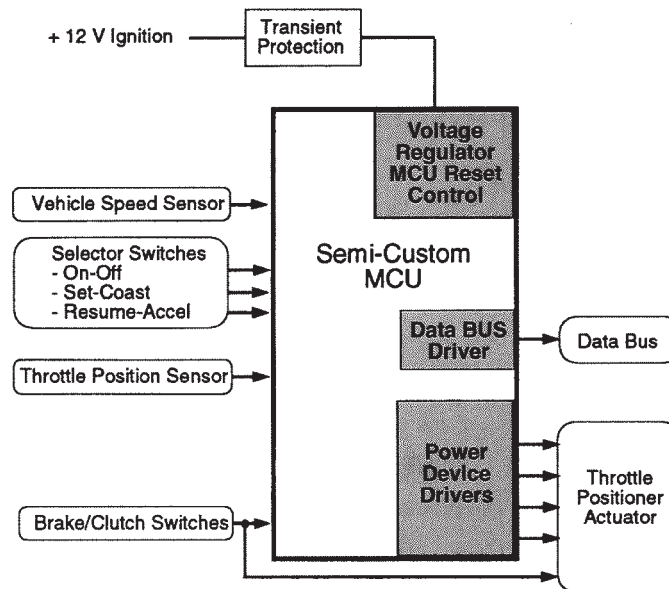


FIGURE 14.4 Automatic cruise control.

14.4.3 EMI and RFI Noise Problems

As with any electronic design, consideration must be given to suppressing RFI (radio frequency interference) from the circuit, besides minimizing effects of external EMI (electromagnetic interference) and RFI to the circuit's normal operation. It is not uncommon that the circuit must operate in RF fields up to 200 V/m intensity. This requires careful layout of the module's PCB (printed circuit board) and RF filters on all lines going in or out of the module. The module case may even have to contain some type of RF shielding. Minimizing generated RFI from the cruise circuit can be accomplished by operating the MCU's crystal oscillator at a minimal power level (this is controlled mostly by the MCU internal design), careful PCB trace layout of the MCU oscillator area, metal shielding over the MCU, ground planes on the PCB under the MCU, and setting the actuator switching edge transition times to over 10 ms. (See Chaps. 27 and 28.)

14.5 FUTURE CRUISE CONCEPTS

Several research projects are underway to develop a crash avoidance system that could be interconnected with a cruise system. The development of a low-cost distance sensor that can measure up to a few hundred meters away with a tight focal point in all weather conditions is proving to be a challenge. When a practical vehicular distance sensor is available, the cruise control can be programmed to maintain either constant speed or constant distance to another vehicle. Other methods of cruise control could include receiving a roadside signal that gives an optimum speed value for the vehicle when travelling within certain traffic control areas.

14.5.1 Road Conditions Integration with IVHS

The IVHS (Intelligent Vehicle-Highway System) network may be a more practical approach to setting optimum cruise speed values for groups of vehicles. The IVHS can monitor road conditions, local weather, etc., and broadcast optimal speed data values for vehicles in its zone. (See Chap. 29.)

GLOSSARY

Analog input Sensors usually generate electrical signals that are directly proportional to the mechanism being sensed. The signal is, therefore, analog or can vary from a minimum limit to a maximum limit. Normally, an 8-bit MCU A/D input using a 5-V reference, the analog input resolution is 1 bit, which is 1/256 of 5 V or 0.0193 V.

Defuzzification The process of translating output grades to analog output values.

Fuzzification The process of translating analog input values to input memberships or labels.

Fuzzy logic Software design based upon a reasoning model rather than fixed mathematical algorithms. A fuzzy logic design allows the system engineer to participate in the software design because the fuzzy language is linguistic and built upon easy-to-comprehend fundamentals.

Inference engine The internal software program that produces output values through fuzzy rules for given input values. The inference process involves three steps: fuzzification, rule evaluation, and defuzzification.

