Higher-speed electronics can generate high power levels, so design techniques to minimize the power or cope with the existing level of power dissipation are being pursued. Novel cooling methods using heat pipes enable self-contained cooling capability. Higher-temperature operating materials such as gallium arsenide (GaAS), silicon carbide (SiC), and diamond are also being investigated by automotive electronics manufacturers to solve the heat problem. The most critical technology required to turn the semiconductor technology roadmap into reality is CAD—computer-aided design.

32.2.1 Design Methodology/CAD

Design is the activity that turns underlying technologies into product solutions that satisfy society's needs. Design, coupled with a testing discipline to ensure quality, is the vehicle that generates revenues for the industries. Today, design activity is based on a loosely coupled, ad hoc collection of tools and techniques. The most successful companies use highly refined design methodologies that are dependent on vendor-supplied point tools and are heavily augmented by proprietary tools that encapsulate each company's accumulated design expertise. Use of these tools outside the company's design groups is next to impossible. Over the next 5 to 10 years the complexity of chips will grow so dramatically that new tools and techniques for IC design will be required. Coupled with continuing pressures on reduced product development cycle time, error-free designs, and affordable test procedures, these CAD tools for IC design will have to extend well into the systems development environment. Electronic design automation (EDA) will not only be a necessity but it will also be the only way of handling the prevailing levels of device and system complexities. Without the advanced level of technology tools, expected performance and reliability levels will not occur.

32.2.2 CPU Architecture

MPUs and MCUs in vehicle control systems have been developed around complex instruction set computer (CISC) architectures. The availability of larger, faster memory technologies allows RISC architecture with simpler instructions to achieve higher throughput and faster cycle times. RISC design philosophy includes:

1. Fixed length, consistently encoded instructions
2. A register-to-register (load/store) architecture with primitive addressing modes
3. Relatively simple instructions
4. A large orthogonal register file
5. Three-operand (nondestructive) instruction format

MPU chips are available in 1994 with floating-point performance of SPECfp92* of 85 at 80 MHz. Over 1.6 million transistors are integrated in a chip that is only 85 mm^2. This performance level is considerably above the highest-performing CISC architecture and utilizes less silicon area.

The core processor has increased from 8 to 16-bits and now 32-bits to handle the number of calculations that are required in complex engine control systems. The 32-bit CPUs can deliver at least 50 times higher processing capability than the 8-bit designs. ABS systems are increasingly using 16-bit machines to reduce the time required to compute wheel speed inputs from analog sensors and activate the appropriate brake solenoids. Air bags have increased from simple to more powerful 8-bit MCUs when the air bag system uses electronic sensors.

Single-chip programmable digital signal processor (DSP) technology is used when mathematically intense algorithms, real-time operation, and high-speed data sampling are required in the control system. DSP units have been designed into sophisticated audio entertainment,

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dynamic ride control, and noise cancellation systems. DSP units incorporate Harvard architecture similar to many MCUs and MPUs; extensive pipelining; dedicated hardware multiplier; special instructions not typically found in MCUs, such as multiply and accumulate (MAC); and fast instruction cycle times, less than 50 ns. DSP design can also be integrated into MCUs to provide similar functionality for systems.

It is important to note that automotive electronics manufacturers will benefit from higher levels of technology, but use of high-level electronics in the auto industry lags behind other segments, partially due to the design-in time and partially due to the cost. Only the level of performance necessary to solve the control problems that are expected to be encountered during the design life of the electronics is implemented. Figure 32.1 shows a general technology roadmap for one semiconductor manufacturer (Motorola) that provides detail for some of the elements of future semiconductors. The products that drive future technology are high-end microprocessors and fast static RAMs (SRAMs). However, other products, including logic, mixed-signal (analog/digital), sensors, and power devices, benefit from the improved process techniques and the tools that are developed to provide them.

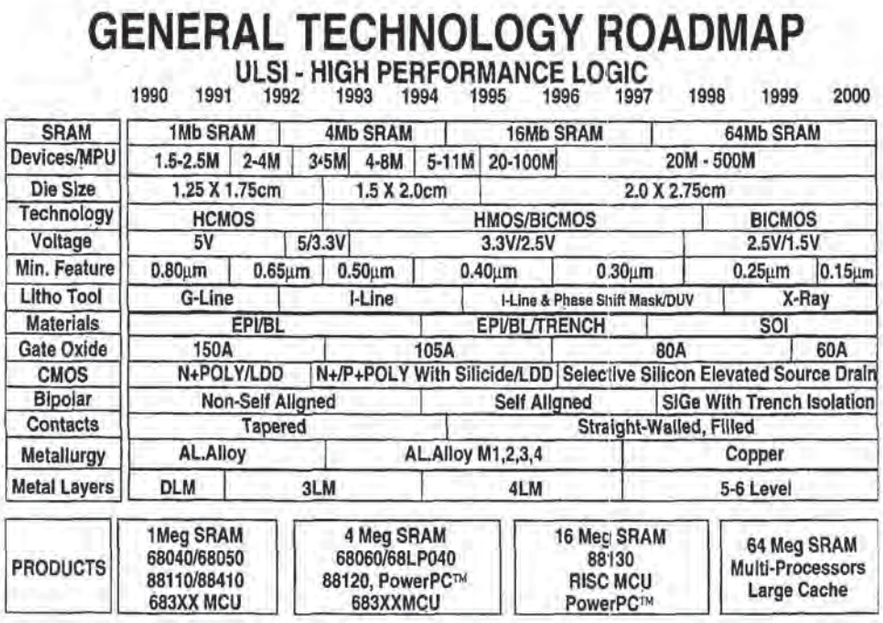


FIGURE 32.1 Operating frequencies/feature size/integration level.

32.2.3 Memory

As part of reduced vehicle development time, electronics module manufacturers need semiconductor suppliers to turn ROM circuits in shorter and shorter design time. Also, new memory types, such as flash memory, are required to allow manufacturers to reprogram when the memory is installed in the module and still be reliable under all vehicle operating modes for the remaining life of the vehicle. Future developments include the ability to reprogram at lower voltages: 5 V and even 3 V.

Figure 32.2 shows the increase in memory, throughput, functions, and inputs and outputs (I/O) since model year 1980 and an estimate for model year 2000. The most dramatic increase has occurred in the memory (RAM). Program memory (ROM) is also increasing. Memory in future MPUs will be limited more by the programmer's ability to generate the code than by the hardware's ability to store or process it—unless fundamental changes occur to the process of code generation.

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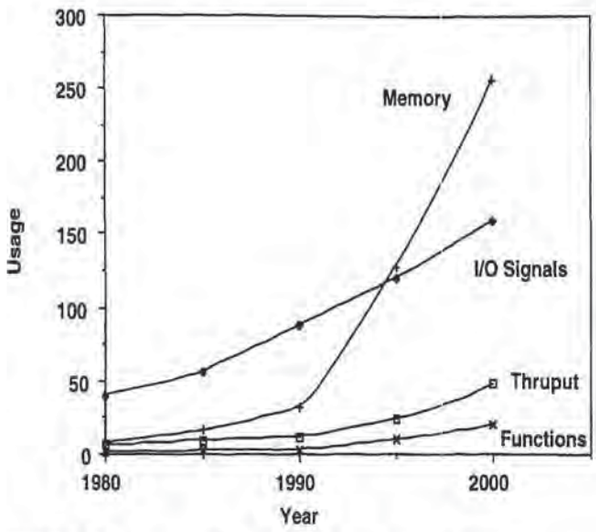


FIGURE 32.2 Automotive usage of microcontroller technology.

32.3 OTHER SEMICONDUCTOR TECHNOLOGIES

Semiconductor technology is also being applied to both the input and output side of the digital control to improve the performance of sensors and provide more efficient power switches. Both sensing and power devices are the focus of increased integration. The extent of integration depends on system constraints in the automobile in addition to the technology that is developed by semiconductor manufacturers. This section will discuss key items affecting future levels of system and component integration.

32.3.1 Micromachining and Microelectronics

Semiconductor technology is also being applied to manufacture mechanical structures in silicon that provide more reliability, higher accuracy, and higher functionality, while also lowering the cost of sensing for the automobile. Continued use of these techniques for more complex structures and combined sensors (e.g., pressure and temperature) will increase as university, government, and industry R&D technology is adapted by sensor and semiconductor manufacturers. Sensor technology has been identified as one of the key factors required to maintain leadership in automotive electronics.

Increased electronics will be used with these sensors either by simultaneously fabricating electronic circuitry with the mechanical structure or by packaging techniques such as multichip modules. Figure 32.3 shows a sensor technology migration path that ultimately has the sensor(s) fabricated directly on CMOS MCUs. While the cost of this final form may be several years away from the level necessary for automotive use, the technology capability can be demonstrated today. Intermediate forms of integration with CMOS memory components used for calibration and localized digital logic providing decisions are extremely likely within the near future (before 2000). The electronics system design will change as inherently digital signals, instead of analog, can be input directly to the MCU. These signals could be at the level that allows usage by several vehicle systems using a multiplex (MUX) bus. However, standards, such as SAE J1850, will be necessary to make the digital output transducers as readily available from many sources like today's analog output sensors.

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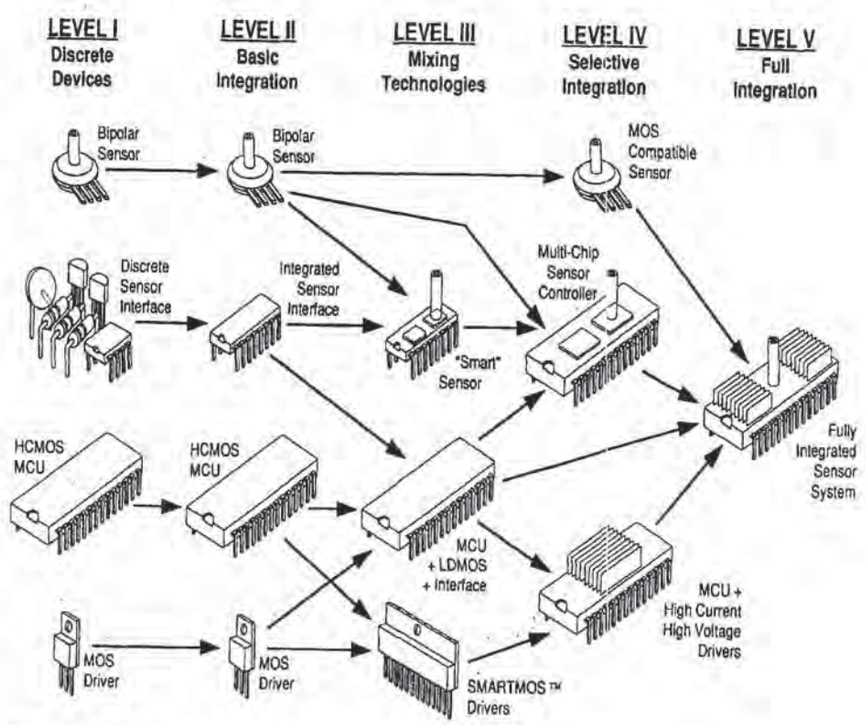


FIGURE 32.3 Sensor technology migration path.

