Automotive Fundamentals

Picture yourself in the not-too-distant future driving your new car along a rural interstate highway on a business trip. You are traveling along one of the new automated highways in which individual cars are controlled electronically to maintain a fixed spacing in a lane at a preferred speed. Typically, these cars are traveling at 70 mph and are spaced about 25 ft apart. The cars are computer controlled via a digital communication link, including a cable buried in the center of the "cruise" lane and follow one another in a pattern known as platooning. Your car will automatically remain in this cruise control lane until you approach your destination exit.

You press a button on the steering column and an image of a road map appears faintly visible (so as not to obscure the road ahead) on the windshield in front of you. This map shows your present position and the position of the destination city. The distance to your destination and the approximate arrival time are displayed on the digital instrument cluster.

You are talking on your cellular phone to your office about some changes in a contract that you hope to negotiate. You are wearing a lightweight headset that enables you to use the cell phone "hands free" to drive. Dialing is accomplished by voice command using voice recognition software in your cell phone controller. After the instructions for the contract changes are completed, a printer in your car generates a copy of the latest contract version.

Your spouse (in the passenger seat) is sending e-mail messages using the on-board computer that is linked by radio to the Internet. Your son (in the rear seat) is watching a movie via an interactive digital link, while your daughter (also in a rear seat) is doing a math lesson from an education center with an interactive video link.

After you finish your phone call, the onboard entertainment system starts playing music for you at a comfortable level relative to the low-level wind and road noise in the car. After completing your phone conversation, you press another button on the steering wheel and the music is replaced by a recorded lesson in French verb conjugation, which you have been studying. Suddenly, the French lesson is interrupted by a message delivered in natural-sounding synthesized speech. "You have fuel remaining for another 50 miles at the present speed. Your destination is 23 miles away. Recommend refueling after exiting the highway. There is a station that accepts your electronic credit near the exit (you know, of course, that the electronic credit is activated by inserting the fuel nozzle into the car). Also, the left rear tire pressure is low and the engine control system reports that the mass air flow sensor is intermittently malfunctioning and should be serviced soon." After this message has been delivered, the French lesson returns.

A short time later, the French lesson is again interrupted by the electronic voice message system: “Replace the disk in the Navigation CD player with disk number 37 for detailed map and instructions to your destination, please.” Then the French lesson returns.

You insert the correct disk in the Navigation CD player as requested and the map display on the windshield changes. The new display shows a detailed map of your present position and the route to your destination. As you approach the city limits, the car speed is automatically reduced to the legal limit of 55 mph. The voice message system speaks again: “Leave the highway at exit 203, which is one-half mile away. Proceed along Austin Road to the second intersection, which is Meyer Road. Turn right and proceed 0.1 mile. Your destination is on the right-hand side of the road. Don’t forget to refuel.”

This scenario is not as farfetched as it sounds. All of the events described are technically possible. Some have even been tested experimentally. The electronic technology required to develop a car with the features described exists today. The actual implementation of such electronic features will depend on the cost of the equipment and the market acceptance of the features.

USE OF ELECTRONICS IN THE AUTOMOBILE

For most people, the automobile has come to be an appliance. It is arguably the most cost effective, most user friendly of appliances available today. The personal computer industry likes to refer to its products as user friendly. However if the automobile had the same user friendliness as a PC, it would arrive in six or more large boxes and require the owner to install the engine wheels and seats and load the programs into its various electronic systems and the documentation would be unreadable. Moreover, in use it would break down every 100 or so miles. This comparison is offered tongue in cheek, but it does illustrate the relatively high reliability of modern automobiles with their various electronic subsystems. Although its utility is primarily for transportation, the new automobile electronics can give it a broad range of auxiliary capabilities, as will be illustrated in this book.

EVOLUTION OF AUTOMOTIVE ELECTRONICS

Microelectronics will provide many exciting new features for automobiles.

Electronics have been relatively slow in coming to the automobile primarily because of the relationship between the added cost and the benefits. Historically, the first electronics (other than radio) were introduced into the commercial automobile during the late 1950s and early 1960s. However, these features were not well received by customers, so they were discontinued from production automobiles.

Environmental regulations and an increased need for economy have resulted in electronics being used within a number of automotive systems.

Two major events occurred during the 1970s that started the trend toward the use of modern electronics in the automobile: (1) the introduction of government regulations for exhaust emissions and fuel economy, which required better control of the engine than was possible with the methods being used; and (2) the development of relatively low cost per function solid-state digital electronics that could be used for engine control and other applications.

Electronics are being used now in the automobile and probably will be used even more in the future. Some of the present and potential applications for electronics are

1. Electronic engine control for minimizing exhaust emissions and maximizing fuel economy
2. Instrumentation for measuring vehicle performance parameters and for diagnosis of on-board system malfunctions
3. Driveline control
4. Vehicle motion control
5. Safety and convenience
6. Entertainment/communication/navigation

Many of these applications of electronics will be discussed in this book.

CHAPTER OVERVIEW

This chapter will give the reader a general overview of the automobile with emphasis on the basic operation of the engine, thus providing the reader with the background to see how electronic controls have been and will be applied. The discussion is simplified to provide the reader with just enough information to understand automotive mechanics. Readers who want to know the mechanics of an automobile in more detail are referred to the many books written for that purpose.

THE AUTOMOBILE PHYSICAL CONFIGURATION

The earliest automobiles consisted of carriages (similar to those drawn by horses) to which a primitive engine and drivetrain and steering controls were added. Typically, such cars had a strong steel frame that supported the body of the car. The wheels were attached to this frame by a set of springs and shock absorbers that permitted the car to travel over the uneven road surfaces of the day while isolating the car body from many of the road irregularities. This same general configuration persisted in most passenger cars until some time after World War II, although there was an evolution in car size, shape, and features as technology permitted. Beginning in the late 1960s, government regulations imposed severe design constraints on automobiles that led (as will be shown) to an evolution of electronic systems in automotive design. It is this evolution that is the primary focus of this book.

For the remainder of this chapter, the basic automobile components and systems are reviewed as they pertained to the post–World War II, preemissions-control era. This review provides a framework within which the present day automobile with its extensive use of electronics can be understood. In this sense, the motivation for applying electronics to solve regulatory problems imposed on the industry can readily be seen. Readers with a solid background in basic automotive systems may want to skip the remainder of the present chapter.

This early configuration is depicted in Figure 1.1, in which many of the important automotive systems are illustrated. These systems include the following:

1. Engine
2. Drivetrain (transmission, differential, axle)
3. Suspension
4. Steering
5. Brakes
6. Instrumentation
7. Electrical/electronic
8. Motion control
9. Safety
10. Comfort/convenience
11. Entertainment/communication/navigation

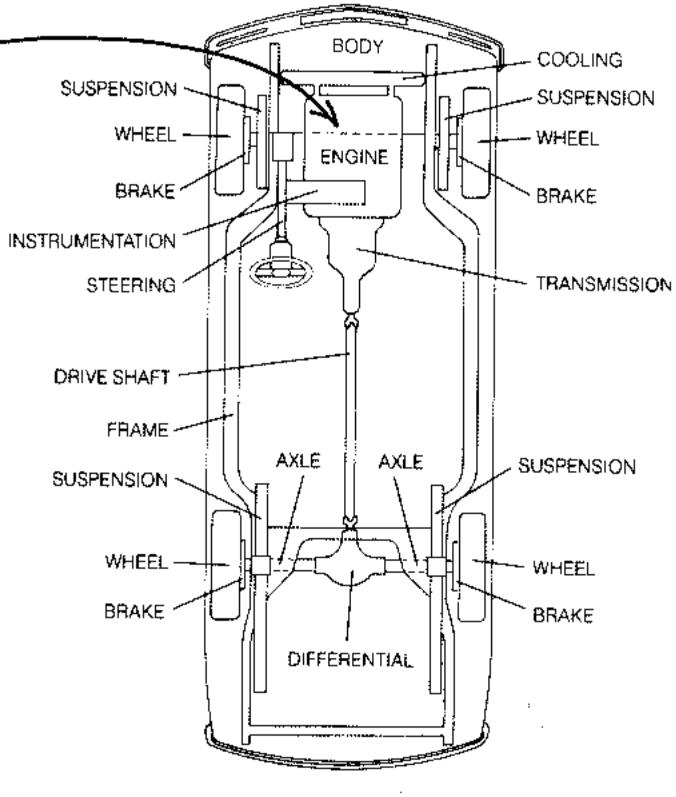
In Figure 1.1 the frame or chassis on which the body is mounted is supported by the suspension system. The brakes are connected to the opposite end of the suspension components. The steering and other major mechanical systems are mounted on one of these components and attached as necessary through mechanical components to other subsystems.

This basic vehicle configuration was used from the earliest cars through the late 1960s or 1970s, with some notable exceptions. The increasing importance of fuel efficiency and government-mandated safety regulations led to major changes in vehicle design. The body and frame evolved into an integrated structure to which the power train, suspension, wheels, etc., were attached.

Once again with a few notable exceptions, most cars had an engine in a front configuration with the drive axle at the rear. There are advantages in having the engine located in the front of the vehicle (e.g., crash protection, efficient engine cooling). Until recently, the so-called drive wheels through which power is delivered to the road have been the rear wheels (as depicted in Figure 1.1). This configuration is known as rear wheel drive. For safety and stability the front wheels are used to steer the vehicle.

This rear wheel drive configuration is not optimal from a traction standpoint since the relatively large weight of the engine/transmission is

Figure 1.1
Systems of the Automobile



In most newer cars the engine is mounted transversely for front wheel drive.

primarily on the front wheels. In order to take advantage of the engine weight for traction, many present-day cars combine steering and drive wheels in the front (i.e., so-called front wheel drive cars). In achieving front wheel drive, certain compromises must be made with respect to complexity and steering radius. Moreover, there is a tendency for the torque applied to the front wheels to adversely affect steering through a phenomenon known as “torque steer.” Nevertheless, the technology of front engine front wheel steering is quite mature and has become commonplace in modern cars.

In front wheel drive cars the engine is mounted transversely (i.e., with the rotation axis orthogonal to the vehicle axis as opposed to along the vehicle axis). In automotive parlance the traditional engine orientation is referred to as *North-South,* and the transverse orientation as *East-West.* The transmission is mounted adjacent to the engine and oriented with its axis parallel to the engine axis. The differential and drive axle configuration is normally mounted in the transmission; the combined unit is thus called the *transaxle.*

All of the systems listed above have been impacted by the introduction of electronics. The evolution of these electronics has been so rapid that a book such as this requires continuous revision to have any hope of reflecting the latest state of the art. New applications of electronics to each of the above systems continually supplement those already in use resulting in an environment in which electronics represents something of the order of 20% of the cost of a modern car.