Input memberships The input signal or sensor range is divided into degrees of membership, i.e., low, medium, high or cold, cool, comfortable, warm, hot. Each of these membership labels is assigned numerical values or grades.

Output memberships The output signal is divided into grades such as off, slow, medium, fast, and full-on. Numerical values are assigned to each grade. Grades can be either singleton (one value) or Mandani (a range of values per grade).

Rule evaluation Output values are computed per the input memberships and their relationship to the output memberships. The number of rules is usually set by the total number of input memberships and the total number of output memberships. The rules consist of IF inputvarA is x , AND inputvarB is y , THEN outvar is z .

Semicustom MCU An MCU (microcontroller unit) that incorporates normal MCU elements plus user-specified peripheral devices such as higher-power port outputs, special timer units, etc. Mixed semiconductor technologies, such as high-density CMOS (HCMOS) and bipolar analog, are available in a semicustom MCU. Generally, HCMOS is limited to 10 V, whereas bipolar-analog is usable to 60 V.

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CHAPTER 15

BRAKING CONTROL

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15.1 INTRODUCTION

This chapter describes braking by first examining vehicle braking fundamentals, including the tire-to-road interface, vehicle dynamics, and conventional brake system components, and progressing to antilock systems objectives, components, safety considerations, control logic, and testing. The chapter concludes with a discussion of future vehicle braking systems.

For simplicity and because of applicability to the majority of automotive vehicles on the road, hydraulic brake systems as used on two-axle, nonarticulated vehicles will be discussed exclusively; this type of brake system is used on passenger cars, light trucks, and, in North America, on medium trucks.

15.2 VEHICLE BRAKING FUNDAMENTALS

Essential to the understanding of the technology associated with modern automotive vehicle braking is knowledge of the tire-to-road interface, vehicle dynamics during braking, and the components of a brake system. This section discusses these subjects to a system level of understanding.

15.2.1 Tire-to-Road Interface

The braking force generated at each wheel of a vehicle during a braking maneuver is a function of the normal force on the wheel and the coefficient of friction between the tire and the road. The simplified relationship between the weight on a wheel and the resulting frictional (braking) force is shown in Eq. (15.1).

$$F_x = \mu W_{wh} \quad (15.1)$$

where F_x = friction force \times direction
 μ = coefficient of friction, tire-to-road
 W_{wh} = static and dynamic weight on the wheel

15.1

The tire-to-road coefficient of friction is not a constant but is a function of factors, most prominent being type of road surface and the relative longitudinal slip between the tire and the road. General curves relating coefficient of friction to wheel slip on various surfaces are shown in Fig. 15.1. From this figure and Eq. (15.1), the following observations are evident:

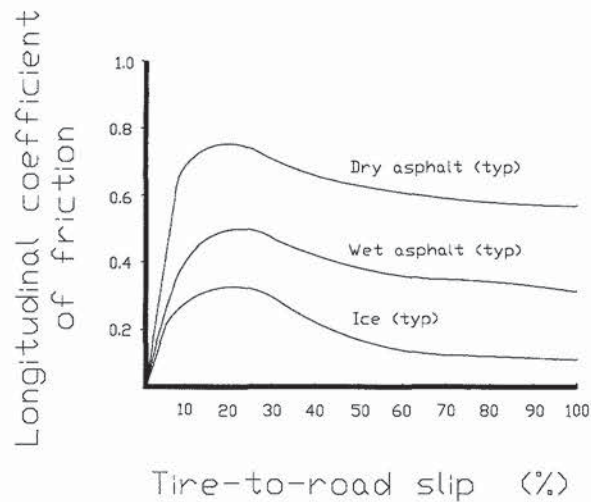


FIGURE 15.1 Longitudinal coefficient of friction as a function of wheel slip.