32.3.2 Voltage Capability

In order to achieve high density in integrated circuits, the maximum voltage is being reduced from 5 to 3 V in computer and portable products. This level will be reduced even further as higher levels of integration require smaller and smaller geometries, and portable products are designed to operate at even lower voltage levels. Since this area is considerably larger than the automotive electronics area, it represents the mainstream of electronics technology. The automobile, however, operates from a 12-V battery today and is being pushed toward higher operating voltages to handle the ever-increasing loads that are part of every new vehicle system. Even the 12-V system has to deal with considerably higher voltage due to transients, including load dump. Electric vehicles will have a battery supply over 200 V. The requirement to withstand higher voltages reduces the efficiency of power semiconductors. Furthermore, the voltage extremes affect the choice of power devices and the level of integration that can be achieved. If the system voltage is increased to 24, 36, or 48 V, semiconductors will be among the system components that are significantly affected by the higher voltage.

32.3.3 Power Control

Depending on the vehicle, every 10 A of electric load reduces fuel economy by 0.3 to 0.5 miles per gallon. Design changes to cope with increased loads include:

- More energy-conserving designs
- Smarter power supplies that manage peak alternator-current demand
- Overvoltage transient protection from one central location, which is even more important if system voltage is increased
- Two 12-V batteries per system, especially on high-end vehicles

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More efficient power devices are required to reduce overall vehicle power consumption and to reduce power dissipated in electronic modules. The on-resistance area product has been reduced nearly tenfold from the early 1980s to 1993, since the first use of power MOSFETs on vehicles. Further improvements are made by reducing all of the resistive elements of the MOSFET, including metal connections to the package, starting material and cell structure. Figure 32.4 shows how the specific on-resistance can be reduced by using high-cell-density power MOSFETs and lower voltage ratings. Ignition coil drivers are high-voltage (greater than 350 V) applications on internal combustion vehicles where insulated gate bipolar transistors are more efficient than power MOSFETs or bipolar power transistors.

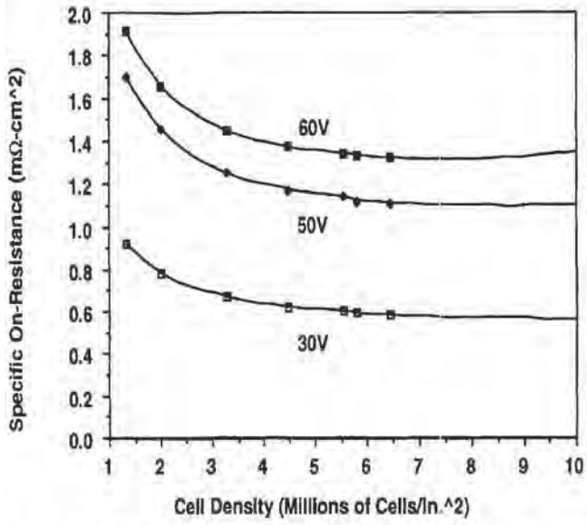


FIGURE 32.4 Power efficiency vs. voltage.

Merging power devices with control circuitry is also part of the integration that is occurring at an increasing rate as system complexity increases. Several design and processing techniques are used to merge these devices depending on the switch type and performance expectations. Table 32.3 provides some indication of differences in commonly used processes. Smart power, or power ICs are the terms that are generally used to describe these types of power devices.

The smart power approach to system design means that a number of circuit elements that would previously have been discrete components or the combination of a standard, or custom IC, and discrete output devices can be consolidated into one single device as illustrated in Fig. 32.5. This provides space saving, component reduction, total system cost reduction, improved performance, and increased reliability from the reduced number of interconnections. The choice of process technology has historically depended upon the type of control elements that were integrated. Some circuit elements, such as operational amplifiers (op amps), compara-

TABLE 32.3 Power ICs Attributes

	Circuit components			Switch type			
Isolation process	Power MOSFET	CMOS	Bipolar	High side	Low side	Complexity	Breakdown voltage
Self	Yes	Yes	No	Yes	No	Simple	Low
Junction	Yes	Yes	Yes	Yes	Yes	Medium	Medium
Dielectric	Yes	Yes	Yes	Yes	Yes	High	High

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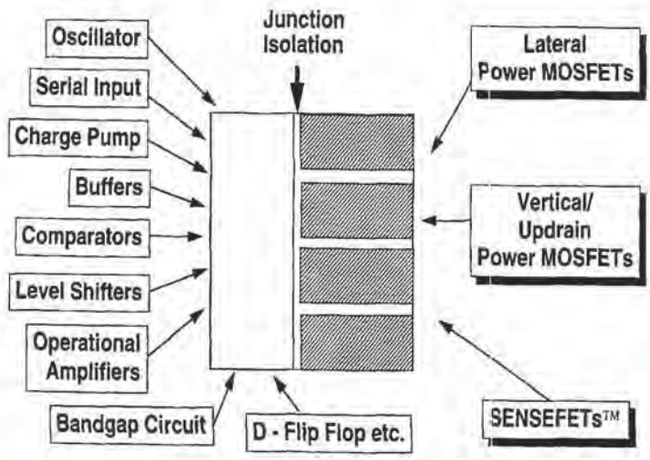


FIGURE 32.5 SMARTMOS™ technology cells.

tors, and regulators, are best implemented using a bipolar IC process. MOS circuitry handles logic, active filters (time delays), and current mirrors better than bipolar circuitry. Some circuits, such as A-D converters or power amplifiers, can be implemented equally well in either technology. A process that has both MOS and bipolar for the control circuitry does not have to sacrifice performance or features and, if it is combined with the appropriate output devices, it can handle the power control functions for a number of vehicle loads.

The need for increased diagnostics to meet legislated requirements, such as OBD-II, and to minimize time required to analyze vehicles experiencing faults is increasing the use and complexity of smart power devices. Power devices that can handle several amperes and operate at voltages in excess of 60 V have already been integrated into MCU processes. The number of loads that are controlled, the current and voltage rating of the output devices, and the power dissipation are factors that system designers must consider when evaluating the level of integration of power devices.

The three levels of power devices involved in automotive systems are power MOSFET, smart power IC with one or more power outputs, and MCU with integrated power devices. Integration in each of these levels and efficiency will improve in future systems. The ability to integrate memory components and transmit and receive digital signals at the power side of the control system is necessary in MUX systems. This also allows the system designer added flexibility in system partitioning.

32.3.4 Semiconductor Operation at High Temperatures

Increased operating temperatures are driving development for new materials such as GaAS (gallium arsenide) and other III-V, wide band gap, semiconductor materials, SiC (silicon carbide), and diamond films. Other wafer-level assembly techniques that can provide more reliable operation at high temperature, such as wafer-to wafer bonding and dielectric isolation, are part of today's semiconductor technologies that will be used in future vehicle electronics. As Chap. 5 pointed out, higher temperatures decrease reliability of electronic components. Therefore, improvements that allow higher temperature operation are being evaluated, and sometimes are a driving force for improving reliability. Some advanced materials, such as GaAs, also allow higher frequency operation or increased efficiency, providing additional incentive. The materials and techniques are being investigated for sensors, power, computing, and communication semiconductors. Their acceptance in one area could increase the effort to

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design and qualify similar technologies in other areas. However, at present these approaches are more expensive and would only be used if they solved a problem that had no alternative solution.

32.3.5 High-Frequency Semiconductors

Increasing communication to and from the vehicle requires radio frequency (RF) transistors to receive and transmit signals and data. High-frequency operation is required for cellular communications and sensing in systems such as near obstacle detection. Several technology choices exist in the RF front end of a communication product that must operate at 900 MHz as Fig. 32.6 demonstrates. Silicon competes with GaAS in the 1- to 2-GHz range, but in the 2- to 18-GHz range, GaAs is the only solution. In 3-V, high-frequency (1-GHz) operation, GaAs has an efficiency of 50 percent versus silicon bipolar's 40 percent or LDMOS's 43 percent. Chipset approaches are frequently used in the early phases of system design and can be cost effective alternatives to higher levels of integration. High-frequency designs for radio frequency are considerably different than high-speed digital processes, which limits the integration of these subsystems. The frequency range is much higher in RF circuits, frequently 800 MHz and higher. Mixed-signal technology in these designs means not only digital and analog but also RF must be processed. Circuit isolation is required to prevent unwanted coupling of signals which can range from 3 V peak-to-peak to less than 1 μ V peak-to-peak. RFIC (radio frequency integrated circuits) technology or MMIC (monolithic microwave integrated circuit), and MESFETs are part of the communications semiconductors that will be used in future vehicles.

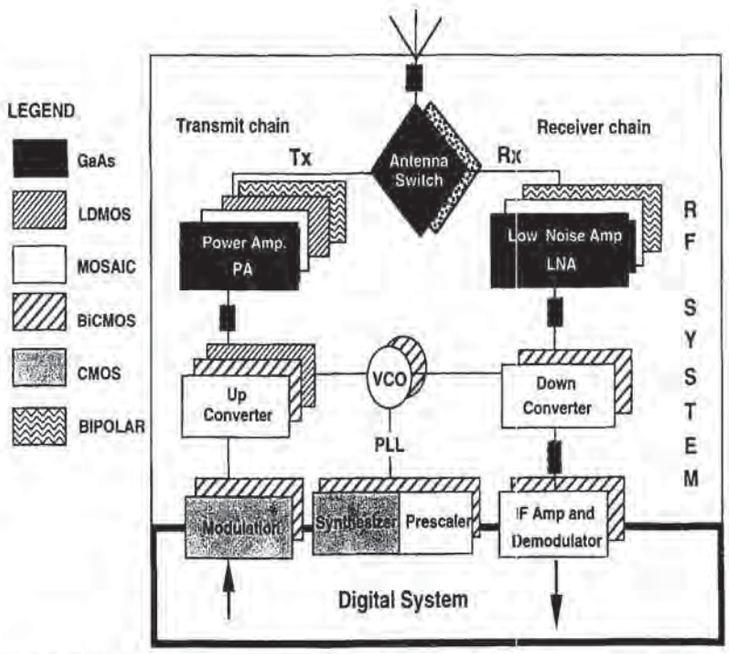


FIGURE 32.6 RF semiconductor technologies.

32.3.6 Semiconductor Packaging

Auto module manufacturers are using surface mount assembly techniques to improve reliability, reduce component size, and incorporate more functions in a given module form factor.

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A number of SOIC packages are available for handling high-pin-count I/O in logic or high power in power ICs. Assembly techniques for surface-mount technology (SMT) also include flip chip, TAB (tape automated bonding), COB (chip on board), and bare die.

In many respects, the packaging requirements for highly integrated devices are similar to those for the full module. These include power distribution, signal distribution, heat dissipation, and circuit protection. In harsh applications, like the underhood mounting of automotive controls, hot and cold temperature extremes can result in severe damage to the electric connections in electronic components. Reducing the number of connections in a module, through the integration possible in a process like smart power ICs, reduces the number of potential failure points.