Evolution of Electronics in the Automobile

This book explores the application of modern solid-state electronics to the various automotive subsystems described above. In order to give the evolution of electronics in automobiles a suitable perspective, it is helpful to consider the history of automotive electronics. Apart from auto radios, some turn signal models, and a few ignition systems, there was very little use of electronics in the automobile until the early 1970s. At about this time, government-mandated emission regulations, fuel economy, and safety requirements motivated the initial use of electronics. The dramatic performance improvements and relatively low cost of electronics have led to an explosive application of electronics in virtually every automotive subsystem. The relative cost/benefit of electronic subsystems in automobiles is largely affected by the production volume. (Some 15 to 16 million new cars and light trucks are sold in the United States each year.) Such a large production volume significantly lowers the unit cost for any electronic system relative to aerospace volumes.

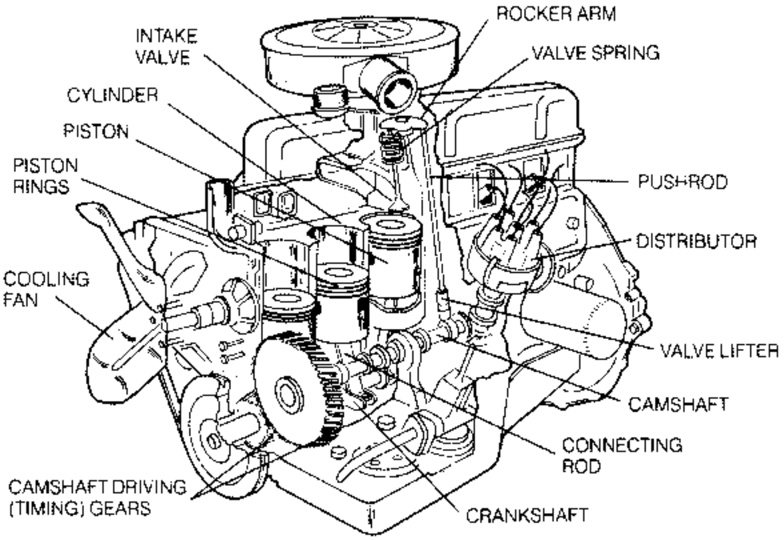
SURVEY OF MAJOR AUTOMOTIVE SYSTEMS

We will be exploring these electronic systems in great detail later in this book, but first it is helpful to review the basic mechanical configurations for each component and subsystem. Modern automotive electronics were first applied to control the engine in order to reduce exhaust emissions and somewhat later to improve fuel economy. Consequently, we review the engine configuration first in this survey.

THE ENGINE

The engine in an automobile provides all the power for moving the automobile, for the hydraulic and pneumatic systems, and for the electrical system. A variety of engine types have been produced, but one class of engine is used most: the internal combustion, piston-type, 4-stroke/cycle, gasoline-

Figure 1.2
Cutaway View of a 6-Cylinder, Overhead-Valve, Inline Engine (*Source:* Crouse)



fueled, spark-ignited, liquid-cooled engine. This engine will be referred to in this book as the spark-ignited, or SI, engine.

Although rapid technological advances in the control of the SI engine have been achieved through the use of electronics, the fundamental mechanical configuration has remained unchanged since this type of power plant was first invented. In addition, the introduction of modern materials has greatly improved the packaging, size, and power output per unit weight or per unit volume. In order that the reader may fully appreciate the performance improvements that have been achieved through electronic controls, we illustrate the engine fundamentals with an example engine configuration from the pre-electronic era.

Figure 1.2 is a partial cutaway drawing of an SI engine configuration commonly found in the period immediately following World War II. The engine there illustrated is a 6-cylinder, overhead-valve, inline engine. Alternate engine configurations today are either a 4-cylinder inline or a V-type engine with either 6 or 8 cylinders (although there are exceptions). Moreover, the materials found in present-day engines permit greatly reduced weight for a given engine power.

Nevertheless, modern electronically controlled engines have much in common with this example configuration. For example, the vast majority of modern engines are 4-stroke/cycle, gasoline fueled, spark ignited, normally aspirated, and water cooled. By illustrating the fundamentals of engine operation using the example engine of Figure 1.2, we can thus explain the differences that have occurred with modern electronic controls.

The major components of the engine include the following:

1. Engine block
2. Cylinder
3. Crankshaft
4. Pistons
5. Connecting rods
6. Camshaft
7. Cylinder head
8. Valves
9. Fuel control system
10. Ignition system
11. Exhaust system
12. Cooling system
13. Electrical system

Electronics play a direct role in all aspects of controlling engine operation, including the fuel and air flow control, ignition, exhaust and evaporative emission systems, and diagnostic and maintenance operations as well as many other secondary functions. It will be shown in Chapters 5, 6, and 7 that in order to meet government regulations for exhaust emissions and fuel economy, these systems combine to optimize performance within regulatory requirements. In the earliest days of government regulation, electronic controls were applied to existing engine designs. However, as electronic technology evolved, the engine mechanical configuration was influenced (at least indirectly) by the electronic controls that were intended to be applied. The evolution of engine control electronics is explained in Chapters 5, 6 and 7 of this book.

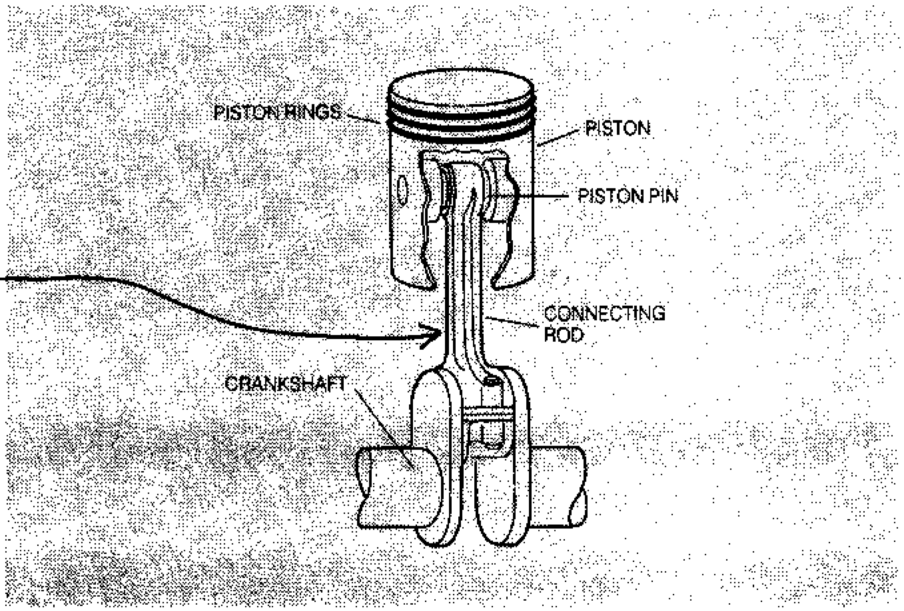
Engine Block

Conventional internal combustion engines convert the movement of pistons to the rotational energy used to drive the wheels.

Mechanical rotary power is produced in an engine through the combustion of gasoline inside cylinders in the engine block and a mechanism consisting of pistons (in the cylinders) and a linkage (connecting rod) coupled to the crankshaft. Mechanical power is available at the crankshaft.

The cylinders are cast in the engine block and machined to a smooth finish. The pistons fit tightly into the cylinder and have rings that provide a tight sliding seal against the cylinder wall. The pistons are connected to the

Figure 1.3
Piston Connection to Crankshaft (*Source:* Crouse)



Force due to combustion pressure is applied through the connecting rod to produce torque at the crankshaft.

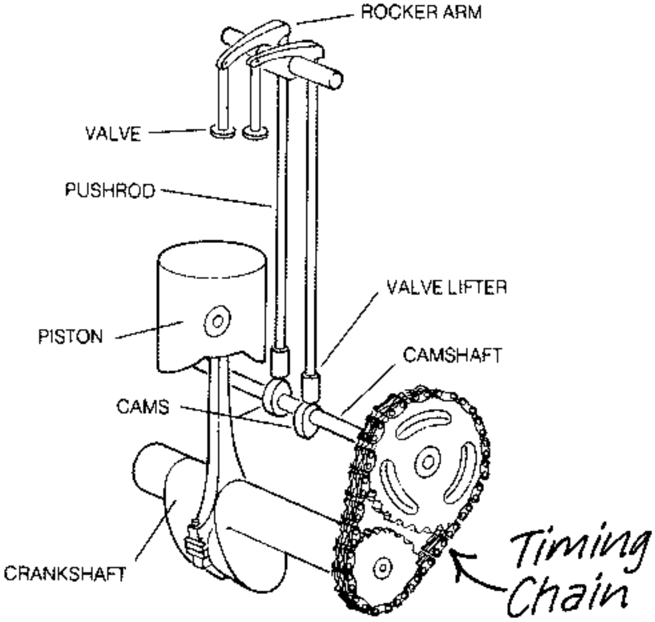
crankshaft by connecting rods, as shown in Figure 1.3. The crankshaft converts the up and down motion of the pistons to the rotary motion and the torque needed to drive the wheels.

Cylinder Head

The cylinder head contains an intake and exhaust valve for each cylinder. When both valves are closed, the head seals the top of the cylinder while the piston rings seal the bottom of the cylinder. During combustion, high pressure is devoloped in the cylinder which, in turn, produces a force on the piston that creates the torque on the crankshaft.

The valves are operated by off-center (eccentric) cams on the camshaft, which is driven by the crankshaft as shown in Figure 1.4. The camshaft rotates at exactly half the crankshaft speed because a complete cycle of any cylinder involves two complete crankshaft rotations and only one sequence of opening and closing of the associated intake and exhaust valves. The valves are normally held closed by powerful springs. When the time comes for a valve to open, the lobe on the cam forces the pushrod upward against one end of the rocker arm. The other end of the rocker arm moves downward and forces the valve open. (*Note:* Some engines have the camshaft above the head, eliminating the pushrods. This is called an *overhead cam* engine.)