- The generation of frictional forces depends on wheel slip. If the tire is rolling at the same tangential velocity as the road surface, there is no longitudinal (braking) force. This relationship is fundamental in understanding braking and is not easily observed: wheel slip other than near 100 percent (no rotational wheel speed) is difficult to discern without instrumentation.
- The peak frictional (braking) force occurs under conditions of relatively little slip. This indicates that a hard apply of the brakes which causes a 100 percent slip typically does not produce the most braking force and an evenly modulated, controlled brake pressure applied by a skilled driver or through antilock control tends to produce shorter stops on most surfaces.
- The frictional (braking) force generated varies widely with road surface. The result of this relationship is obvious to both drivers and passengers in terms of stopping distance and deceleration if dry asphalt braking is compared with braking on ice.
- Typically, beyond the peak coefficient of friction attainable on a given road surface, the slope of the curve becomes negative. This phenomenon (essentially indicating that, beyond the slip resulting in peak frictional force, more pedal force results in less braking) explains why a skilled driver can attain significantly shorter stopping distances than can a less experienced driver and why electronic vehicle braking control is as complicated as it is. Also, the amount of "peak" in the coefficient of friction curves varies widely with road surface. More braking force benefit can be gained through slip control on surfaces such as ice than on dry asphalt, for example.

Another characteristic of automotive tires important in braking is lateral force versus slip. Lateral force is the force keeping a tire from sliding in a direction normal to the direction of the vehicle. The equation for lateral force is as follows:

$$F_y = \mu_{\text{lateral}} W_{wh}$$

where F_y = friction force, by direction
 μ_{lateral} = lateral coefficient of friction, tire-to-road

The lateral coefficient of friction drops off quickly once a wheel begins to slip longitudinally, as can happen during braking. Excessive wheel slip at the rear wheels of a vehicle and the resulting loss of lateral frictional force will contribute to instability as the rear of the vehicle tends to slide sideways with relatively small lateral forces on the vehicle. Excessive wheel slip and the resulting loss of lateral friction force on the front wheels of a vehicle will contribute to loss of steerability; this loss of steering phenomenon is common during panic stops on low coefficient surfaces such as ice, as a hard apply of the brakes puts the tires in a 100 per cent slip situation.

15.2.2 Vehicle Dynamics During Braking

An equation for braking performance can be obtained from Newton's second law: the sum of the external forces acting on a body in a given direction is equal to the product of its mass and the acceleration in that direction. Relating this law to straight-line vehicle braking, the significant factors are shown in Eq. (15.2) and the sum of the forces acting on the vehicle is shown in Fig. 15.2.¹

$$\Sigma F = Ma_x = \frac{+W}{g} D_x = +F_{xf} + F_{xr} + D_A + W \sin \Theta + f_r W \cos \Theta \quad (15.2)$$

where M = mass of the vehicle
 a_x = linear acceleration in the x direction
 W = weight of the vehicle
 g = acceleration due to gravity
 $D_x = -a_x$ = linear deceleration
 F_{xf} = front axle braking force
 F_{xr} = rear axle braking force
 D_A = aerodynamic drag (considered to be acting at a point)
 Θ = angle of roadway
 f_r = rolling resistance coefficient = $(R_{xf} + R_{xr}) / W \cos \Theta$

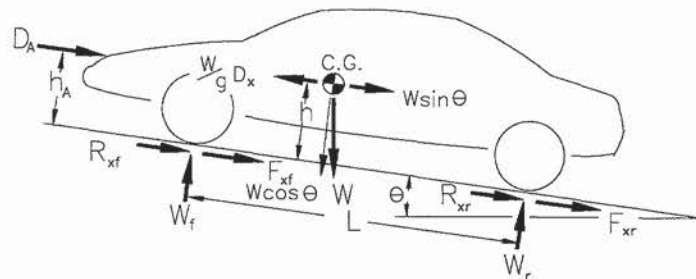


FIGURE 15.2 Significant forces' action on a vehicle during braking.