As more and more functionality is included in an IC design, the number of external components is reduced. This inherently lowers the number of solder joints that are required in a particular pc board layout. This can significantly reduce the potential for rejects in the surface-mount soldering operation. Unfortunately, in highly integrated silicon designs, packages are also required with power-dissipating capability and/or access to sense a mechanical input, such as a pressure port. These "combined" packaging problems have been solved at the module and not the semiconductor level. Smart power packaging engineers address the requirement for more complex I/O and higher power dissipation with increased lead count packages and integral heat-spreading capability. Sensor packaging engineers cope with increased media compatibility and higher pin count issues with new materials and unique attachment/access methods for pressure, acceleration, magnetic, or light sensing. Complex microcontrollers have high pin counts (≥256 pins) with close spacing and high coplanarity requirements. Still other silicon processing technologies are required to provide system glue-chips that provide interfaces that are not cost-effectively integrated in a particular time frame. As a result, three or more packaging roadmaps are pursued.

To achieve increased functionality without increased silicon complexity, available silicon technologies are being combined at the package level in packages based on semiconductor, not module manufacturer, assembly techniques. These multichip modules (MCMs) are being evaluated for automotive applications. There has been a decline in the use of the previously popular DIP (dual in-line plastic) package. Other through-hole packages, such as SIP (single in-line plastic) and PGA (pin grid array), will also not increase. New SMT approaches, such as BGA (ball grid array) packages, are the focus of present packaging development. For future highly-integrated components, packaging techniques must take into account more complex, system-level requirements, as well as SMT assembly requirements.

Testing is also a major consideration as more and more functionality is combined into one package. In some instances, the ability to provide fully functional, fully tested silicon die is required for products that are provided in packaged form today.

32.3.7 System-Level Integration

Increased integration is occurring to achieve increasingly more cost-effective systems. However, integration necessary to have all system components, MCU+power+sensor(s), on the same chip, can lead to mask levels that are well beyond the level necessary to obtain reasonable yields. Those components that would significantly add to the cost or detract from the performance must be partitioned as a separate system component. Integration can minimize some unwanted components, such as parasitic capacitances or lead inductances, but it can also lead to unexpected interaction of other circuit elements. Proven building blocks or modules increase the confidence that a new silicon design will work properly the first time.

System-level chips based on structured design approach are just starting to appear. For example, Motorola's CSIC, or Customer Specified Integrated Circuit, is a modular design approach that has over 150 developed combinations for solving a variety of 8-bit control problems. Figure 32.7 shows the concept of a System Chip™ integrated solution that combines input, output, and computation in a monolithic silicon chip. The MC68HC705V8 is an exam-

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ple of today's level of system integration. It is a necessary first step towards the more complex systems of tomorrow. This chip has an on-chip voltage regulator, a complete single-wire multiplex interface message data link controller, and various memory functions. The voltage regulator provides a regulated 5 V (±5 percent) from battery voltages between 7 and 26.5 V and can withstand alternator transients up to 40 V. As noted in Sec. 32.2.2, required cost-effectiveness by automotive electronics also applies to levels of integration. In a given time frame, higher levels of integration may be possible, but not cost effective. The ability to shift portions of the system from one unit to another, and partition the system for the most cost-effective approach in the most timely manner, is the goal of auto electronics manufacturers and the force behind approaches like Motorola's Seamless Silicon System™ methodology. This technique will allow common design rules for various silicon components, including MCUs, smart power and sensors, that will facilitate integration paths like the one shown in Fig. 32.3. However, when separate devices are determined to be more cost effective, the decision to have them as separate components will be a simple choice of the designer.

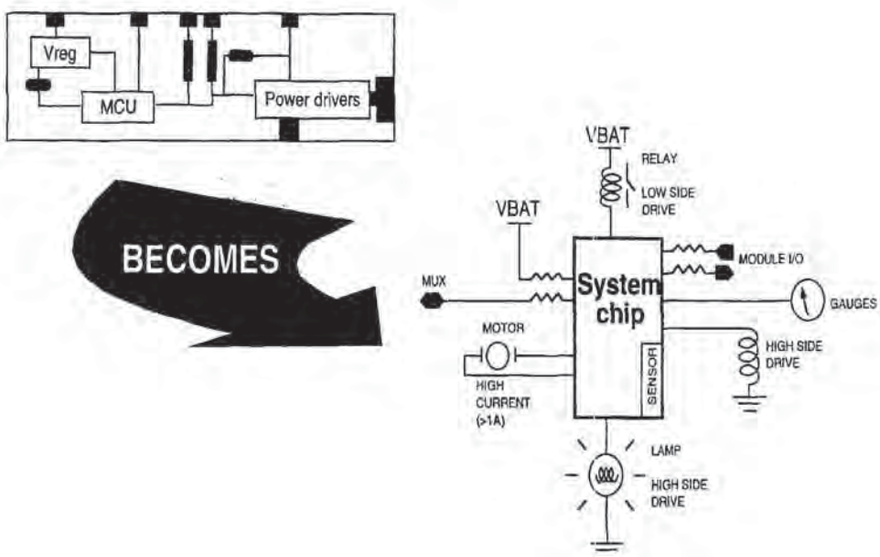


FIGURE 32.7 System Chip™ integrated solution.

32.4 ENABLING THE FUTURE

Driving forces for automotive manufacturers ultimately drive the electronic content of future vehicles. The major areas that impact electronics include meeting government regulations, environmental responsibility including recyclable materials, automotive manufacturing technology (and the transition from lean to agile manufacturing), improved security, increased safety to eliminate auto fatalities, reduced vehicle development time, high-efficiency 80-mpg super car, and the "personalized" car.

The first five items will be covered in more detail later in this section. The last three items on the list reflect key topics that are extremely timely and may not have appeared on a list developed in the 1980s.

United States manufacturers have gone on record with their goals of developing new vehicles in less time. In the mid-90s these goals are three years or less instead of the historical five years. Japanese manufacturers are already at the three-year design level and Chrysler has demonstrated the ability to design new vehicles in as little as 18 months. This will result in even shorter design cycles in the future. As a result, the more complex electronics that will be

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part of these systems must be designed and verified in even less time than in the early 90s. This will require even closer linkage between semiconductor suppliers and automotive electronics manufacturers not only in hardware but also in the tools and software area as well.

The goal of a high-efficiency super car that can achieve 80 mpg is among the changes that can suddenly shape the direction of future electronics. While continuously more fuel-efficient vehicles have been developed over the past 20 years, government support for a reach-out goal can reduce the R&D time for enabling technologies.

Personalization in an increasingly nonpersonal world is among the marketing strategies that can impact electronics. The memory and automatic adjustments that are possible with electronics are already used to preset seat position and favorite radio stations when the automatic door opener identifies the driver of a multiple-driver vehicle. Electronics is also an essential part of the features used to differentiate vehicles. Increased marketing and manufacturing approaches to customize vehicles will increase the amount and variety of electronics, and of course, semiconductors in the vehicle. An excellent example is an office-on-wheels that has cellular phone, FAX, and printing capabilities as key accessories.

Achieving the goals of the auto manufacturer will require that automotive electronics and semiconductor manufacturers work together to provide fewer boxes, higher levels of integration, increased reliability, cost reduction (system, component, and assembly), surface-mount components, electronic replacements for mechanical components (relays, sensors, etc.), and reduced hardware and software design/development time.

The systems approach must be applied to a specific vehicle system, to the vehicle itself, the vehicle as a part of the transportation system, and, ultimately, as part of society (i.e., ecology, and the use of resources). A further understanding of the forces that are driving automotive electronics is gained by reviewing the changes that will occur by implementing IVHS, increased safety, the potential for antitheft/security, issues driving the EPA, consumer demands, and the effect of other industries on automotive electronics.

32.4.1 Changes from IVHS

Worldwide efforts in intelligent vehicle-highway system (IVHS) will change the electronics in the vehicle and the way systems are configured (see Chap. 29). The goals of IVHS will determine the nature of hardware that is required: reducing traffic congestion; improving safety; enhancing mobility of travelers, especially the elderly and disabled; increasing the productivity of the transportation infrastructure; reducing energy use; reducing pollution; reducing capital and operating costs; increasing the viability of public transportation; responding more effectively to incidents; and increasing the ease and convenience of travel.

Achieving these goals will require several new vehicle and infrastructure systems and associated electronics to enable the control strategies. On the hardware side, sensors are the most critical enabling technology. However, software is predicted to be the most labor-intensive aspect of the development activities.

32.4.2 Safety

Harry Mathew, a vehicle safety expert at Arthur D. Little, has made several predictions based on the need for improved safety in vehicles. Implementation of technologies that are discussed today is shown in Table 32.4. These areas and timing can be compared to projected penetration of super-smart vehicle systems (SSVS) in Japan that are shown in Table 32.5.

The emphasis that government and consumers place on aspects of vehicle technology will determine which elements are exploited in production vehicles. For example, the reporting of safety performance of vehicles in 35-mph frontal crashes by the National Highway Traffic Safety Administration (NHTSA) is intended to be a more consumer-oriented look at the probability of injury. This could result in even greater focus being placed on air bags, especially dual air bags and their effectiveness in preventing injuries by auto manufacturers.

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TABLE 32.4 Timing and Implementation of New Vehicle Systems

System/Technology	Timing
Air bags	Mandatory by 2010
Keyless entry	Widespread use by 2030
Remote control starting	Widespread use by 2030
Programmable position controls	Widespread use by 2030
Integrated traction control and ABS	2030
Addition of power steering to above	2060
IVHS	2050
Collision avoidance (radar & auto pilot)	Late 21st century

TABLE 32.5 Penetration of SSVS Technologies in Automobiles

SSVS technology	Phase I yr 2000	Phase II yr 2010	Phase III yr 2020
Obstacle detection	20%	50%	80%
Road geometry detection	10%	40%	40%
Collision warning	10%	60%	80%
Auto braking/steering		10%	60%
Pedestrian detection		10%	60%
Driver assistance		10%	60%
Auto lane following			10%
Accident reduction	4%	20%	43%

32.4.3 Antitheft/Security

Antitheft equipment is an area that has developed from aftermarket implementation of products into OEM level. Auto theft cost American consumers nearly $10 billion per year. NHSTA estimates that between 10 and 16 percent of auto thefts are by professional chop shops that strip and sell the parts. The effectiveness of antitheft systems against professional versus novice-level thieves is among the criteria that may have deterred their use by OEMs. However, electronic antitheft devices (see Chap. 24) are available that range from simple sensing and warning devices to cellular tracking systems with the ability to locate and disable the vehicle. For example, GM's Pass-Key™ system is offered as an OEM product and is expected to be installed on more than 40 percent of GM vehicles by 1995. Auto theft is a worldwide problem that varies in significance in other regions. This could be an area of increased usage and the target of integrated control strategy in the future for OEMs.

32.4.4 EPA Driving Forces

The top official in the EPA has the following issues to address:

- Finalize rules for on-board vapor recovery during refueling
- Monitor implementation of California's Low Emission Vehicle (LEV) program
- Determine whether Northeast states can adopt California's LEV standards
- Resolve third-car controversy (states adopting California LEV standards without California clean-fuel standards)
- Monitor phase-out of CFCs and phase-in of replacement coolants
- Finalize regulations for on-board diagnostic computers to monitor emission control systems
- Finalize rules for cold temperature carbon dioxide emissions controls
- Finalize rules for evaporative emission controls

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The involvement of electronics and next-generation semiconductors to solve these problems has been discussed in several chapters.