Figure 1.4
Valve Operating Mechanism (*Source:* Crouse)



The 4-Stroke Cycle

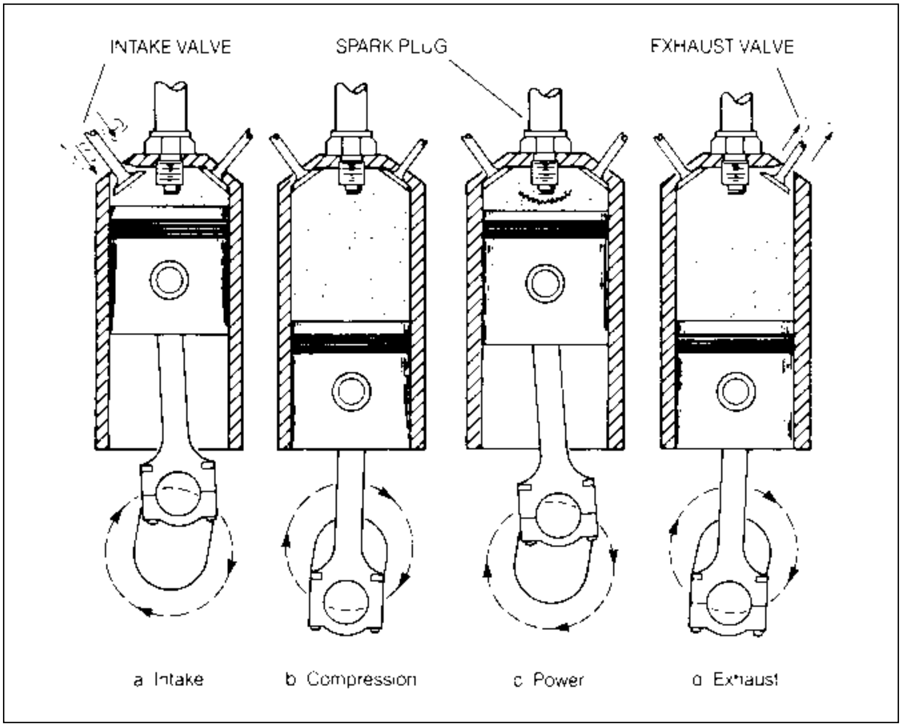
Conventional SI engines operate using four "strokes," with either an up or down movement of each piston. These strokes are named *intake, compression, power,* and *exhaust.*

The operation of the engine can be understood by considering the actions in any one cylinder during a complete cycle of the engine. One complete cycle in the 4-stroke/cycle SI engine requires two complete rotations of the crankshaft. As the crankshaft rotates, the piston moves up and down in the cylinder. In the two complete revolutions of the crankshaft that make up one cycle, there are four separate strokes of the piston from the top of the cylinder to the bottom or from the bottom to the top. Figure 1.5 illustrates the four strokes for a 4-stroke/cycle SI engine, which are called:

1. Intake
2. Compression
3. Power
4. Exhaust

There are two valves for each cylinder. The left valve in the drawing is called the *intake valve* and the right valve is called the *exhaust valve.* The intake valve is normally larger than the exhaust valve. Note that the crankshaft is assumed to be rotating in a clockwise direction. The action of the engine during the four strokes is described in the following sections.

Figure 1.5
The Four Strokes of a Typical Modern Gasoline-Fueled, Spark-Ignition Engine



Intake

During the intake stroke (Figure 1.5a), the piston is moving from top to bottom and the intake valve is open. As the piston moves down, a partial vacuum is created, which draws a mixture of air and vaporized gasoline through the intake valve into the cylinder.

It will be shown in Chapters 5, 6, and 7 that, in modern, electronically controlled engines, fuel is injected into the intake port and is timed to coincide with the intake stroke. The intake valve is closed after the piston reaches the bottom. This position is normally called *bottom dead center* (BDC).

Compression

During the compression stroke (Figure 1.5b), both valves are closed, and the piston moves upward and compresses the fuel and air mixture against the cylinder head. When the piston is near the top of this stroke, the ignition system produces an electrical spark at the tip of the spark plug. (The top of the stroke is normally called *top dead center*—TDC.) The spark ignites the air–fuel mixture and the mixture burns quickly, causing a rapid rise in the pressure in the cylinder.

Power

During the power stroke (Figure 1.5c), the high pressure created by the burning mixture forces the piston downward. The cylinder pressure creates the force on the piston that results in the torque on the crankshaft as described above. It is only during this stroke that actual usable power is generated by the engine.

Exhaust

During the exhaust stroke (Figure 1.5d), the piston is again moving upward. The exhaust valve is open and the piston forces the burned gases from the cylinder through the exhaust port into the exhaust system and out the tailpipe into the atmosphere.

Each piston on a 4-stroke SI engine produces actual power during just one out of four strokes.

This 4-stroke cycle is repeated continuously as the crankshaft rotates. In a single-cylinder engine, power is produced only during the power stroke, which is only one-quarter of the cycle. Modern automotive engines have multiple cylinders, each of which contributes power during its associated power stroke. In a multicylinder engine, the power strokes are staggered so that power is produced during a larger fraction of the cycle than for a single-cylinder engine. In a 4-cylinder engine, for example, power is produced almost continually by the separate power strokes of the four cylinders. The shaded regions of Figure 1.6 indicate which cylinder is producing power for each 180 degrees of crankshaft rotation. (Remember that one complete engine cycle requires two complete crankshaft rotations of 360 degrees each, for a total of 720 degrees.)

ENGINE CONTROL

Control of the engine in any car means regulating the power that it produces at any time in accordance with driving needs. The driver controls

Figure 1.6
Power Pulses from a 4-Cylinder Engine

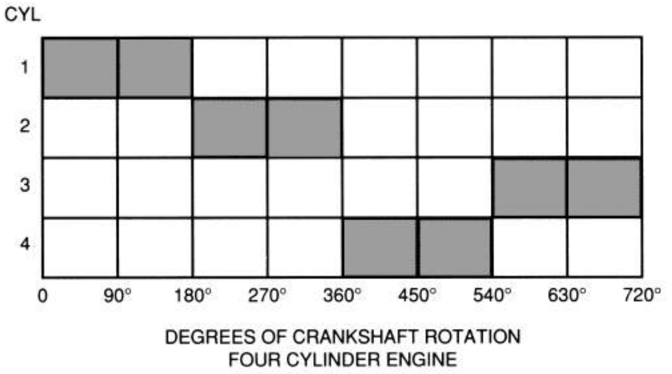
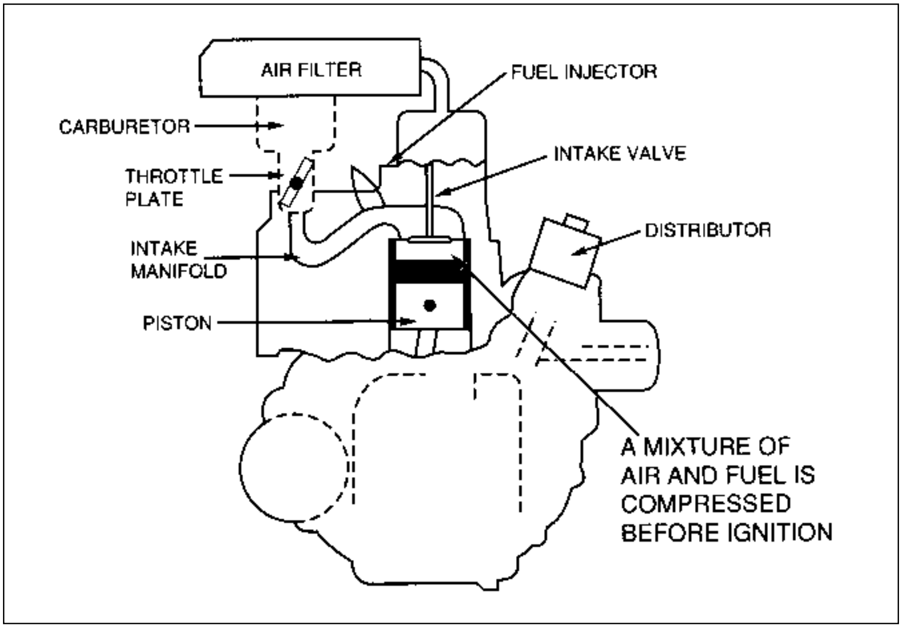


Figure 1.7
Intake Manifold and Fuel Metering



engine power via the accelerator pedal, which, in turn, determines the setting of the throttle plate via a mechanical linkage system. The throttle plate is situated in the air intake system and is, in effect, a rotary valve that impedes the air flowing past it (Figure 1.7). The intake system is an assembly of pipes or passageways through which the air flows from outside into each cylinder. The air flowing into the engine flows past the throttle plate, which, in fact, controls the amount of air being drawn into the engine during each intake stroke.

As we will show in later chapters, the power produced by the engine is proportional to the mass flow rate of air into the engine. The driver then controls engine power directly by controlling this air mass flow rate with the throttle plate. As the accelerator pedal is depressed, the throttle plate rotates, permitting air to flow at an increased rate.

Of course, the power produced by the engine depends on fuel being present in the correct proportions. Fuel is delivered to each cylinder at a rate that is proportional to air flow. The fuel flow rate is determined by fuel injectors (one for each cylinder), which are operated by an electronic engine control system as explained in Chapters 5 and 7. There it is shown that fuel flow rate is regulated so as to minimize exhaust gas pollutant concentration. It should be noted that before the advent of electronic engine controls fuel flow was regulated by a device known as a carburetor (as depicted in Figure 1.7).

IGNITION SYSTEM

To produce power, the gasoline engine must not only have a correct mixture of fuel and air, but also some means of initiating combustion of the mixture. Essentially the only practical means is with an electric spark produced across the gap between a pair of electrodes of a spark plug. The electric arc or spark provides sufficient energy to cause combustion. This phenomenon is called *ignition*.

Once a stable combustion has been initiated, there is no further need for the spark during any engine cycle. Typically, the spark must persist for a period of about a millisecond (one thousandth of a second). This relatively short period makes spark ignition possible using highly efficient pulse transformer circuits in which a circuit having a relatively low average current can deliver a very high-voltage (high peak power) pulse to the spark plug.

The ignition system itself consists of several components: the spark plug, one or more pulse transformers (typically called *coils*), timing control circuitry, and distribution apparatus that supplies the high-voltage pulse to the correct cylinder.

Spark Plug

The spark is produced by applying a high-voltage pulse of from 20 kV to 40 kV (1 kV is 1,000 volts) between the center electrode and ground. The actual voltage required to start the arc varies with the size of the gap, the compression ratio, and the air–fuel ratio. Once the arc is started, the voltage required to sustain it is much lower because the gas mixture near the gap becomes highly ionized. (An ionized gas allows current to flow more freely.) The arc is sustained long enough to ignite the air–fuel mixture.

A typical spark plug configuration is shown in Figure 1.8. The spark plug consists of a pair of electrodes, called the *center* and *ground electrodes,* separated by a gap. The gap size is important and is specified for each engine. The gap may be 0.025 inch (0.6 mm) for one engine and 0.040 inch (1 mm) for another engine. The center electrode is insulated from the ground electrode and the metallic shell assembly. The ground electrode is at electrical ground potential because one terminal of the battery that supplies the current to generate the high-voltage pulse for the ignition system is connected to the engine block and frame.