If braking forces are held constant and the vehicle velocity effects on aerodynamic drag and rolling resistance are neglected, the time for a vehicle velocity change, Eq. (15.3), and the distance traveled during a velocity change, Eq. (15.4), can also be derived from Newton's second law.²

$$t = \frac{M}{F_{xt}} (V_o - V_f) \quad (15.3)$$

where F_{xt} = total of all longitudinal deceleration forces on the vehicle
 t = time
 V_o = initial velocity
 and V_f = final velocity

$$x = \frac{M}{F_{xt}} \left(\frac{V_o^2}{2} - \frac{V_f^2}{2} \right) \quad (15.4)$$

where x = distance in forward direction

These approximations indicate that the time to stop is proportional to vehicle velocity and the stopping distance is proportional to the square of the vehicle velocity.

During braking, the dynamic load transfer that occurs is a function of the height of the center of gravity, the weight of the vehicle, the wheelbase, and the deceleration rate. Equation 15.5 describes this dynamic load shift.

$$W_d = \left(\frac{h}{L} \right) \left(\frac{W}{g} \right) D_x - \frac{h_A}{L} D_A \quad (15.5)$$

where W_d = dynamic weight
 h = center of gravity height
 L = wheelbase
 W = static vehicle weight
 g = acceleration due to gravity
 D_x = deceleration in the forward direction
 h_A = height of the aerodynamic drag

Considering two-axle vehicles, this load transfer is additive to the front wheels and subtractive to the rear wheels during braking, as shown in Eq. (15.6) and (15.7), respectively.

$$F_{xmf} = \mu_p \left(W_{fs} + \frac{hWD_x}{Lg} - \frac{h_A}{L} D_A \right) \quad (15.6)$$

where F_{xmf} = maximum friction force in the longitudinal direction on the front wheels
 μ_p = peak coefficient of friction
 W_{fs} = static weight on the front wheels

$$F_{xmr} = \mu \left(W_{rs} - \frac{hWD_x}{Lg} + \frac{h_A}{L} D_A \right) \quad (15.7)$$

where F_{xmr} = maximum friction force in the longitudinal direction on the rear wheels
 W_{rs} = static weight on the rear wheels

Simplifying Eq. (15.2) for the case of $\Theta = 0^\circ$ and negligible aerodynamic drag and rolling resistance yields the following:

$$\sum F = \frac{W}{g} D_x = +F_{xf} + F_{xr}$$

Solving for D_x and substituting in simplified Eqs. (15.6) and (15.7) yields Eq. (15.8) and (15.9), respectively:

$$F_{xmf} = \mu \frac{\left(W_{fs} + \frac{hF_{xmr}}{L} \right)}{1 - \mu_p \frac{h}{L}} \quad (15.8)$$

$$F_{xmr} = \mu \frac{\left(W_{rs} + \frac{hF_{xmf}}{L} \right)}{1 - \mu_p \frac{h}{L}} \quad (15.9)$$

These relationships indicate that the maximum braking force on the front wheels is dependent on the braking force on the rear wheels through the deceleration and the associated forward load transfer and, in a similar fashion, the braking force on the rear wheels is dependent on the braking force on the front wheels.

Through application of the preceding equations, brake systems designers can determine the total braking force required to achieve the desired deceleration, and the brake system components can be sized appropriately. Safety and legal requirements dictate that system designers consider deceleration under vehicle loaded and unloaded conditions as well as under partially failed brake system conditions (either half-system failures or loss of brake boost to the entire system). Because of these considerations and numerous others, such as desired customer pedal stroke and pedal force/deceleration expectations, vehicle brake system sizing is a complicated engineering effort usually accomplished with the aid of a vehicle simulator computer program.

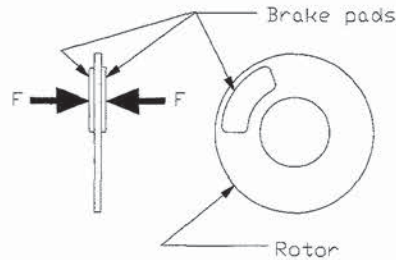


FIGURE 15.3 Disk brake schematic.