32.4.5 Consumer Demands

A consumer survey of 1000 Southern California drivers indicated the following preferences for 1997 vehicle power sources with more than one choice possible: gasoline (34 percent), hybrid—electric and gasoline (29 percent), electric (26 percent), natural gas (16 percent), methanol (15 percent), diesel (4 percent), and don't know (7 percent). Satisfying these different vehicle preferences should be the target of manufacturers' product plans. Electric vehicles specifically require a broad range of semiconductor technology, some of which will be unique to the operating voltage of these vehicles. With growing concern for the environment, vehicle manufacturers can potentially segment their market and address a previously undefined customer.

Industry monitoring by groups like *Consumer Reports* of vehicle reliability can shift manufacturers' emphasis towards other items, such as owner satisfaction indices. Electronics has been recognized for its ability to provide more reliable automobiles in spite of the increased complexity.

32.4.6 Effect of Other Industries on Automotive Electronics

Looking outside the industry for technology driving forces can provide insight to avoid being blindsided by new approaches. Many of today's automotive controls result from the use of aerospace technology and displaced engineers during the 1970s. Today's use of military-developed technology, defense engineers, and national laboratories to develop next-generation hardware and software may change automotive systems. However, the computer industry is a prime mover of the highest level of integrated semiconductors and has over eight times the sales of automotive semiconductors. In the computer industry, the term *convergence* is being used to describe the merging of computing, communications, and consumer electronics that is occurring in new products aimed at highly portable computing.

The vehicle of the future could provide a docking/recharging station for a device that provides paging, cellular phone, digital notebook, calendar of events, personal tracking, FAX modem, and all the programs of a personal computer (pc), yet weighs only a few kilograms. The linkage of this unit to other vehicle systems could appeal to a new classification of automotive consumers. Manufacturers already have incorporated cellular phones into the steering wheel to provide a safer, more user-friendly means to dial. However, portable units that individuals will want to take to and from their vehicle will define new automotive products.

32.4.7 Software

Making the transition from one technology to the other and providing a transparent-to-the-driver feel for any future system will require extensive software. Three phases have been previously identified in the evolution of automotive electronics. Initial electronic components were diodes, transistors, and analog ICs in alternators, voltage regulators, AM-FM radios, and clocks. Phase II was the result of government regulations and enabled by the usage of microcontrollers in vehicle control systems. Phase III is marked by the use of smart peripherals, smart power drivers, and smart sensors, to bring the hardware closer to the capability of MCUs. The next phase will be the "software era," in which emphasis will be focused on standard open architecture; in-vehicle network backplane; factory, dealer, and consumer levels of configurability; neutral programming languages, and user-friendly software.

Advanced tools are required to deal with the increased level of software. From the semiconductor perspective, schematic capture, VHDL (VHSIC hardware description language)

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simulation, and synthesis generator tools are already used with products like field-programmable gate arrays (FPGAs). The extension of electronic design automation (EDA) software linking control system requirements to silicon design is necessary to complete the process. This is only one part of the software issues. Others are increased memory = increased development time, code reliability/ruggedness, code portability/upward compatibility, tools for code development, verification/testing aspects including tools, software—the "differentiator" for future systems, software design cycle time reduction, software independent of hardware, and digital and analog simulation.

Along with more complex hardware and software comes the need for improved testability to ensure that these more complex systems work the way they were designed. Powertrain vehicle personalization, IVHS, and hybrid vehicles are expected to be even more important to future automotive growth than air bags and antilock braking systems were in the early 90s. Testing is critical during assembly, at the end of line, and in service. Design for testability (DFT) methodology must be implemented at the beginning of the design process to satisfy the full range of test requirements. Techniques have been developed, including boundary scan and built-in self-test (BIST), that must be utilized. The IEEE JTAG (Joint Test Access Group) standard, OBD-II, and others that may be developed must be implemented to allow equipment manufacturers a common methodology for developing new equipment.

Today's high-end microprocessor designs already have clock rates that exceed 80 MHz and are capable of executing several millions of instructions per second (MIPs). To utilize this, and even greater, capability in future automotive products, automotive designers will have to spend far more time developing software than they did in the previous generations of products. This will require a different approach to software—one that starts with a formal software department dedicated to developing structured code. Sophisticated debug and system integration tools developed for the semiconductor industry must be implemented in a networked environment to support and facilitate a team approach to software.

In addition to digital simulation, complex analog systems also require analysis techniques beyond those used in today's vehicles. A simulator, such as Analogy's Saber™ simulator, can provide templates for various power supply topologies and evaluate virtual silicon prototypes in place of actual units to reduce cycle time and ensure adequate performance in production units.

EDA has been recognized for its ability to help vehicle manufacturers. Benefits that car makers are realizing include more effective and productive design engineers; parallel efforts in the design phase; simulation of more alternatives, early problem resolution, and optimization of final design; and the ability to incorporate more value-added electronic features for product differentiation.

The extent of interaction that must be analyzed and understood to provide future vehicle controls is extremely complex and will require several systems that simulate everything from vehicle combustion process to air bag deployment and driving simulation. Figure 32.8 shows a simple interrelation among the driver, his vehicle, and the environment. The ability to link together these systems and provide increased control to the driver will be the challenge for designers of future vehicles. This will require new semiconductor hardware, advanced development tools, and an unprecedented amount of software.

32.5 IMPACT ON FUTURE AUTOMOTIVE ELECTRONICS

Section 32.2.1 brought out the designer's role in future, sophisticated electronic systems. The enabling semiconductor technologies will be available. One potential system evolution path that could be taken to consolidate electronics in the passenger compartment is shown in Fig. 32.9. Given the level of complexity in the final stage, changes must be made in the way systems are designed.

A typical synthesis pipeline of today's design for digital electronics, which shows how an idea becomes a finished semiconductor product, is shown in Fig. 32.10. The RTL (register

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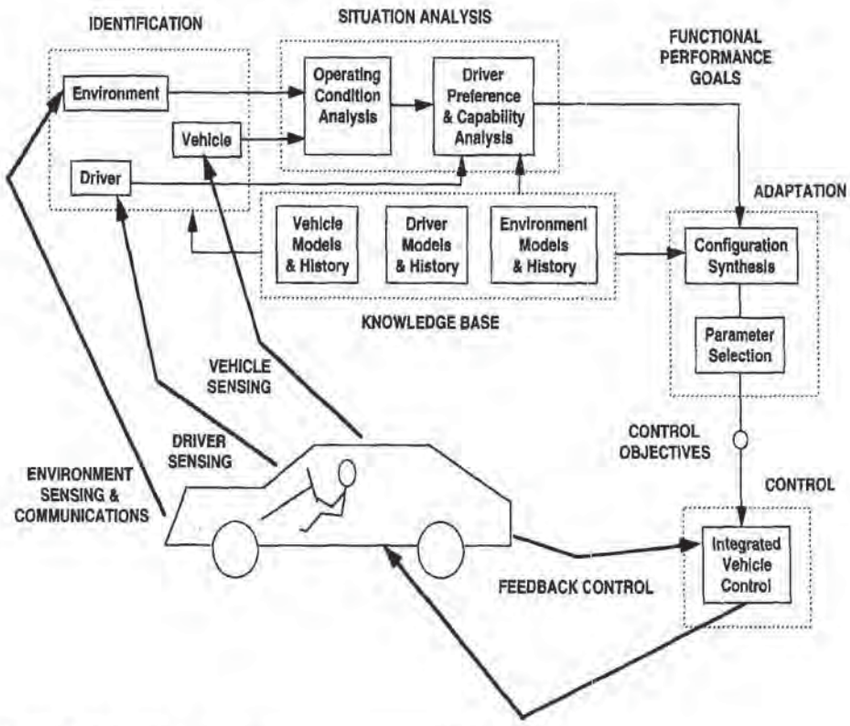


FIGURE 32.8 Vehicle, driver, and environment interrelationships.

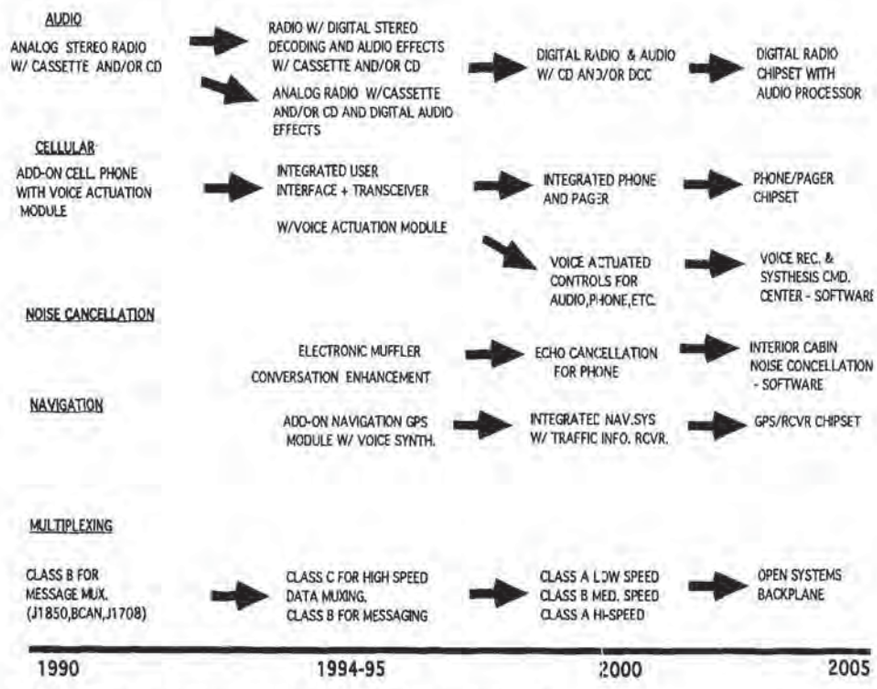


FIGURE 32.9 Audio, communication, navigation systems evolution.