High-Voltage Circuit and Distribution

The ignition system provides the high-voltage pulse that initiates the arc. Figure 1.9 is a schematic of the electrical circuit for the ignition system as it existed before electronic control systems. The high-voltage pulse is generated by inductive discharge of a special high-voltage transformer commonly called an *ignition coil.* The high-voltage pulse is delivered to the appropriate spark plug at the correct time for ignition by a distribution circuit. In a modern

Figure 1.8 Spark Plug Configuration

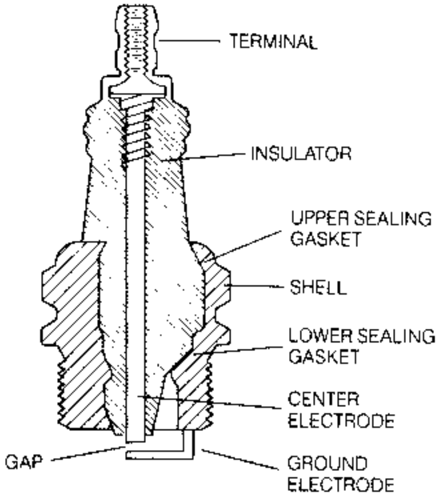


Figure 1.9 Schematic of the Ignition Circuit

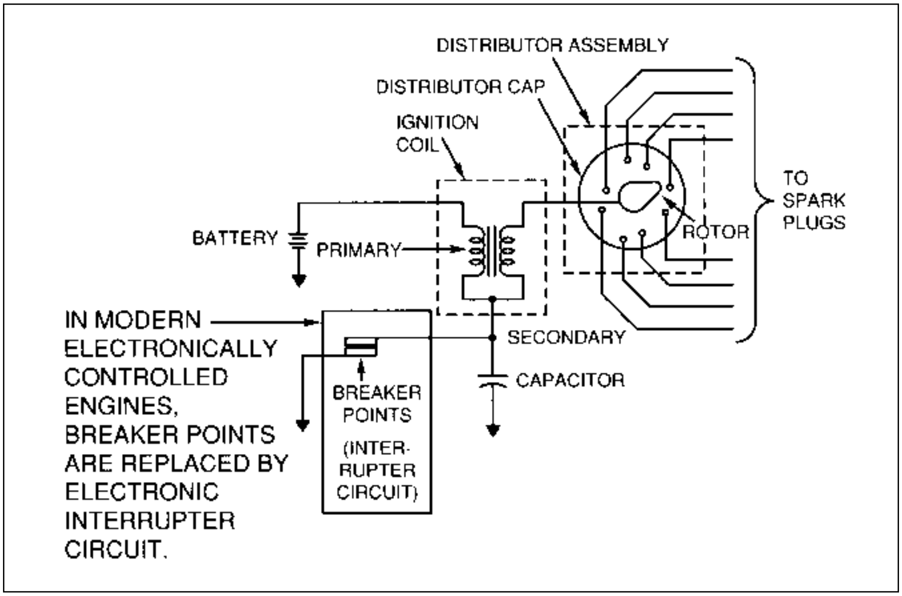
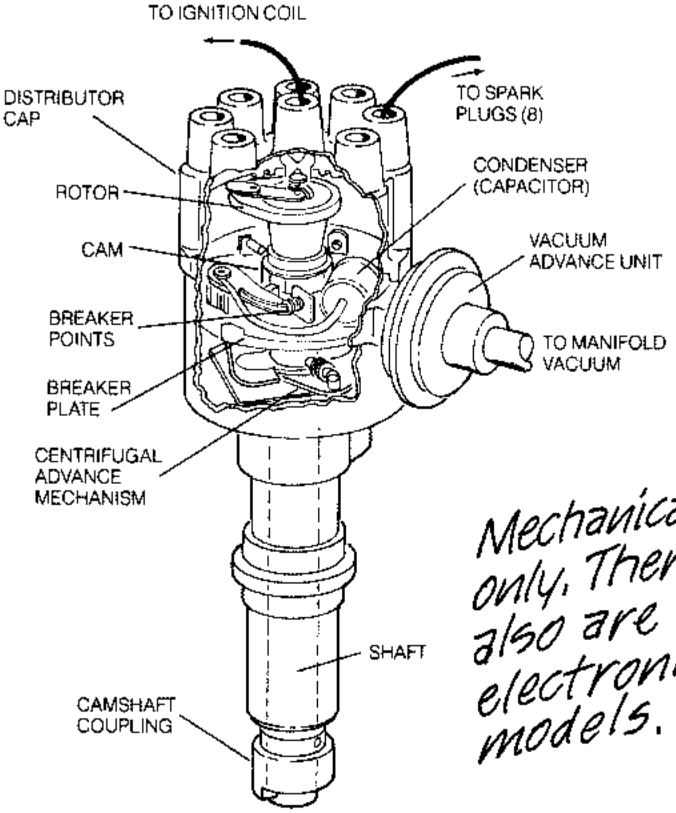


Figure 1.10
Distributor



Mechanical only. There also are electronic models.

engine, the breaker points have been replaced with an electronic control module in which a power transistor controls the coil current as explained in Chapter 5.

Before the advent of modern electronic controls, the distribution of high-voltage pulses was accomplished with a rotary switch called the *distributor.* Figure 1.9 shows a schematic of a typical distributor; Figure 1.10 is a typical physical layout. The center electrode is mechanically driven by the camshaft (via gears) and rotates synchronously at camshaft speed (i.e., one-half of crankshaft speed). The distributor is an obsolete means for distribution of the spark to the appropriate spark plug, and is being replaced by multiple coils, typically one each for a pair of cylinders (or one for each cylinder), as explained in Chapter 7.

Once again, as in the case of fuel delivery, we explain spark distribution in terms of the distributor and spark initiation in terms of breaker points in order to provide a framework for the discussion of the modern distributorless ignition systems. In this way the reader can see the benefits of the electronic controls.

A set of electrical leads, commonly called *spark plug wires,* is connected between the various spark plug center terminals and the individual terminals in the distributor cap. The center terminal in the distributor cap is connected to the ignition coil secondary.

Spark Pulse Generation

The actual generation of the high-voltage pulse is accomplished by switching the current through the primary circuit (see Figure 1.9). The mechanism in the distributor of a traditional ignition system for switching the primary circuit of the coil consists of opening and closing the breaker points (of a switch) by a rotary cam in the distributor (explained later). During the intervals between ignition pulses (i.e., when the rotor is between contacts), the breaker points are closed (known as *dwell*). Current flows through the primary of the coil, and a magnetic field is created that links the primary and secondary of the coil.

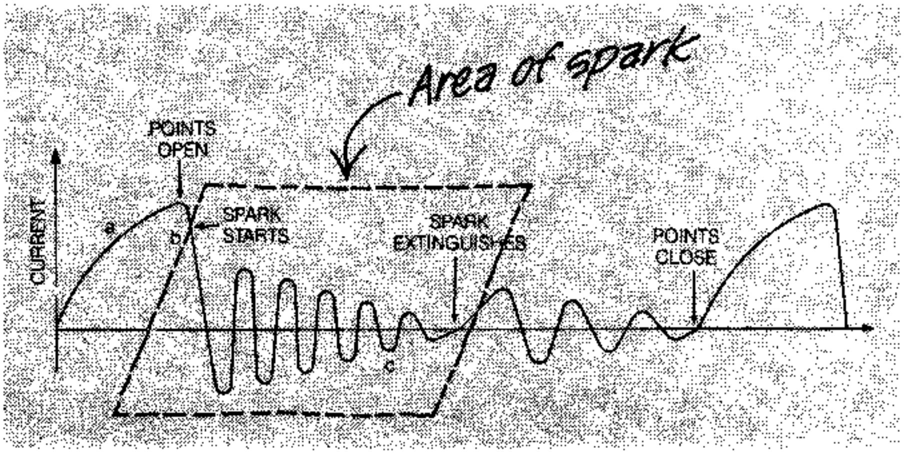
The distributor in a conventional ignition system uses a mechanically activated switch called *breaker points.* The interruption of ignition coil current when the breaker points open produces a high-voltage pulse in the secondary.

At the instant the spark pulse is required, the breaker points are opened. This interrupts the flow of current in the primary of the coil and the magnetic field collapses rapidly. The rapid collapse of the magnetic field induces the high-voltage pulse in the secondary of the coil. This pulse is routed through the distributor rotor, the terminal in the distributor cap, and the spark plug wire to the appropriate spark plug. The capacitor absorbs the primary current, which continues to flow during the short interval in which the points are opening, and limits arcing at the breaker points.

The waveform of the primary current is illustrated in Figure 1.11. The primary current increases with time after the points close (point *a* on waveform). At the instant the points open, this current begins to fall rapidly. It is during this rapid drop in primary current that the secondary high-voltage pulse occurs (point *b*). The primary current oscillates (the “wavy” portion; point *c*) because of the resonant circuit formed between the coil and capacitor.

It will be shown in Chapter 7 that in electronic ignition systems the breaker points are replaced by a solid-state switch (in the form of a transistor). In Chapter 3 it will be shown that a transistor in saturation is equivalent to a closed switch, and a cutoff transistor is equivalent to an open switch. It is further explained in Chapter 7 that the transistor state (i.e., saturation or cutoff) is controlled electronically in order to set dwell and spark timing.

Figure 1.11 Primary Current Waveform



A multisurfaced cam, mounted on the distributor shaft, is used to open and close the breaker points.