15.2.3 Brake System Components

Disk Brakes. Figure 15.3 shows a schematic diagram of a disc brake. In this type of brake, force is applied equally to both sides of a rotor and braking action is achieved through the frictional action of inboard and outboard brake pads against the rotor. The pads are contained within a caliper (not shown), as is the wheel cylinder. Although not a high-gain type of brake, disk brakes have the advantage of providing relatively linear braking with lower susceptibility to fading than drum brakes.

Force applied to the rotor by the pads is a function of hydraulic pressure in the brake system and the area of the wheel cylinder (or cylinders, as the design dictates). Static brake torque can be calculated using the following equation:

$$T = PAER \quad (15.10)$$

where T = brake torque
 P = application pressure
 A = wheel cylinder area
 E = effectiveness factor: ratio of the disk rubbing surface to the input force on the shoes
 R = brake radius

The static brake force can be calculated with the following relationship:

$$F_b = \frac{T}{r}$$

where F_b = brake force
 r = tire rolling radius

Drum Brakes. Figure 15.4 depicts a schematic diagram of a drum brake. In drum brakes, force is applied to a pair of brake shoes in a variety of configurations, including leading/trailing shoe (simplex), duo-duplex, and duo-servo. Drum brakes feature high gains relative to disk brakes, but some configurations tend to be more nonlinear and sensitive to fading and other brake lining coefficient-of-friction changes.

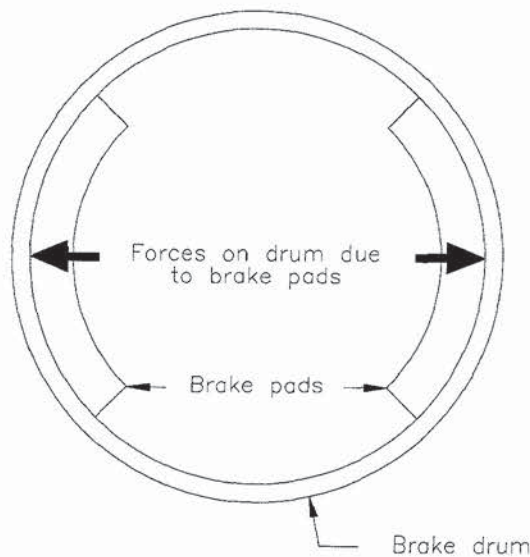


FIGURE 15.4 Drum brake schematic.

The static brake torque equation previously presented for disk brakes, Eq. (15.10), is equally applicable to drum brakes with design-specific changes for drum brake radius and effectiveness factor. By design, the brake radius for a drum brake is one-half the drum diameter. The effectiveness factor represents the major functional difference between drum and disk brakes; the geometry of drum brakes may allow a moment to be produced by the friction force on the shoe in such a manner as to rotate it against the drum and increase the friction force developed. This action can yield a mechanical advantage that significantly increases the gain of the brake and the effectiveness factor as compared with disk brakes. The dynamic brake force calculation for drum and disk brakes is more complex since the brake lining coefficient of friction is a function of temperature; as the lining heats during a braking maneuver, the effective coefficient of friction increases and less pressure is needed to maintain a constant brake torque.

Booster and Master Cylinder. Figure 15.5 is a schematic of a brake pedal, a vacuum booster, and a master cylinder. In actual practice, in passenger cars and light trucks the mechanical force gain due to the brake pedal geometry is usually 3 to 4 and the gain through a vacuum