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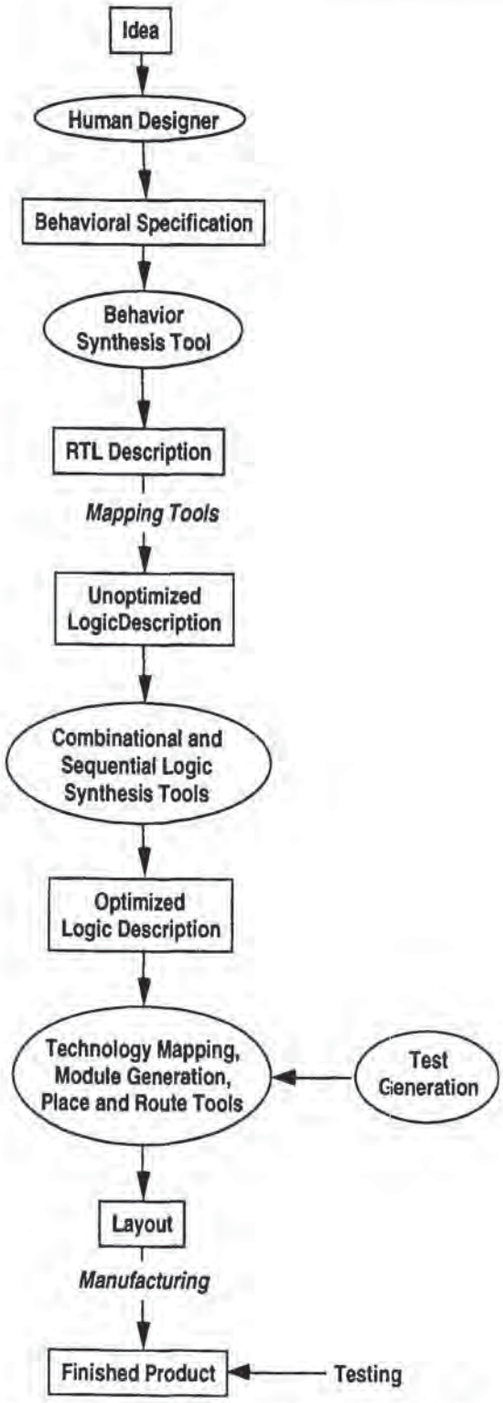


FIGURE 32.10 Typical synthesis pipeline of today's design of VLSI silicon chip.

transfer level) description is the area where the functionality of the ALUs (arithmetic logic units) and buses are specified by the chip architect. The RTL description is an interconnection of predefined modules such as adders, multipliers, or finite state machines that comprise controllers. The sequential logic description that accomplishes the desired behavior of the system is performed by logic designer(s). Finally, circuit designers optimize the transistor-level design created by logic designers.

Challenges in automating this process include the need for a new breed of designer, the system architect, who will have to simultaneously deal with software and hardware systems; unified formalism for specifying, analyzing, and designing mixed software/hardware systems; and development of design automation software to aid system-level partitioning.

The leading edge in today's electronics is demonstrated by the totally automated development of silicon based on the use of behavior synthesis and high-level physical design tools. DSP ICs have already been developed using AutoCircuit behavioral synthesis technology from General Motors R & D Center and high-level physical tools developed by Cascade Design Automation. IC engineers at Delco Electronics used Verilog language to describe the DSP algorithms. After simulating the algorithms, AutoCircuit converted them into a Verilog list of datapath modules, such as adders, subtracters, ALUs, and state machines. The Verilog net lists were fed directly into Cascade's tools, which automatically compiled all of the datapath modules and synthesized the state machine control-logic modules. The Cascade tools placed and routed the modules, and extracted post-layout timing information for gate-level timing simulation.

This approach will be used extensively in the development of future ICs. In addition, the linkage of the system(s) performance simulation to silicon generating systems will be required.

32.5.1 Changing Role of the Automotive Electronics Designer

Software will drive IC technology. At the same time, the automotive engineer's role will change. Already this role has changed from that of a board-level designer using transistors to one using integrated circuits. Today, a systems approach is being pursued, but the systems have to be designed with a top-down methodology. Product development with system engineering guidance is shown in Fig. 32.11. This is today's approach and probably will not significantly change from the organizational side, except for a stronger role for software development. However, the activities performed by these functions must change through the use of more interactive tools. Starting with the total concept for the car, every module, every subsystem, every piece of electronic technology must be considered. Integration, system partitioning, design functionality, and distributed versus centralized intelligence are part of this approach. Audio system evolution, shown in Fig. 32.12, provides an excellent example of the transition. This figure will be examined closer in the next section.

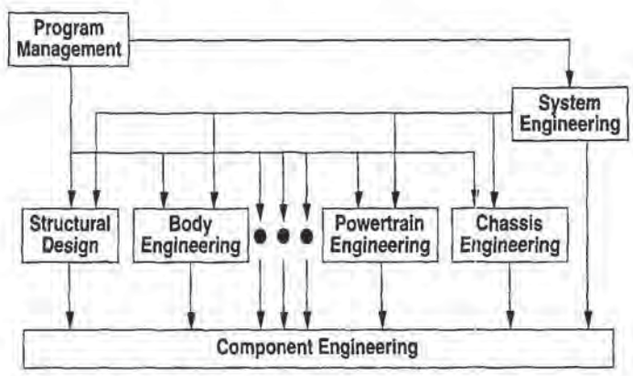


FIGURE 32.11 Product development with system engineering operation.

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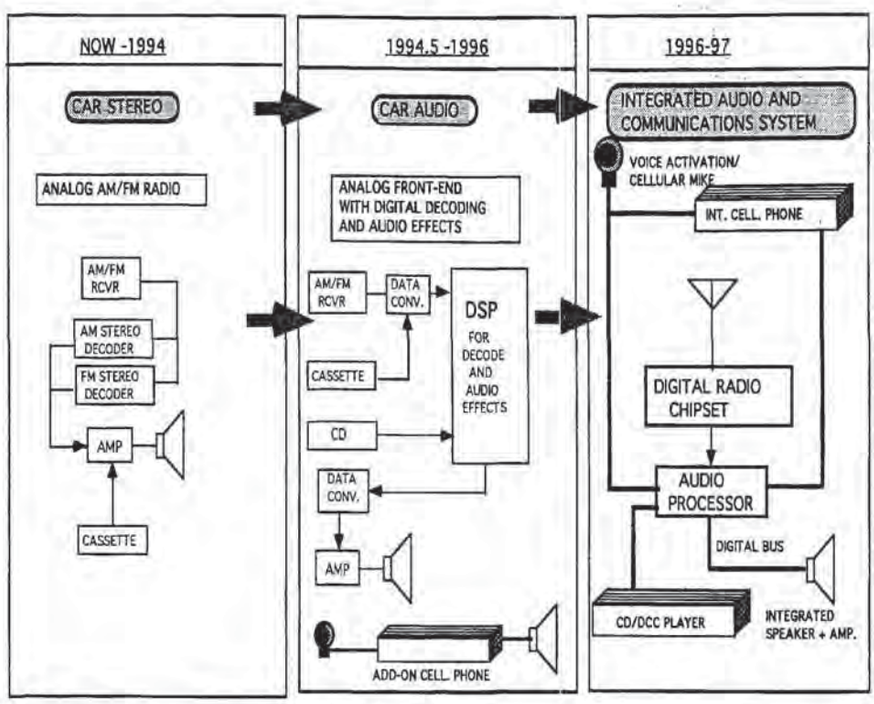


FIGURE 32.12 Audio evolution.

32.5.2 Potential System Architectures of the Future

It is apparent by now that the trend in automotive electronics is toward up-integration, with designers taking advantage of the compute power available, along with packaging technologies and adding more functionality to the modules. For example, engine management is being combined with cruise control and transmission control to form the powertrain controller. This trend is mainly driven by the need to reduce the cost of the modules—*value engineering* is the term being used, where value = function/cost. Value can be increased by either decreasing the cost of given functionality or by increasing functionality for the same cost. Integration then becomes a series of decisions or tradeoffs involving packaging, pc board, and semiconductor technologies. The designer continually makes cost/performance tradeoffs in selecting the technologies, and as technologies evolve, these tradeoffs must be updated.

So, given the technology scenario described earlier in this chapter, one can ask where will this evolution of up-integration end? Will everything eventually be integrated into a central control module? Or, given the trend in multiplexing, will ECUs be added ad infinitum, creating a distributed intelligence architecture? The answer is most probably "no" for both scenarios, and for several reasons, the key ones being cost effectiveness, reliability, heat dissipation, serviceability, and space requirements. The more likely scenario will be a combination of centralization and distributed intelligence where the centralization would be based along the lines of body, chassis and safety, powertrain, and audio/entertainment and communications. Within these centralized systems would be distributed intelligence based on multiplex wiring with smart sensors, switch decoders, and smart actuators all controlled by a central intelligence.

The strongest case for this scenario is the body system controller (refer to Table 32.1). Here functions such as door locks, interior dome lights, trunk lock, remote entry, antitheft alarm, electronic window lift, and electronic seat control with memory could all be centralized with multiplex wiring connecting the smart actuators (i.e., door locks, trunk release solenoids, etc.), switch decoders, and lamp and motor drivers. Another alternative to centralizing the whole

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car into one system could be partitioning the system into four systems controlling the four quadrants of the vehicle. The multiplex wiring within each quadrant linking the switches and actuators could be class A type, while the quadrants could be interlinked with a class B multiplex bus for diagnostic purposes and to provide a gateway into the driver information system.

The audio/entertainment system is probably the most interesting system from an architecture viewpoint because of how it has evolved, its uniqueness from the standpoint of standardization, and the possibilities that integrated semiconductor technology could provide. To understand the possibilities, let's examine how the radio has evolved. As shown in Fig. 32.12, the initial analog-based AM radio has integrated functions to include stereo (both AM and FM) and cassette or compact disc (CD) in the early 90s. Audio effects similar to ones found in home stereo systems are made possible with DSPs and are being offered on high-end vehicles today. With the availability of high-resolution, high-speed data conversion devices (e.g., 16- to 18-bit sigma-delta A/Ds and D/As), the radio will move from the analog domain to a digital domain, with the DSPs performing the task of AM/FM stereo decoding along with the audio effects.

A new dimension to the car audio system has been the addition of cellular phones. Instead of being an add-on aftermarket feature, the cellular phone is being integrated into the audio system. Bosch and Pioneer both have introduced stereo systems with the cellular phone integrated. This integration allows features such as automatic muting of the radio when a call comes in and better quality sound because the phone now uses the audio speakers instead of it's own tiny speaker. The next feature to be added to the audio system will be global positioning system (GPS) based navigation.

In the next few years all three functions—radio/audio, cellular phone, and GPS receivers—will be reduced to single-chip functions or chipsets. The system designer will then design a motherboard for an audio/phone/navigation system where each function could be offered simply by putting in the chipset—the plug-and-play concept similar to that used in the pc world. Taking this one step further, if all three functions were made available as a standard package, the system designer could take a total systems approach and develop one chip or chipset and implement the three functions in software. This would eliminate redundant computing power from the three-function chipsets scenario. This is possible because at any given time either the radio/audio system or the phone would be functioning, and the same hardware could handle the functions with context-switching software. Since the GPS receiver function is not time critical, it could be handled again by the same hardware on a cycle-stealing basis. Features such as voice recognition could also be added in software. The designer would need to develop an operating system to handle all the function switching and the user interface—perhaps, the automotive operating systems (AOS). Again, the analogy of the pc world is appropriate.

This would lead us to conclude that software is going to play an increasingly important role in future automotive electronics. Given that the capability of the semiconductor industry and the IC design tools will evolve, the differentiating factor will be software.

32.6 CONCLUSIONS

A universally accepted approach to electronics in all regions of the world does not appear very likely. Europe, North America, Japan, and other regions of the world have differences in use and design that are obvious in the electronic requirements. Europe may be the most likely to favor a backplane approach. In the United States, captive electronics support can provide individuality, but independent electronic suppliers in Europe support several different automotive customers in several countries with a wide range of requirements. Obviously, this requires standards that allow users to specify within the capabilities of several suppliers and still configure the functions that are required.