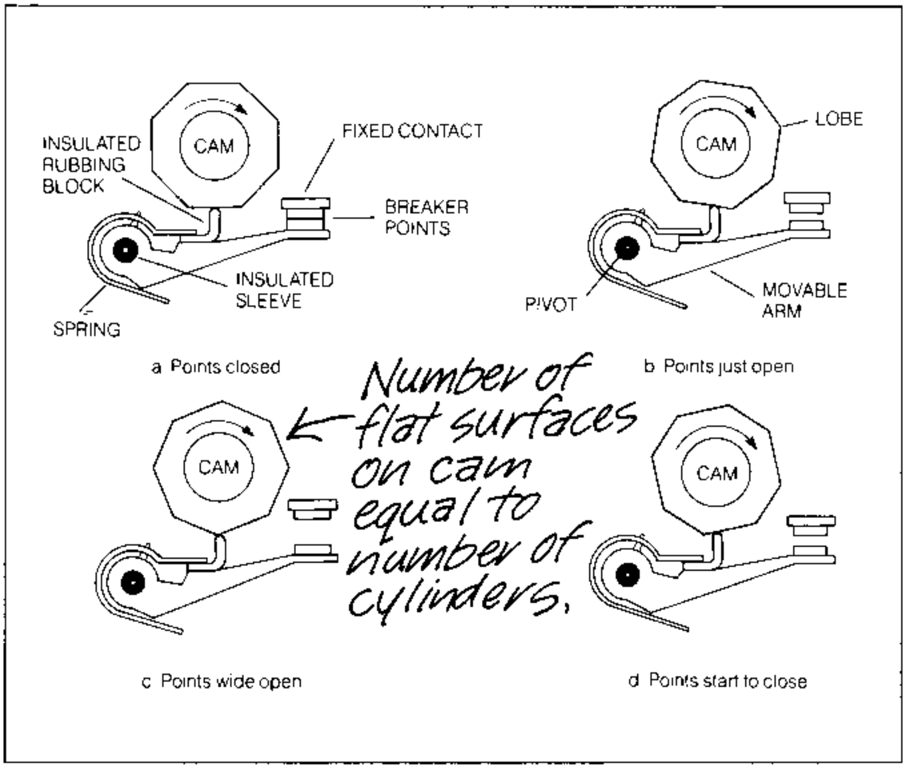
The mechanism for opening and closing the breaker points of a conventional distributor is illustrated in Figure 1.12. A cam having a number of lobes equal to the number of cylinders is mounted on the distributor shaft. As this cam rotates, it alternately opens and closes the breaker points. The movable arm of the breaker points has an insulated rubbing block that is pressed against the cam by a spring. When the rubbing block is aligned with a flat surface on the cam, the points are closed (i.e., dwell period), as shown in Figure 1.12a. As the cam rotates, the rubbing block is moved by the lobe (high point) on the cam as shown in Figure 1.12b. At this time, the breaker points open (corresponding to point b of Figure 1.11) and spark occurs.

The rotary switch that connects the coil to the appropriate spark plug wire is connected to the same shaft as the cam, thereby synchronizing the actions of spark creation with the switching of the high-voltage pulse to each spark plug. The distributor shaft is coupled to the camshaft and rotates at the same speed and is positioned relative to the camshaft so that the spark occurs at the correct time during each engine cycle to produce optimum combustion. This relative position of distribution and camshaft is known as “ignition timing.”

IGNITION TIMING

The point at which ignition occurs, in relation to the top dead center of the piston’s compression stroke, is known as ignition timing.

Ignition occurs some time before top dead center (BTDC) during the compression stroke of the piston. This time is measured in degrees of crankshaft rotation BTDC. For a modern SI engine, this timing is typically 8 to 10 degrees for the basic mechanical setting with the engine running at low speed (low rpm). This basic timing is set by the design of the mechanical coupling between the crankshaft and the distributor. The basic timing may be adjusted slightly in many older cars by physically rotating the distributor housing, during routine maintenance.



a Points closed

b Points just open

c Points wide open

d Points start to close

Number of flat surfaces on cam equal to number of cylinders.

Figure 1.12 Breaker Point Operation

As the engine speed increases, the angle through which the crankshaft rotates in the time required to burn the fuel and air mixture increases. For this reason, the spark must occur at a larger angle BTDC for higher engine speeds. This change in ignition timing is called *spark advance.* That is, spark advance should increase with increasing engine rpm. In a conventional ignition system, the mechanism for this is called a *centrifugal spark advance.* It is shown in Figure 1.10. As engine speed increases, the distributor shaft rotates faster, and the weights are thrown outward by centrifugal force. The weights operate through a mechanical lever, so their movement causes a change in the relative angular position between the rubbing block on the breaker points and the distributor cam, and advances the time when the lobe opens the points.

In addition to speed-dependent spark advance, the ignition timing needs to be adjusted as a function of intake manifold pressure. Whenever the throttle is nearly closed, the manifold pressure is low (i.e., nearly a vacuum). The combustion time for the air–fuel mixture is longer for low manifold pressure conditions than for high manifold pressure conditions (i.e., near atmospheric pressure). As a result, the spark timing must be advanced for low pressure conditions to maintain maximum power and fuel economy. The mechanism to do this is a vacuum-operated spark advance, also shown in Figure 1.10. The vacuum advance mechanism has a flexible diaphragm connected through a rod to the plate on which the breaker points are mounted. One side of the diaphragm is open to atmospheric pressure; the other side is connected through a hose to manifold vacuum. As manifold vacuum increases, the diaphragm is deflected (atmospheric pressure pushes it) and moves the breaker point plate to advance the timing. Ignition timing significantly affects engine performance and exhaust emissions; therefore, it is one of the major factors that is electronically controlled in the modern SI engine.

The performance of the ignition system and the spark advance mechanism has been greatly improved by electronic control systems. Because ignition timing is critical to engine performance, controlling it precisely through all operating conditions has become a major application of digital electronics, as explained in Chapter 7.

It will be shown in Chapter 7 that ignition timing is actually computed as a function of engine operating conditions in a special-purpose digital computer known as the electronic engine control system. This computation of spark timing has much greater flexibility for optimizing engine performance than a mechanical distributor and is one of the great benefits of electronic engine control.

ALTERNATIVE ENGINES

The vast majority of automobile engines in North America are SI engines. Alternative engines such as the diesel have simply not been able to compete effectively with the SI engine in the United States. Diesel engines are used mostly in heavy-duty vehicles such as large trucks, ships, railroad locomotives, and earth-moving machinery. However, there is some use of these engines in light-duty trucks and some passenger cars. These engines are being controlled electronically, as explained later in this book.

Diesel Engine

Physically, the diesel engine is nearly identical to the gasoline engine and can be either 4 stroke or 2 stroke/cycle. It consists of cylinders cast into a block with pistons, connecting rods, crank shaft, camshaft, and valves (4-stroke engine). Torque and power are produced during the 4 strokes as in the case of the 4-stroke gasoline engine. The diesel engine fuel is supplied via a fuel injection system that injects fuel either directly into the cylinder (direct injection system) or into the intake port during the intake stroke (indirect injection system).

Diesel engines are subject to exhaust emission regulations similar to those applied to gasoline engines. Emissions are influenced by the timing of fuel injection relative to the compression and power strokes. The evolution of electronic control of diesel engines is explained in Chapters 5, 6, and 7.

Another alternative to the SI engine has been the Wankel, or rotary, engine. As in the case of the diesel engine, the number of Wankel engines has been very small compared to the SI engine. One limitation to its application has been somewhat poorer exhaust emissions relative to the SI engine.

Still another potential competitor to current automotive engines is the 2-stroke/cycle engine. This engine, which is similar in many respects to the traditional engine, is a gasoline-fueled, spark-ignited, reciprocating engine. It has achieved widespread use in lawnmowers, small motorcycles, and some outboard marine engines. It had (at one time) even achieved limited automotive use, though it suffered from poor exhaust emissions.

Just as in the case of the 4-stroke/cycle engine, electronic controls have significantly improved 2-stroke/cycle engine performance relative to mechanical controls. At the present time, it does not appear likely that the 2-stroke/cycle engine will have sufficient passenger car application in the foreseeable future to justify its discussion in this book.

An alternative to the internal combustion engine as an automotive power plant is electric propulsion in which the mechanical power required to move the car comes from an electric motor. Electric propulsion of automobiles is not new. Electric motors were used to propel cars in the early part of the twentieth century. The necessary electric energy required was supplied by storage batteries. However, the energy density (i.e., the energy per unit weight) of storage cells has been and continues to be significantly less than gasoline or diesel fuel. Consequently, the range for an electrically powered car has been much less than that for a comparably sized IC engine-powered car.

On the other hand, the exhaust emissions coming from an electrically powered car are (theoretically) zero, making this type of car very attractive from a pollution standpoint. At the time of this writing, only a handful of relatively expensive electrically powered cars are in operation, and generally their performance and range are inferior to those of gasoline-fueled cars.

One attractive option for electrically powered cars is a combination of a gasoline-fueled engine with an electric propulsion system. Such cars are known as hybrid cars and can be operated either as purely electric propulsion (with energy supplied by storage cells) or as a combination of an engine driving a generator to supply the electric power for the motor.

A hybrid car can be operated with electric propulsion in urban areas where exhaust emissions are required to be low (or zero) and as a gasoline-fueled, engine-driven car in rural areas where the range advantage of the gasoline-fueled option is superior to the electric propulsion and where exhaust emissions are somewhat less of an issue.

The efficiency of electric propulsion is improved by raising the operating voltage from the present-day 14-volt systems (i.e., using 12-volt-rated batteries). This efficiency gain is responsible in part for the evolution of car electrical systems from the present 14-volt to 42-volt systems.

In the early years following the introduction of cars with 42-volt electrical systems, there will be two separate electrical buses, one at 14 volts and the other at 42 volts. The 14-volt bus will be tied to a single 12-volt (nominal) battery. The 42-volt electrical bus will be tied to three 12-volt batteries connected in series. The 14-volt bus will supply power to those components and subsystems that are found in present-day vehicles including, for example, all lighting systems and electronic control systems. The 42-volt bus will be associated with the electric drive system of the hybrid car where it can provide more efficient propulsion than would be possible with a 14-volt system.

The hybrid vehicle is capable of operation in three modes in which power comes from: (a) the engine only; (b) the electric motor only; and (c) the combined engine and electric motor. In achieving these modes of operation, the engine and electric motor must be coupled to the drivetrain. It is beyond the scope of this book to discuss all of the mechanical configurations for coupling the engine and the motor. The two major types of coupling methods are known as a series or parallel hybrid electric car.

Rather, we consider one system that has proven effective for this coupling in which the electric motor rotor is constructed on an extended crankshaft of the engine. The motor stator is constructed in a housing that is part of or attached to the engine case. The electric motor in this configuration is the starting motor for the engine, as well as the generator/alternator for electric power as well as the motor for the electric propulsion. Under mode (a), the motor rotates freely and neither produces nor absorbs any power. In modes (b) and (c), the motor receives electric power from an electronic control system and delivers the required power to the drivetrain.

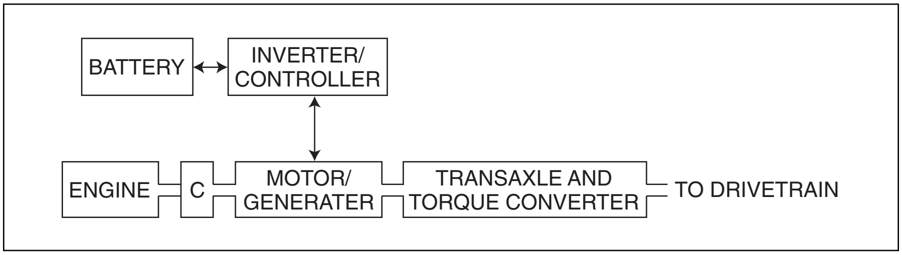
Although many electric motor types have the potential to provide the mechanical power in a hybrid vehicle, the brushless d-c motor seems to be the preferred type in practical application. This type of motor is described in Chapter 6, which deals with automotive sensors and actuators.