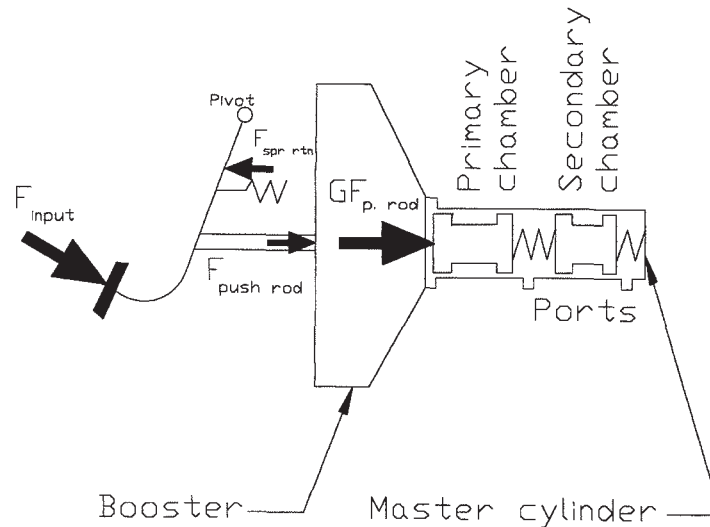


FIGURE 15.5 Brake pedal, vacuum booster, and master cylinder schematics.

booster is typically 5 to 9 after the booster reaches its crack point and before runout occurs. Therefore, force applied by the operator typically will be multiplied by a factor of 12 to 36 at the master cylinder in order to achieve the pressure necessary for braking. The resulting pressure in the master cylinder is as follows:

$$P_{MC} = \eta \frac{(F_{op} G_{mech} G_{boost} - F_s)}{A_{piston}}$$

where η = mechanical efficiency

P_{MC} = master cylinder pressure

F_{op} = operator force on the brake pedal

G_{mech} = mechanical gain primarily related to the brake pedal assembly geometry and the instantaneous return spring force

G_{boost} = brake booster gain, a function with the nonlinearities of a minimum crack force being necessary to initiate boost and a runout phenomenon resulting in a decreased force gain after a given input force is applied

F_s = return spring force

A_{piston} = area in the master cylinder on which the force is acting (chamber piston area)

Master cylinders are separated into primary and secondary chambers to improve safety by avoiding total brake system loss in case of a failure in one portion of the system. The most common configuration is shown in Fig. 15.5 with two chambers in a single bore.

Proportioning Valve. Due to the dynamic weight shift, as shown in Eq. (15.5), brake pressures that are appropriate for high-deceleration braking on front wheels usually are too high for the rear wheels; the result is that the rear wheels will tend to lock during braking. This problem can be decreased significantly through the use of proportioning valves. Standard proportioning valves allow equal front and rear brake pressures during low input pressures (corresponding to low deceleration rates and little dynamic load shift) but decrease the gain through the valve to less than one when a fixed input pressure (crack pressure) is reached. More sophisticated load-sensing valves are used in some applications when necessary, such as

when dynamic load shifts and vehicle loading changes are wide enough to make a fixed proportioning valve insufficient for proper braking in all conditions. Load-sensing valves feature a means to measure the weight on the rear wheels and adjust the gain through the valve accordingly.

Figure 15.6 shows the two most common passenger car and light truck system schematics including proportioning valves. The vertically split brake system typically is used on rear-wheel-drive vehicles and the diagonally split system is typically used on front-wheel-drive vehicles.