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With rapid advances that are occurring in research, the technology of choice for semiconductors is a moving target which can change in the present design cycle time for vehicles. Problems for one approach can be solved, making it a viable alternative. Based on the kinds of systems that will drive future vehicle technology, and the potential for more drive power options—four- or two-stroke internal combustion, electric, hybrid and diesel—automobile manufacturers will continue to look to electronics and semiconductor technology to provide cost-effective solutions. Software will be the next frontier for semiconductor, electronics, and automotive manufacturers.

This chapter has described activities that are occurring or are likely to occur based on information that is widely discussed in public electronic and automotive forums. Several sources of new information that will provide an update or revise these projections can be found in:

- Semiconductor Industry Association (SIA) reports
- Proceedings of International Congress on Transportation Electronics (Convergence)
- University of Michigan Delphi Report (Rev. VII or later)
- Morgan Stanley research
- Hansen Report on automotive electronics, published monthly
- BIS strategic decisions
- Arthur D. Little reports
- *Inside IVHS,* published biweekly
- Automotive periodicals (e.g., *Automotive Engineering, Automotive Industries, Automotive News, Ward's Auto World*)
- Electronics periodicals (e.g., *EE Times, Electronic Design, Electronic Design News, IEEE Spectrum*)
- Other SAE or IEEE publications

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GLOSSARY

ASIC Application-specific integrated circuit, an IC designed for a custom requirement, frequently a gate array or programmable logic device.

ATPG Automation test program/pattern generator.

BIST Built-in self-test, design technique that allows a chip to be tested for a guaranteed level of functionality.

CISC Complex instruction set computer, standard computing approach as compared to RISC architecture.

Combinational technologies Integrated mixed-signal, analog and digital technology.

DFT Design for testability, methodology that takes test requirements into account early in the design process.

EPROM Erasable programmable read-only memory, a semiconductor technique used for permanent storage but can be erased by ultraviolet light.

EEPROM Electrically erasable programmable read-only memory, a semiconductor technique used for permanent storage. It can be reprogrammed in the system.

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Engine (micro engine) The computational portion of an IC.

Flash Semiconductor memory, faster than EEPROM, that can be used for permanent storage and is easily electrically reprogrammed in the system.

Flops Floating-point operations per second, a measurement of microprocessor performance.

FPGA Field-programmable gate array, an IC that can be programmed.

Harvard architecture On-chip program and data are in two separate spaces and are carried in parallel by two separate buses.

HDL Hardware description language.

HLL High-level language, a programming language that utilizes macro statements and instructions that closely resemble human language or mathematical notation to describe the problem to be solved or the procedure to be used.

Integration The combination of previous levels of separate circuit designs.

Mechatronics The combination of mechanical and electronic technology as in motor controls.

MESFET (metal semiconductor field effect transistor) A high-frequency semiconductor device produced in GaAs semiconductor technology.

Micromachining The chemical etching of mechanical structures in silicon, or other semiconductor material, usually to produce a sensor or actuator.

Mips Millions of instructions per second, a measurement of microprocessor throughput.

Mixed-signal The combination of analog and digital circuitry in a single semiconductor process.

Multiprocessing The simultaneous execution of two or more instructions by a computer.

MCU Microcontrol unit, or microcontroller unit, a semiconductor that has both a CPU, memory, and I/O capability on the same chip.

MMIC Monolithic microwave integrated circuit, a high-frequency integrated circuit.

Partitioning System design methodology that determines which portion of the circuit is integrated using a particular silicon process instead of completely integrating design using one process.

Pipeline Bus structure within an MPU that allows concurrent operations to occur.

Protocol The rules governing the exchange of data between networked elements.

RISC Reduced instruction set computer, a CPU architecture which optimizes processing speed by the use of a smaller number of basic machine instructions.

Scalable Ability of MCU or MPU architecture to be modified to meet the needs of several applications providing competitive price-performance points.

Silicon compiler A tool that translates algorithms into a design layout for silicon.

SMD Surface-mount device (see **SMT**).

SMT Surface-mount technology, method of attaching components, both electrically and mechanically, to the surface of a conductive pattern.

SPECfp92 Floating-point benchmark test and rating (1992) for comparing microprocessor computing power.

SPECint92 Integer benchmark test and rating (1992) for comparing microprocessor computing power.

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State machine Logic circuitry that when clocked sequences through logical operations and can be a preprogrammed set of instructions or logic states.

SSVS Super-smart vehicle systems, term used in Japan for vehicles with several new electronic systems, typically used in IVHS.

Submicron Measurement of the geometries or critical spacing used for complex, highly integrated circuits.

Superscalar The ability of an MPU to dispatch multiple instructions per clock from a conventional linear instruction stream.

Verilog A hardware description language for behavior-level circuit design placed in public domain by Cadence Design Systems Inc.

VHDL VHSIC Hardware Description Language, a hardware description language for behavior-level circuit design developed by the U.S. Department of Defense.

Von Neumann (architecture) Program and data are carried sequentially on the same bus.

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ABOUT THE EDITOR

Ronald K. Jurgen recently retired as senior editor at *IEEE Spectrum*, where he specialized in automotive and consumer electronics. He performed a broad range of editorial functions for the magazine since its inception in 1964, including writing more than 100 articles. He also served as chief editor for *Spectrum*'s special issues devoted to a wide variety of automotive technology. A graduate of Rensselaer Polytechnic Institute, he was editor in chief of the book *Computers and Manufacturing Productivity* (IEEE Press, 1987).

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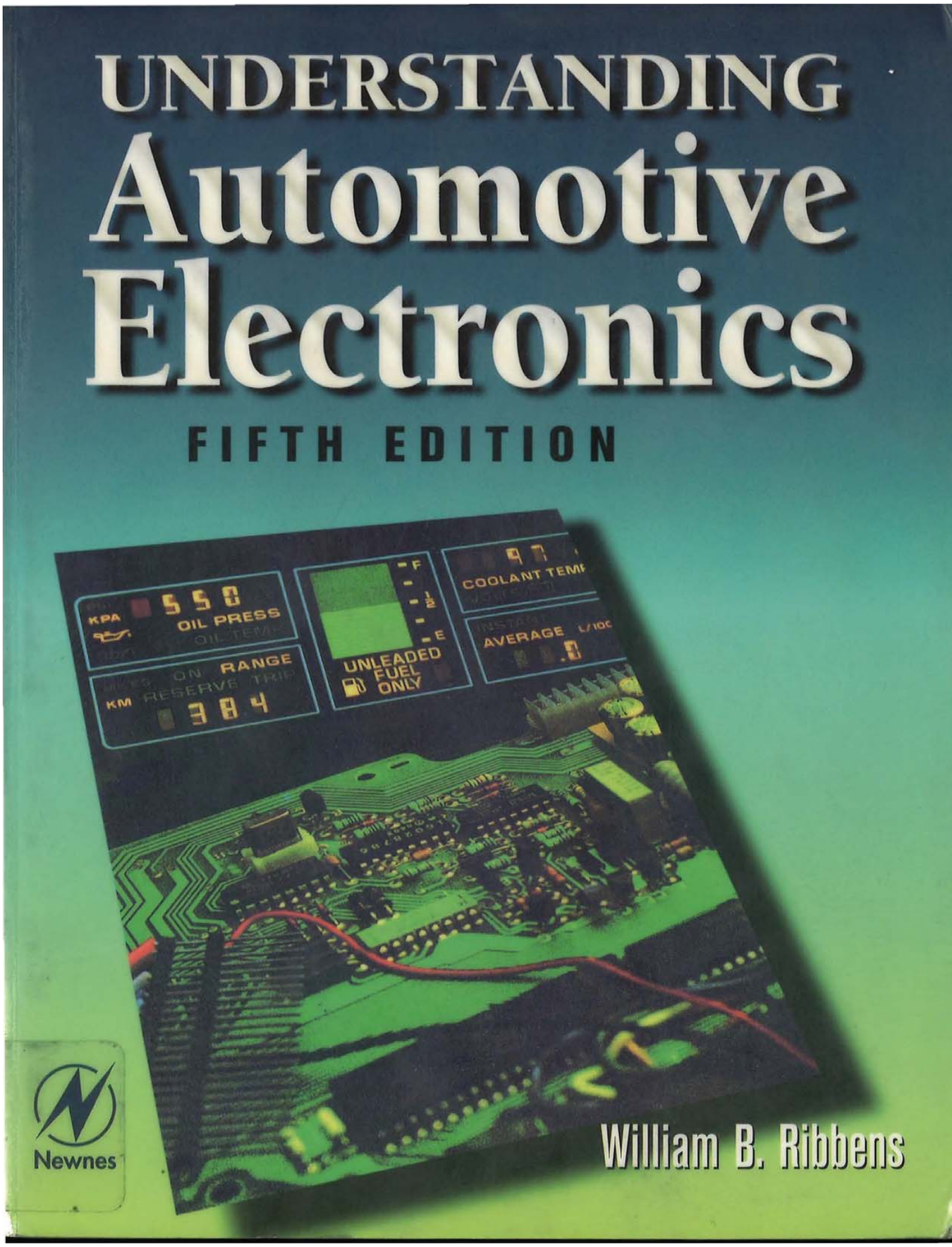
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Preface

Since the introduction of electronics for emission control on engines, the evolution of electronics in automobiles has advanced rapidly. The pace of development has inspired four revisions of this book in roughly ten years to avoid obsolescence. Rarely in history have technical developments moved at such a pace.