A schematic depiction of a hybrid vehicle power train is shown in Figure 1.13. There are a variety of hybrid vehicle configurations, and the type shown in Figure 1.13 is a representative one illustrating the main features of such a configuration.

The power to move the vehicle can come from the engine alone, from the battery via electric power to the motor/generator (motor in this case), or by both acting together. The motor generator/rotor is connected on the shaft between the crankshaft and the transaxle assembly. The engine is connected to the transaxle by a mechanism that permits the modes of operation stated above.

In Figure 1.13, this mechanism is denoted C and can be one of many possible devices. In some configurations, it is an electrically activated clutch

Figure 1.13
Example of Hybrid Vehicle Configuration



that disconnects the engine from the transaxle when it is switched off for electric propulsion but connects the engine to the transaxle for engine-only power or for combined engine electric motor operation. In other vehicles, the engine and motor are coupled to the drivetrain via a power-splitting device capable of controlling the power split between IC engine and electric motor.

In a typical hybrid vehicle, the relative power from the IC engine and the electric motor is adjusted to give optimum performance during normal driving. In those exhaust emission-sensitive geographic areas, the vehicle can be powered solely by the electric propulsion. The distribution of power as well as the generation of power for both systems are electronically controlled.

Yet another option for electric propulsion involves the use of fuel cells to generate the electric power to drive the associated motors. As will be shown in the last chapter of this book, a fuel cell uses hydrogen and oxygen to directly generate electric power, with exhaust consisting only of water. A great many technical problems must be solved before the fuel-cell-powered car can become a practical reality, but this type of car has great potential for reducing automobile-generated pollution. A detailed discussion of fuel cells for automotive propulsion appears in the final chapter of this book.

DRIVETRAIN

The engine drivetrain system of the automobile consists of the engine, transmission, drive shaft, differential, and driven wheels. We have already discussed the SI engine and we know that it provides the motive power for the automobile. Now let’s examine the transmission, drive shaft, and differential in order to understand the roles of these devices.

Transmission

The transmission is a gear system that adjusts the ratio of engine speed to wheel speed. Essentially, the transmission enables the engine to operate within its optimal performance range regardless of the vehicle load or speed. It provides a gear ratio between the engine speed and vehicle speed such that the engine provides adequate power to drive the vehicle at any speed.

The transmission provides a match between engine speed and vehicle speed.

To accomplish this with a manual transmission, the driver selects the correct gear ratio from a set of possible gear ratios (usually three to five for passenger cars). An automatic transmission selects this gear ratio by means of an automatic control system.

The configuration for an automatic transmission consists of a fluid-coupling mechanism, known as a torque converter, and a system of planetary gear sets. The torque converter is formed from a pair of structures of a semitoroidal shape (i.e., a donut-shaped object split along the plane of symmetry). Figure 1.14a is a schematic sketch of a torque converter showing the two semitoroids. One of the toroids is driven by the engine by the input shaft. The other is in close proximity and is called the turbine. Both the pump and the turbine have vanes that are essentially in axial planes. In addition, a series of vanes are fixed to the frame and are called the reactor. The entire structure is mounted in a fluid, tight chamber and is filled with a hydraulic fluid (i.e., transmission fluid). As the pump is rotated by the engine, the hydraulic fluid circulates as depicted by the arrows in Figure 1.14a. The fluid impinges on the turbine blades, imparting a torque to it. The torque converter exists to transmit engine torque and power to the turbine from the engine. However, the properties of the torque converter are such that when the vehicle is stopped corresponding to a nonmoving turbine, the engine can continue to rotate (as it does when the vehicle is stopped with the engine running).

The planetary gear system consists of a set of three types of gears connected together as depicted in Figure 1.14b. The inner gear is known as the sun gear. There are three gears meshed with the sun gear at equal angles, which are known as planetary gears. These three gears are tied together with a cage that supports their axles. The third gear, known as a ring gear, is a section of a cylinder with the gear teeth on the inside. The ring gear meshes with the three planetary gears.

In operation, one or more of these gear systems are held fixed to the transmission housing via a set of hydraulically actuated clutches. The action of the planetary gear system is determined by which set or sets of clutches are activated. For example, if the ring gear is held fixed and input power (torque) is applied to the sun gear, the planetary gears rotate in the same direction as the sun gear but at a reduced rate and at an increased torque. If the planetary gear cage is fixed, then the sun gear drives the ring gear in the opposite direction as is done when the transmission is in reverse. If all three sets of gears are held fixed to each other rather than the transmission housing, then direct drive (gear ratio = 1) is achieved.

A typical automatic transmission has a cascade connection of a number of planetary gear systems, each with its own set of hydraulically actuated clutches. In an electronically controlled automatic transmission, the clutches are electrically or electrohydraulically actuated.

Most automatic transmissions have three forward gear ratios, although a few have two and some have four. A properly used manual transmission

Figure 1.14a Schematic Cross Section of a Torque Converter

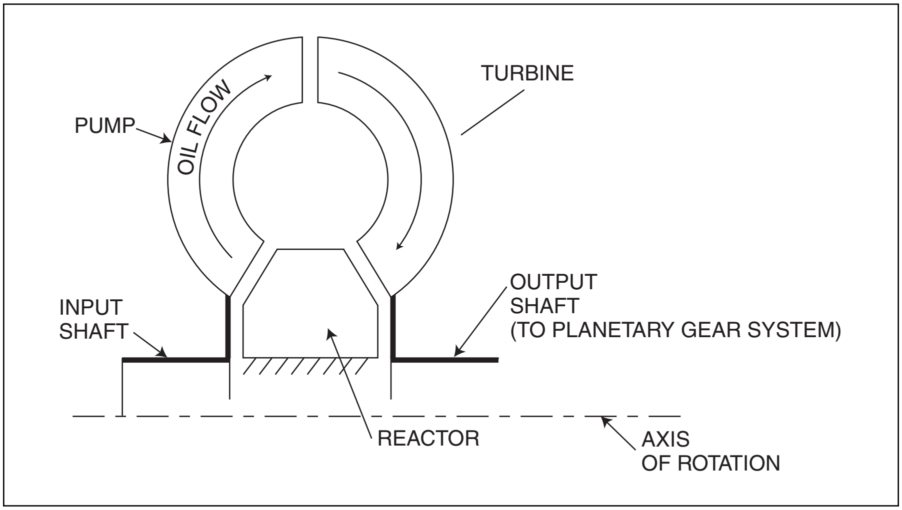


Figure 1.14b Planetary Gear System

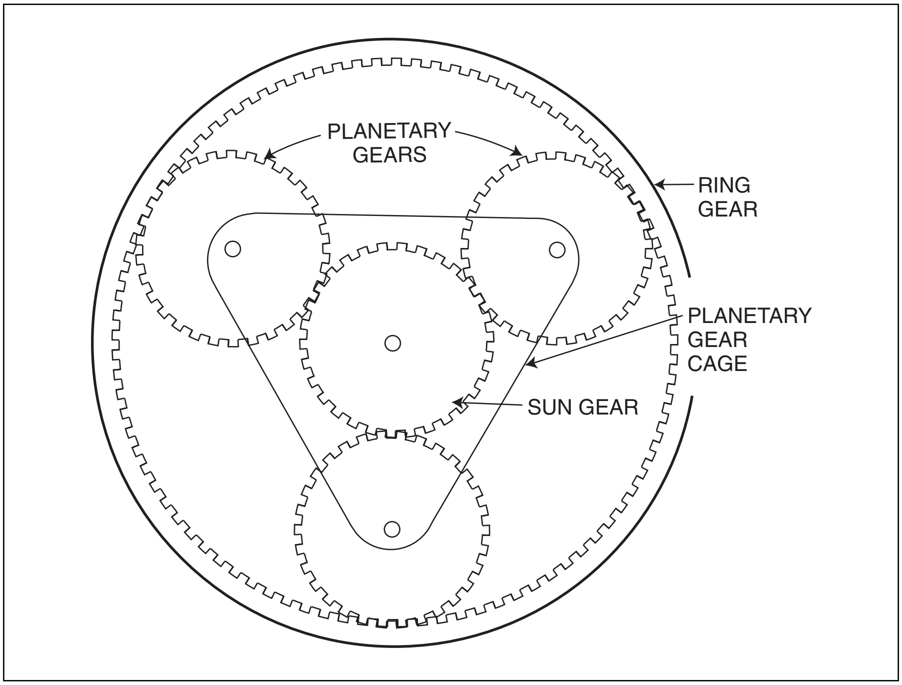
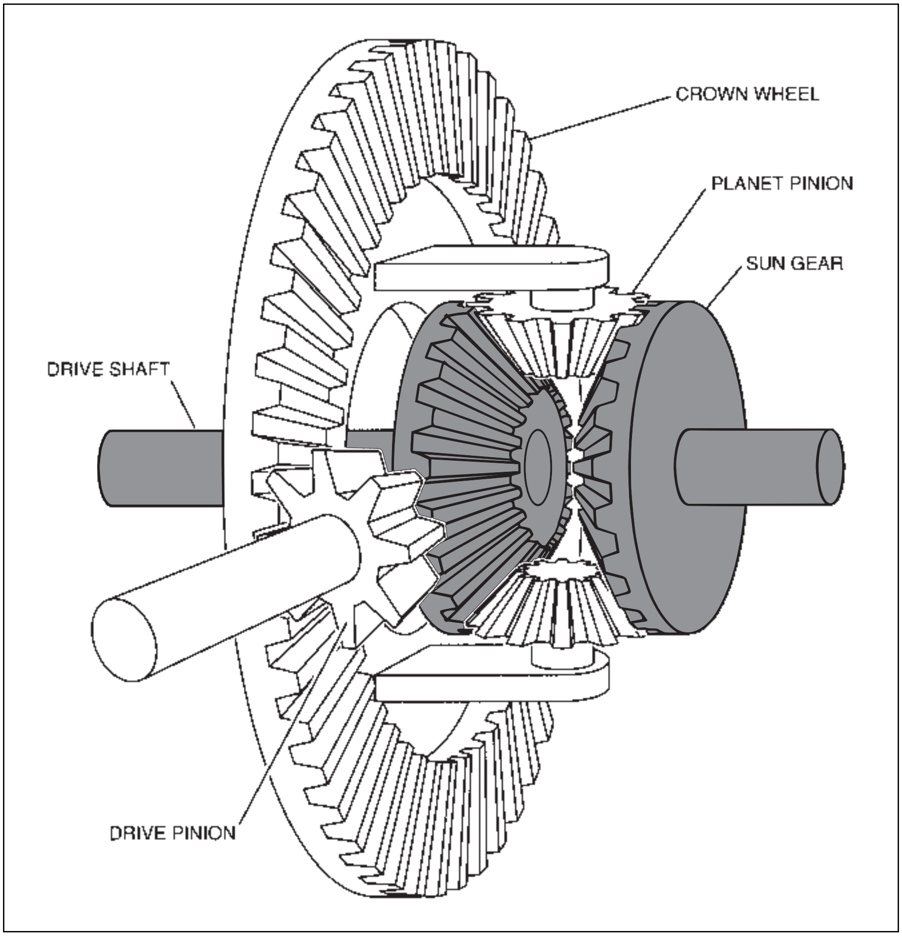


Figure 1.14c Schematic of a Differential



normally has efficiency advantages over an automatic transmission, but the automatic transmission is the most commonly used transmission for passenger automobiles in the United States. In the past, automatic transmissions have been controlled by a hydraulic and pneumatic system, but the industry is moving toward electronic controls. The control system must determine the correct gear ratio by sensing the driver-selected command, accelerator pedal position, and engine load.