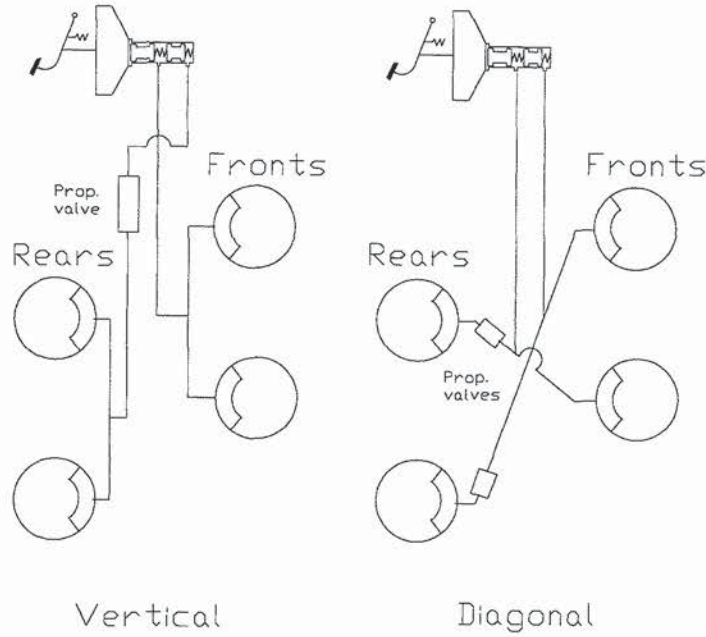


FIGURE 15.6 Vertical and diagonal split brake systems schematics.

Widespread use of diagonally split systems has been a direct result of the popularity of front-wheel-drive vehicles. Current law requires a half-system (hydraulic) failure stopping rate that is difficult to meet if the half system is the rear brakes (on a vertically split system) and the vehicle weight is significantly shifted towards the front as it is in front-wheel-drive vehicles. Diagonally split systems afford the use of one front brake regardless of the half-system failure, and front-wheel-drive vehicles can be made to pass the legal requirements despite the typically large difference between the weight on the front and on the rear wheels. However, diagonally split systems require two proportioning valves and tend to require more complex hydraulic plumbing than do vertically split systems.

15.3 ANTILOCK SYSTEMS

Although antilock concepts have been known for decades, widespread use of antilock (also called antiskid and ABS) began in the 1980s with systems developed with digital microprocessors/microcontrollers replacing the earlier analog units. An antilock system consists of a

hydraulic modulator and hydraulic power source that may or may not be integrated with the system master cylinder and booster, wheel speed sensors, and an electronic control unit. The fundamental function of an antilock system is to prohibit wheel lock by sensing impending wheel lock and taking action through the hydraulic modulator to reduce the brake pressure in the wheel sufficiently to bring the wheel speed back to the slip level range necessary for near-optimum braking performance.

15.3.1 Objectives

The objectives of antilock systems are threefold: to reduce stopping distances, to improve stability, and to improve steerability during braking.

Stopping Distance. As shown in Eq. (15.4), the distance to stop ($V_f = 0$) is a function of the initial velocity, the mass of the vehicle, and the braking force. From this equation it can be seen that by maximizing the braking force the stopping distance will be minimized, all other factors remaining constant. From Fig. 15.1 it is evident that on all types of surfaces, to a greater or lesser extent, there exists a peak frictional force. It follows that by keeping all of the wheels of a vehicle near the peak, an antilock system can attain maximum frictional force and, therefore, minimum stopping distance. This is an objective of antilock systems; however, it is tempered by the need for vehicle stability and steerability.

Stability. Although decelerating and stopping vehicles constitutes a fundamental purpose of braking systems, maximum friction force may not be desirable in all cases. For example, if a vehicle is on a split-coefficient surface, (asphalt and ice, for example), such that significantly more braking force is obtainable on one side of the vehicle than on the other side, applying maximum braking force on both sides will result in a yaw moment that will tend to pull the vehicle to the high-coefficient side and contribute to vehicle instability. Typically, on short-wheelbase vehicles a control strategy is employed to control the pressure in the rear wheels together to improve stability; similarly, it is common for a front-wheel strategy to be employed to limit the initial side-to-side pressure difference so as to not induce excessive moment changes in the steering wheel and force the operator to make excessive steering corrections to counteract the yaw moment.

If an antilock system can keep the vehicle wheels near the peak frictional force range, then lateral force is reasonably high, though not maximized. This contributes to stability and is an objective of antilock systems.

Steerability. Steerability depends on high lateral force. Good peak frictional force control is necessary in order to achieve satisfactory lateral force and, therefore, satisfactory steerability. Steerability while braking is important not only for minor course corrections but also for the possibility of steering around an obstacle. Antilock systems provide this feature through control to the peak frictional force range.