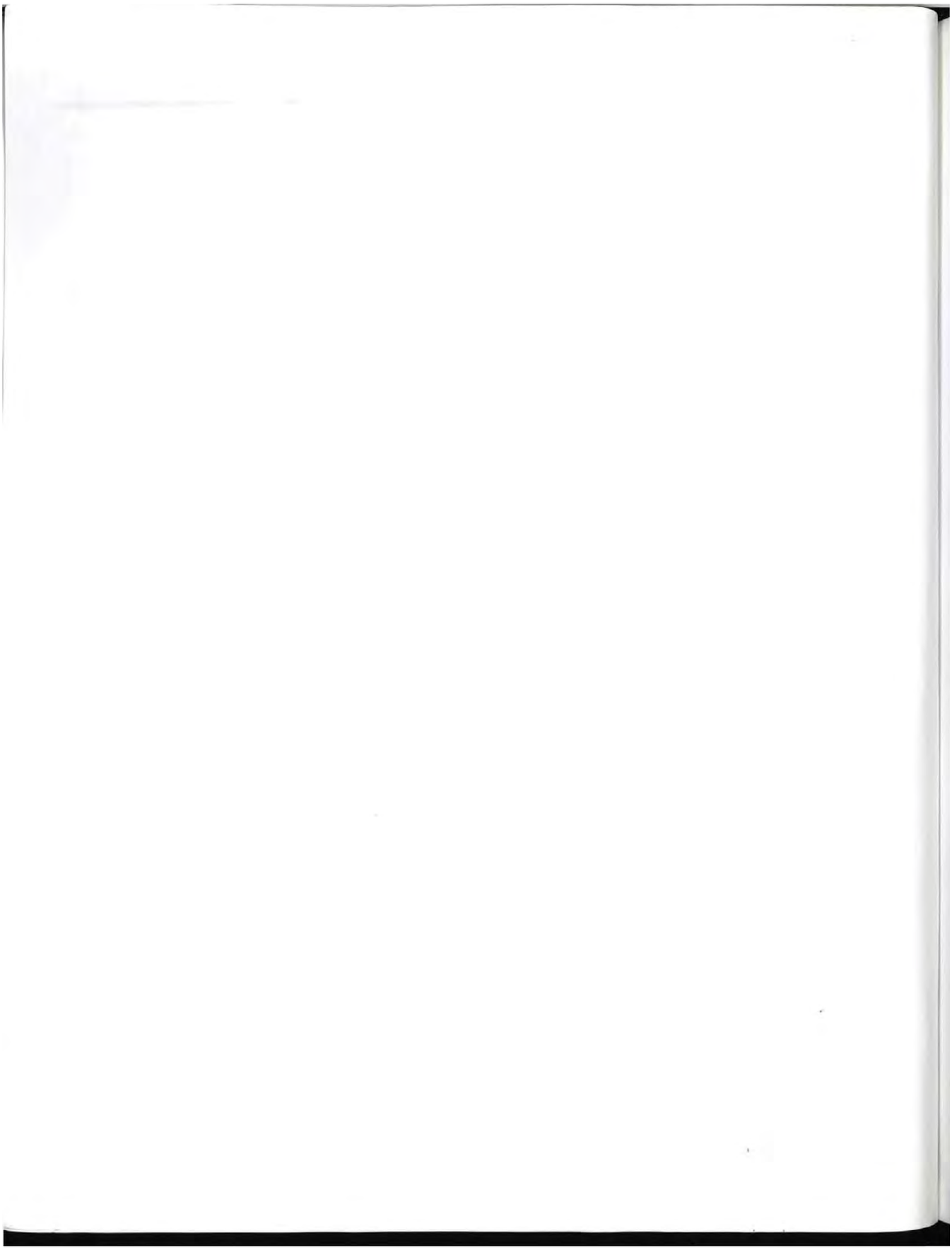
Electronics have recently been incorporated on new automotive subsystems and have become standard implementation on many others. Such features as antilock braking systems and airbags could only be achieved practically through the use of electronics. These features are rapidly becoming standard features owing to strong pressures in the highly competitive North American automotive market.

The first edition of this book was devoted primarily to electronic engine control because this was the chief application at that time. A number of automotive systems which were discussed in the chapter on the future of automotive electronics in the second, third, and fourth editions are now in production. These systems are presented in the appropriate chapters of this fifth edition. This latest edition covers most of the automotive subsystems incorporating electronics except for entertainment systems. These systems have been omitted partly due to space limitations and because automotive entertainment systems are closely related to home entertainment systems, which are discussed in many excellent publications.

In its revised form, this book explains automotive electronics as of the late 1990s. It should prepare the reader for an understanding of present as well as future developments in this field into at least the early part of the next century.

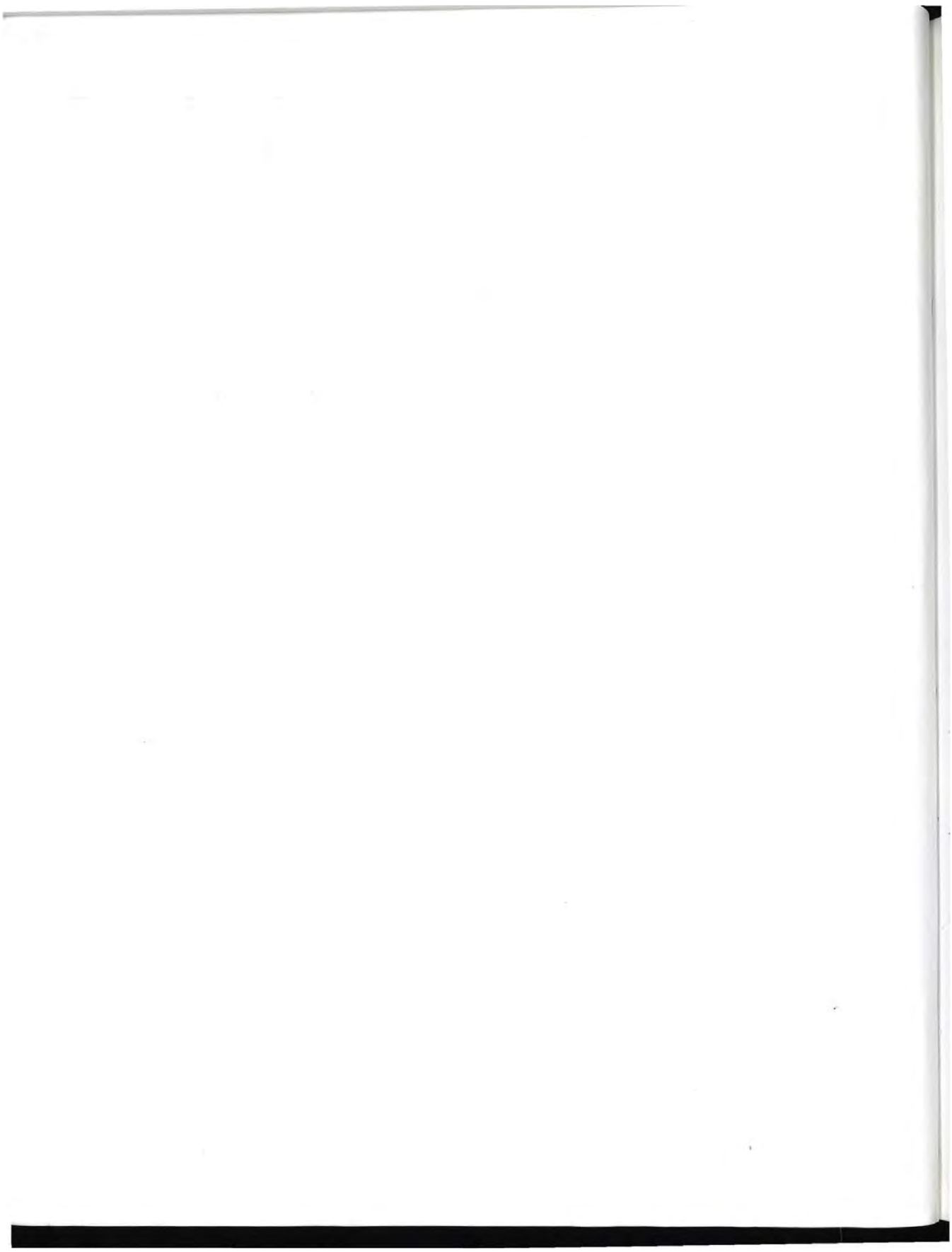
William B. Ribbens
November 1997

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Understanding Automotive Electronics

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Automotive Fundamentals

Picture yourself in the not-too-distant future driving your new car along a rural interstate highway on a business trip. The cruise control is maintaining the speed at a steady 100 km/hr (62 mph) and there is relatively little traffic. As you approach a slower car, the speed-control system slows your car to match the speed of the slower car and maintain a safe distance of about 53 m (165 ft) behind the slower car. When oncoming traffic clears, you enter the passing lane and your car automatically increases speed as you pass the slower car.

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. After the instructions for the contract changes are completed, a printer in your car generates a copy of the latest contract version.

The onboard entertainment system is 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

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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

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.

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

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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 much 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.

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. Comfort/convenience
10. Entertainment/communication/navigation

In Figure 1.1 the frame or chassis on which the body is mounted is supported by the suspension system. The wheels' 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.

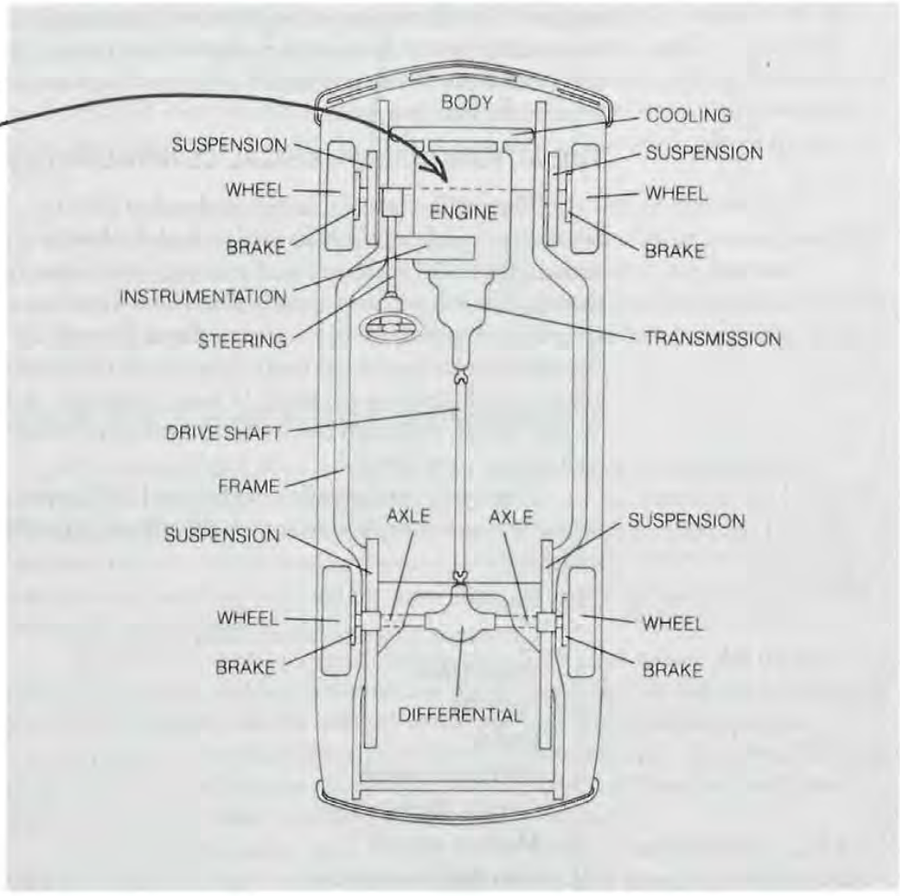
This basic vehicle configuration was used from the earliest cars through the late 1960s or 1970s, with some notable exceptions. The increasing importance of fuel efficiency and government-mandated safety regulations led to major changes in vehicle design. The body and frame evolved into an integrated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

Once again with a few notable exceptions, most cars had an engine in front configuration with the drive axle at the rear. While it is an advantage for several reasons (e.g., crash protection, efficient engine cooling) to have the engine in front, this location has a disadvantage from a traction standpoint. Because the engine is a

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Figure 1.1. Systems of the Automobile

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



relatively heavy component, its location influences weight distribution (fore and aft).

Ideally, the engine should be located near the drive wheels for optimal drive traction. It is this fact that has led car makers to configure the front wheels as drive wheels. This change has led to the engine being 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.*

For stability purposes the steering is still via the front wheels. The combination of steering and drive mechanisms results in a somewhat more complicated front-wheel system configuration than the traditional orientation.

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Evolution of Electronics in the Automobile

This book explores the application of modern solid-state electronics to the various automotive subsystems described above. 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. 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. 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.

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-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. An engine of this configuration is rarely found in present-day cars. Rather, a more common engine configuration today would be 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, 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.