The proper gear ratio is actually computed in the electronic transmission control system. Once again, as in the case of electronic engine control, the electronic transmission control can optimize transmission control. However, since the engine and transmission function together as a power-producing unit, it is sensible to control both components in a single electronic controller.

Drive Shaft

The drive shaft is used on front-engine, rear wheel drive vehicles to couple the transmission output shaft to the differential input shaft. Flexible couplings, called *universal joints*, allow the rear axle housing and wheels to move up and down while the transmission remains stationary. In front wheel drive automobiles, a pair of drive shafts couples the transmission to the drive wheels through flexible joints known as constant velocity (CV) joints.

Differential

The combination of drive shaft and differential completes the transfer of power from the engine to the rear wheels.

The differential serves three purposes (see Figure 1.14c). The most obvious is the right angle transfer of the rotary motion of the drive shaft to the wheels. The second purpose is to allow each driven wheel to turn at a different speed. This is necessary because the "outside" wheel must turn faster than the "inside" wheel when the vehicle is turning a corner. The third purpose is the torque increase provided by the gear ratio. This gear ratio can be changed in a repair shop to allow different torque to be delivered to the wheels while using the same engine and transmission. The gear ratio also affects fuel economy. In front wheel drive cars, the transmission differential and drive shafts are known collectively as the *transaxle assembly*.

SUSPENSION

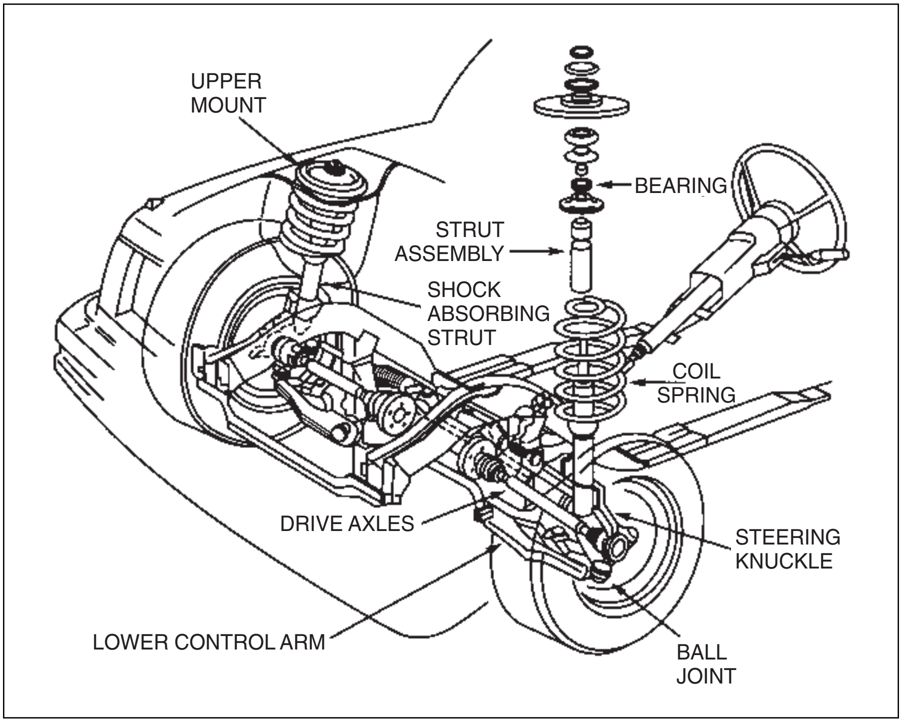
Another major automotive subsystem is the suspension system, which is the mechanical assembly that connects each wheel to the car body. The primary purpose of the suspension system is to isolate the car body from the vertical motion of the wheels as they travel over the rough road surface.

The suspension system can be understood with reference to Figure 1.15, which illustrates the major components. Notice that the wheel assembly is connected through a movable assembly to the body. The weight of the car is supported by springs. In addition, there is a so-called *shock absorber* (sometimes a *strut*), which is in effect a viscous damping device. There is a similar assembly at each wheel, although normally there are differences in the detailed configuration between front and rear wheels.

The mass of the car body is called the *sprung mass*, that is, the mass that is supported by springs. The mass of the wheel assemblies at the other end of the springs is called *unsprung mass.*

All springs have the property that the deflection of the spring is proportional to the applied axial force. The proportionality constant is known as the *spring rate.* The springs are selected for each car such that the car body height is as desired for the unloaded car. Typically, the weight on the front wheels is greater than on the rear wheels, therefore, the front springs normally have a higher spring rate than the rear.

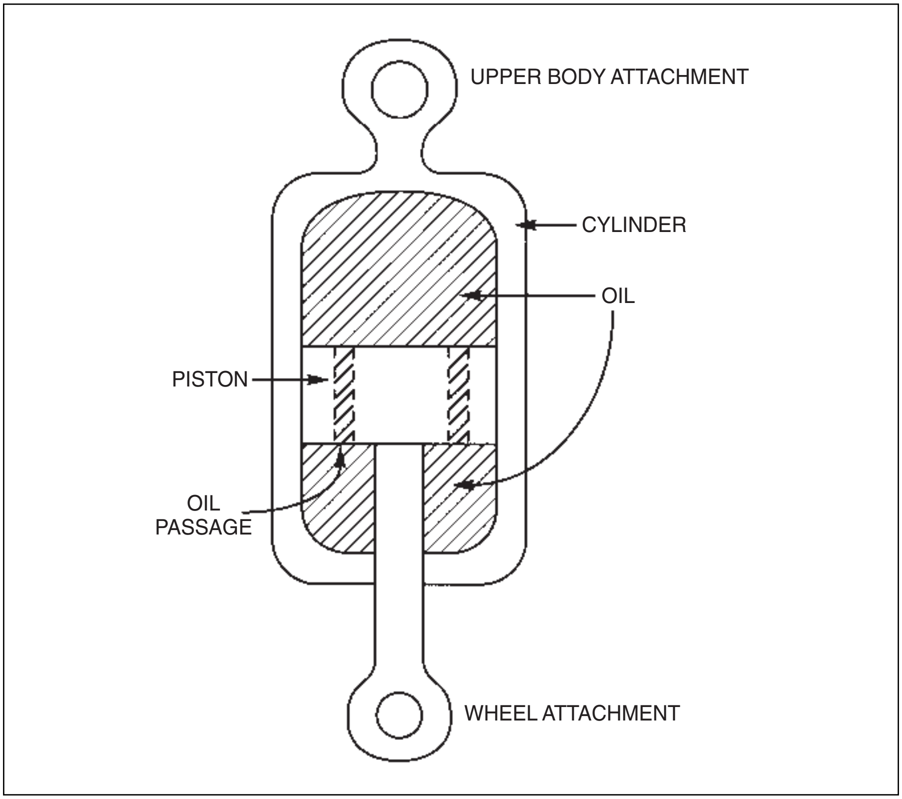
Figure 1.15
Major Components of a Suspension System



Similar to the springs, the shock absorbers (struts) also produce a force that acts to support the weight of the car. However, unlike the springs, the shock absorbers produce a force in response to the motion of the wheel assembly relative to the car body. Figure 1.16 is an illustration of a typical shock absorber.

The shock absorber consists of a cylinder and piston assembly. The cylinder is filled with a viscous oil. There are small oil passages through the piston through which the oil can flow. As the wheel assembly moves up and down, the piston moves identically through the cylinder. The oil (which is essentially incompressible) flows through the oil passages. A force is developed in response to the piston motion that is proportional to the piston velocity relative to the cylinder. This force acts in combination with the spring force to provide a damping force. The magnitude of this force for any given piston velocity varies inversely with the aperture of the oil passages. This aperture is the primary shock absorber parameter determining the damping effect and influencing the car's ride and handling. In Chapter 2, the influence of the shock absorber damping on wheel motion is explained. In Chapter 8, the mechanism for varying the shock absorber characteristics under electronic control to provide for variable ride and handling is explained.

Figure 1.16 Shock Absorber Assembly



BRAKES

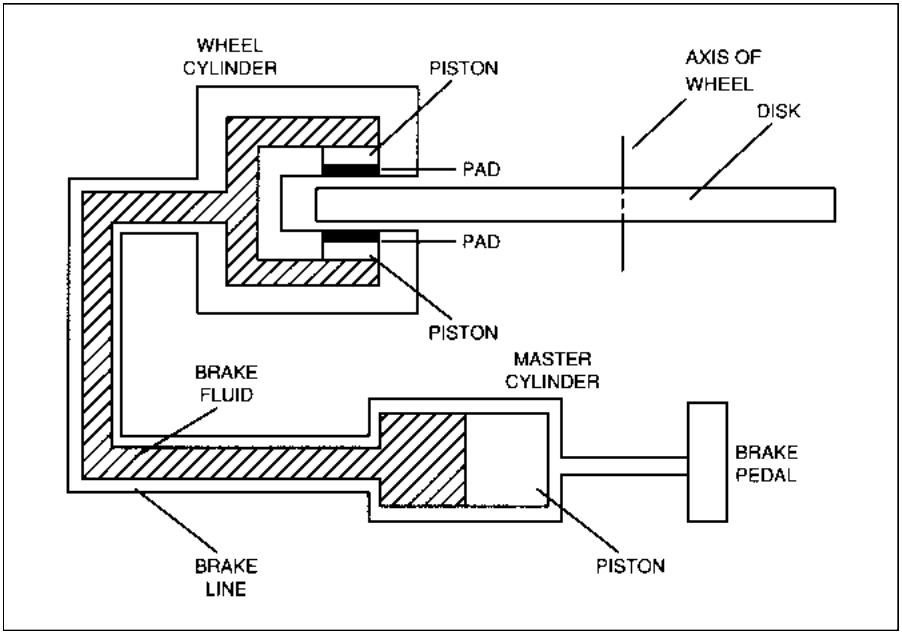
Brakes are as basic to the automobile as the engine drivetrain system and are responsible for slowing and stopping the vehicle. Most of the kinetic energy of the car is dissipated by the brakes during deceleration and stopping (with the other contributions coming from aerodynamic drag and tire rolling resistance).