15.3.2 Antilock Components

The components of an antilock system are the wheel speed sensors, the hydraulic modulator, the hydraulic power source (usually an electric motor/pump), and the electronic control unit.

Wheel Speed Sensors. Due to simplicity and proven reliability, variable reluctance wheel speed sensors typically are used in antilock systems. Used in conjunction with exciter rings, this type of sensor produces a sinusoidal output that is directly proportional in frequency and amplitude to the angular velocity of the sensed wheel.

Depending on the design of the sensor and exciter ring and the gap between them, the sensor output amplitude may be as low as 100 mV at very low vehicle speeds and over 100 V at high vehicle speeds.

Both single-pole and dual-pole variable reluctance sensors are used, depending on the application: single-pole sensors tend to have higher outputs and dual-pole sensors tend to have better immunity to some types of noise. A limitation of this technology is that the very low speed output tends to be too low to be sensed reliably by the electronic control unit, given the electrically noisy environment typical of vehicles. This can result in errors below 1 to 3 m/h and cumulative inaccuracies if this sensor is used in conjunction with an odometer function; normally, antilock function is inhibited at very low speeds. Both single-ended and balanced inputs are used in electronic control units to receive wheel speed signals. A variety of active sensor technologies, including Hall effect and magnetoresistive, can be used in applications requiring very low speed sensing and in applications in which an appropriate signal level cannot be achieved with conventional variable reluctance sensors.

Hydraulic Modulators. Hydraulic modulators typically take two forms in production antilock systems: solenoid valves and electric motors. A simplified solenoid valve system schematic is shown in Fig. 15.7. In this system, if the solenoid valves are de-energized, hydraulic fluid is free to flow between the master cylinder and the brakes. If too much pressure is presented to the brakes and wheel lock is imminent, the antilock system will actuate a solenoid valve and energize the hydraulic pump. Actuation of the solenoid valve allows pressure to decrease from the brake through the valve to a low-pressure accumulator/sump. The fluid is temporarily stored in the sump prior to being pumped back into the system by the hydraulic pump. Through repetitive energization/de-energization cycles, average pressure to a given wheel can be regulated to the level necessary to achieve the desired braking force. Typical brake pressure and resulting wheel speed cycling is shown in Fig. 15.8.

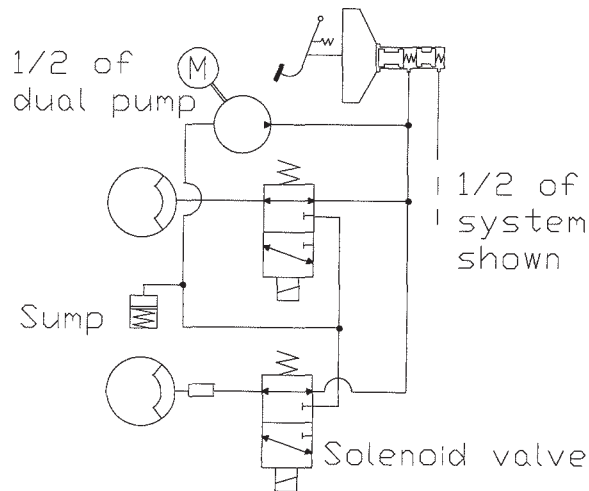


FIGURE 15.7 Simplified solenoid valve antilock system schematic.

Electric Motor/Pump. Although some antilock systems use multiple electric motors driving pistons to provide multiple-channel pressure reduction and rebuild, usually an electric motor-driven pump is used in conjunction with solenoid valves to achieve individual brake or brake channel pressure reduction and rebuild. A dual pump is often used to maintain a complete hydraulic separation of the two channels of the brake system. This is done to ensure that failure in one channel of the brake system will not affect operation of the other channel.

Electronic Control Unit. Control of the hydraulic modulator and electric motor/pump is performed by the electronic control unit. Modern customer expectations coupled with