There are two major types of automotive brakes: drum and disk brakes. Drum brakes are an extension of the types of brakes used on early cars and horsedrawn wagons. Increasingly, automobile manufacturers are using disk brakes. Consequently, it is this type that we discuss here.

Disk brakes are illustrated in Figure 1.17. A flat disk is attached to each wheel and rotates with it as the car moves. A wheel cylinder assembly (often called a *caliper*) is connected to the axle assembly. A pair of pistons having brakepad material are mounted in the caliper assembly and are close to the disk.

Under normal driving conditions, the pads are not in contact with the disk, and the disk is free to rotate. When the brake pedal is depressed,

Figure 1.17
Disk Brake System



hydraulic pressure is applied through the brake fluid to force the brake pads against the disk. The braking force that decelerates the car results from friction between the disk and the pads.

Electronic control of braking benefits safety by improving stopping performance in poor or marginal braking conditions. Chapter 8 explains the operation of the so-called *antilock braking system* (ABS).

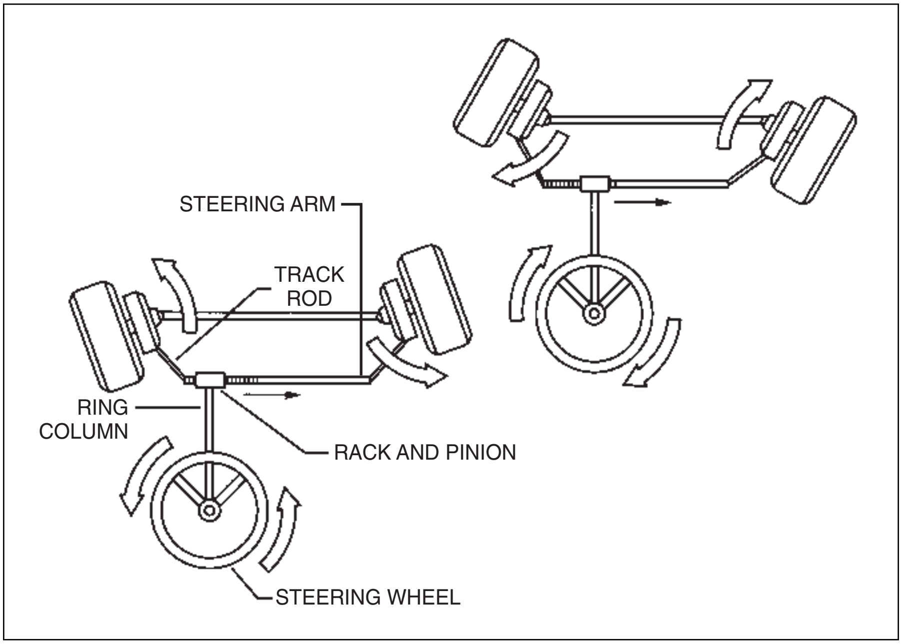
STEERING SYSTEM

A steering system is one of the major automotive subsystems required for operation of the car (see Figure 1.18). It provides the driver control of the path of the car over the ground. Steering functions by rotating the plane of the front wheels in the desired direction of the turn. The angle between the front wheel plane and the longitudinal axis of the car is known as the *steering angle*. This angle is proportional to the rotation angle of the steering wheel.

Traditionally, automotive steering systems have consisted solely of mechanical means for rotating the wheels about a nominally vertical axis in response to rotation of the steering wheel. The inclination of this axis gives rise to a restoring torque that tends to return the wheels to planes that are parallel to the vehicle's longitudinal axis so that the car will tend to travel straight ahead. This restoring torque provides a steering stability for the car.

When steering the car, the driver must provide sufficient torque to overcome the restoring torque. Because the restoring torque is proportional to

Figure 1.18
One Type of Steering Mechanism



the vehicle weight for any given steering angle, considerable driver effort is required for large cars, particularly at low speeds and when parking.

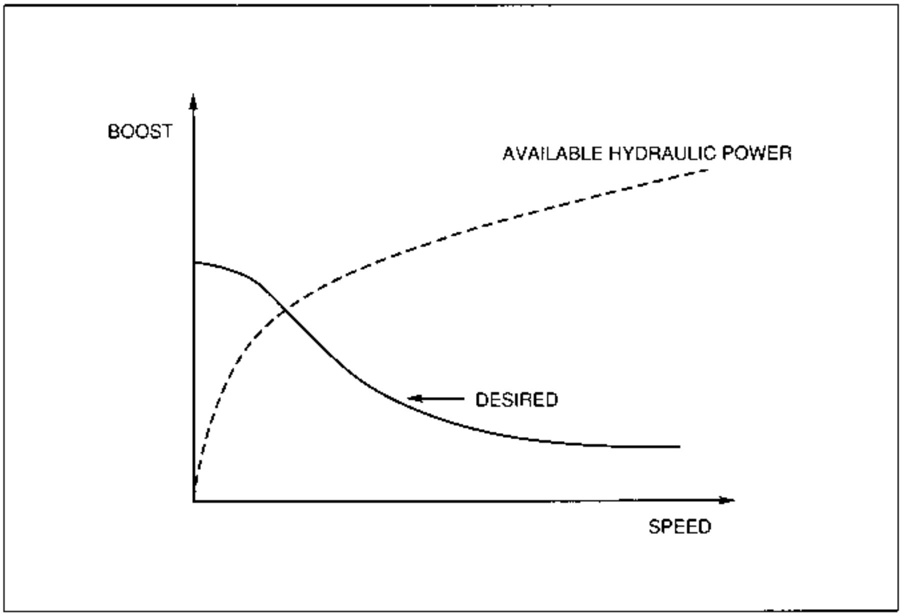
In order to overcome this effort in relatively large cars, a power steering system is added. This system consists of an engine-driven hydraulic pump, a hydraulic actuator, and control valve. Whenever the steering wheel is turned, a proportioning valve opens, allowing hydraulic pressure to activate the actuator. The high-pressure hydraulic fluid pushes on one side of the piston. The piston, in turn, is connected to the steering linkage and provides mechanical torque to assist the driver in turning. This hydraulic force is often called steering *boost*. The desired boost varies with vehicle speed, as depicted in Figure 1.19.

This graph shows that the available boost from the pump increases with engine speed (or vehicle speed), whereas the desired boost decreases with increasing speed. In Chapter 8, we discuss an electronic control system that can adjust the available boost as a function of speed to desirable levels.

In addition to the automotive systems described above, electronics is involved in the implementation of cruise control systems, heating and air conditioning systems, as well as entertainment and some safety systems. Moreover, electronics is responsible for introducing new systems that could, in fact, not exist without electronics, such as navigation systems, communication systems, and electronic diagnostic systems.

Once electronics had achieved successful application in engine control, the ball was rolling, so to speak, for the introduction of electronics in a variety

Figure 1.19 Desired Boost Versus Speed



of systems in the automobile. It will be seen that the very high cost-effectiveness of electronics has strongly motivated their application to various other systems.

SUMMARY

In this chapter, we have briefly reviewed the major systems of the automobile and discussed basic engine operation. In addition, we have indicated where electronic technology could be applied to improve performance or reduce cost.

The next few chapters of this book are intended to develop a basic understanding of electronic technology. Then we'll use all this knowledge to examine how electronics has been applied to the major systems. In the last chapter, we'll look at some ideas and methods that may be used in the future.

Quiz for Chapter 1

1. The term *TDC* refers to
   - **a.** the engine exhaust system
   - **b.** rolling resistance of tires
   - **c.** crankshaft position corresponding to a piston at the top of its stroke
   - **d.** the distance between headlights

2. The distributor is
   - **a.** a rotary switch that connects the ignition coil to the various spark plugs
   - **b.** a system for smoothing tire load
   - **c.** a system that generates the spark in the cylinders
   - **d.** a section of the drivetrain

3. The air–fuel ratio is
   - **a.** the rate at which combustible products enter the engine
   - **b.** the ratio of the mass of air to the mass of fuel in a cylinder before ignition
   - **c.** the ratio of gasoline to air in the exhaust pipe
   - **d.** intake air and fuel velocity ratio

4. Ignition normally occurs
   - **a.** at BDC
   - **b.** at TDC
   - **c.** just after TDC
   - **d.** just before TDC

5. Most automobile engines are
   - **a.** large and heavy
   - **b.** gasoline-fueled, spark-ignited, liquid-cooled internal combustion type
   - **c.** unable to run at elevations that are below sea level
   - **d.** able to operate with any fuel other than gasoline

6. An exhaust valve is
   - **a.** a hole in the cylinder head
   - **b.** a mechanism for releasing the combustion products from the cylinder
   - **c.** the pipe connecting the engine to the muffler
   - **d.** a small opening at the bottom of a piston

7. Power is produced during
   - **a.** intake stroke
   - **b.** compression stroke
   - **c.** power stroke
   - **d.** exhaust stroke

8. The transmission
   - **a.** converts rotary to linear motion
   - **b.** optimizes the transfer of engine power to the drivetrain
   - **c.** has four forward speeds and one reverse
   - **d.** automatically selects the highest gear ratio

9. The suspension system
  a. partially isolates the body of a car from road vibrations
  b. holds the wheels on the axles
  c. suspends the driver and passengers
  d. consists of four springs

10. The camshaft
  a. operates the intake and exhaust valves
  b. rotates at the same speed as the crankshaft
  c. has connecting rods attached to it
  d. opens and closes the breaker points

11. An SI engine is
  a. a type of internal combustion engine
  b. a Stirling engine
  c. always fuel injected
  d. none of the above

12. The intake system refers to
  a. the carburetor
  b. a set of tubes
  c. a system of valves, pipes, and throttle plates
  d. the components of an engine through which fuel and air are supplied to the engine