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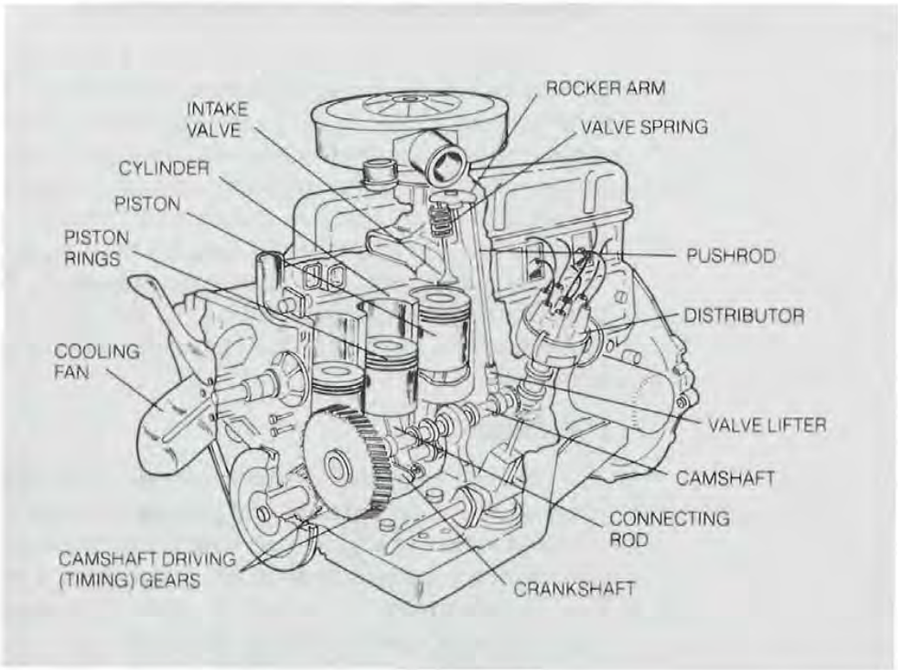


Figure 1.2
Cutaway View of a 6-Cylinder, Overhead-Valve, Inline Engine
(Source: Crouse)

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

Electronics play a direct role in only the fuel control, ignition, and exhaust systems. 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 constraints. 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.

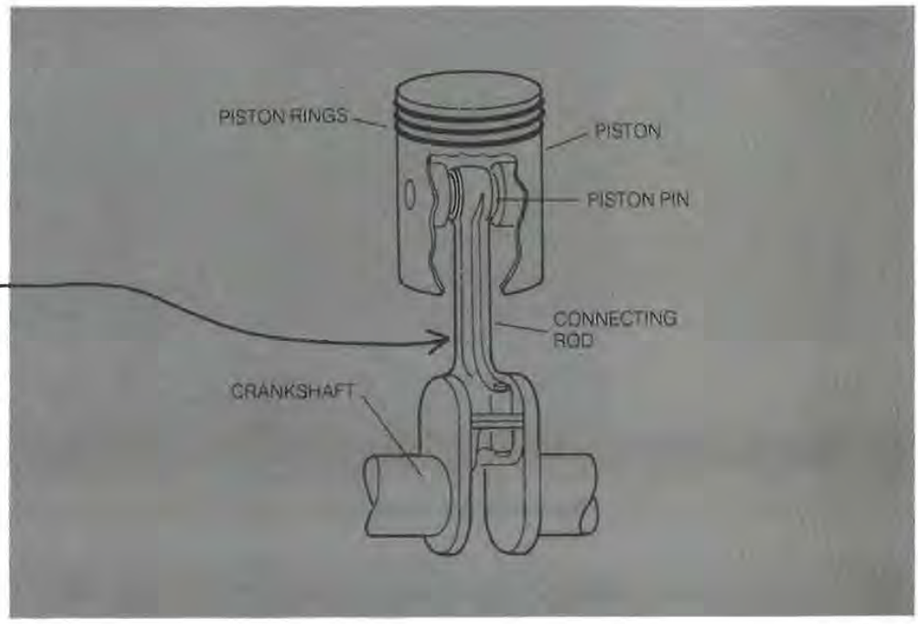
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Engine Block

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

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 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 needed to drive the wheels.

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.

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.

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.)

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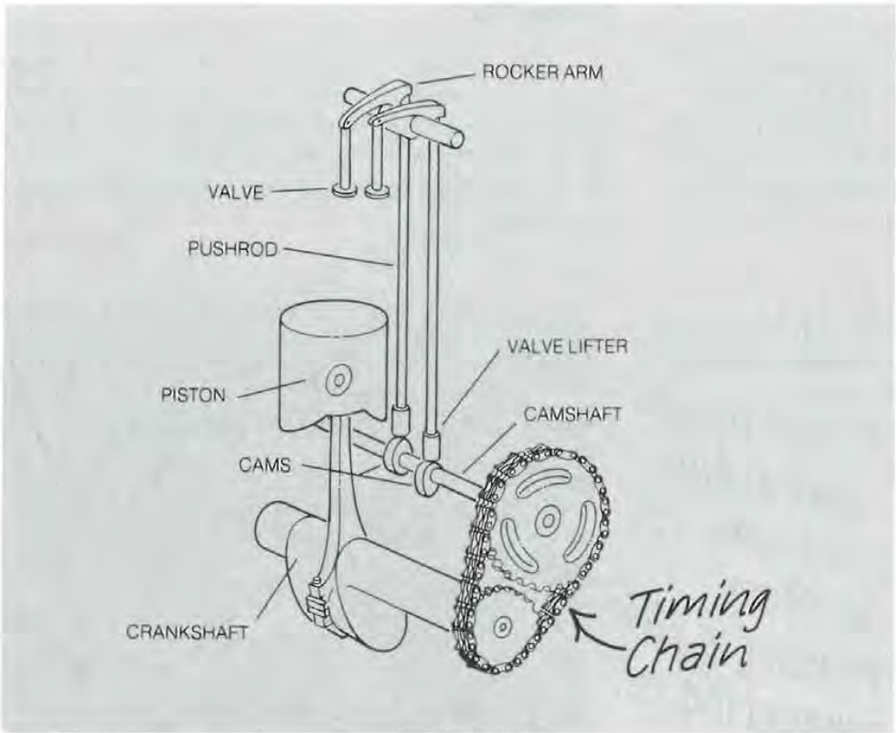


Figure 1.4 Valve Operating Mechanism *(Source: Crouse)*

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.*

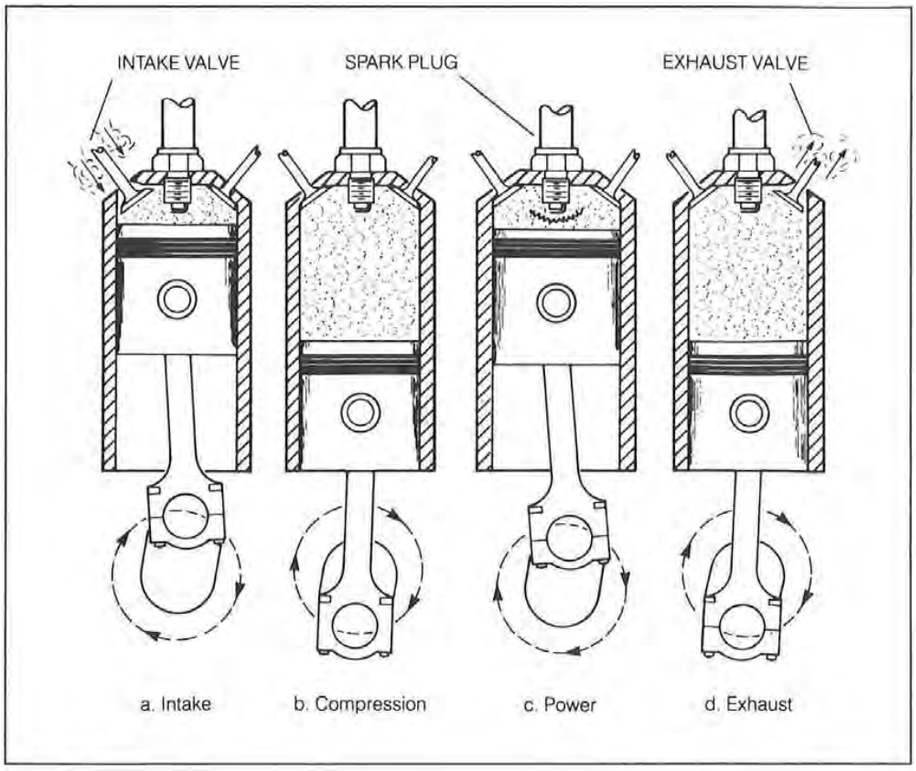
The operation of the engine can be understood by considering the actions in any one cylinder during a complete cycle of the engine. One complete cycle in the 4-stroke/cycle SI engine requires two complete rotations of the crankshaft. As the crankshaft rotates, the piston moves up and down in the cylinder. 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.

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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), 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.

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Power

During the power stroke (Figure 1.5c), the high pressure created by the burning mixture forces the piston downward. It is only during this stroke that actual usable power is generated by the engine.

Exhaust

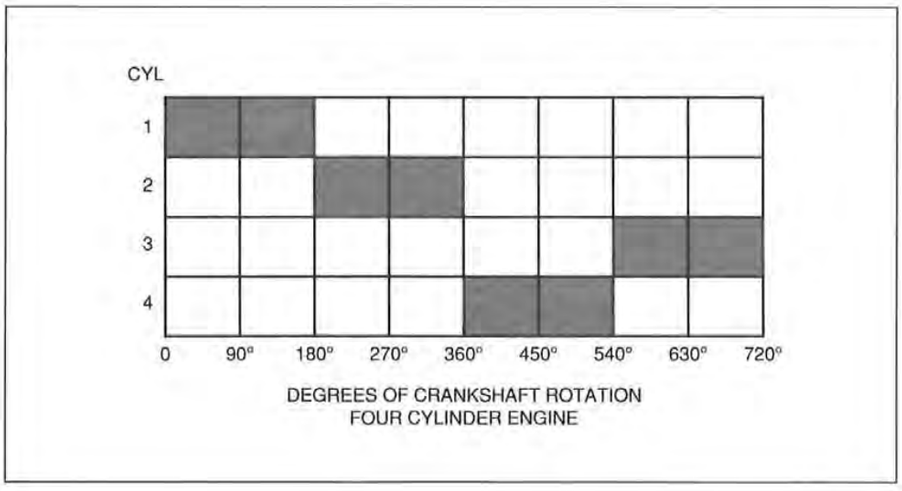
During the exhaust stroke (Figure 1.5d), the piston is again moving upward. The exhaust valve is open and the piston forces the burned gases from the cylinder through the exhaust port into the exhaust system and out the tailpipe into the atmosphere.

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. In order to maintain crankshaft rotation during the other three-quarters of the cycle, a flywheel is used. The flywheel has traditionally been a relatively large, heavy, circular object that is connected to the crankshaft, although in modern engines the mass of the flywheel has been reduced relative to very early engines. The primary purpose of the flywheel is to provide inertia to keep the crankshaft rotating during the three non-power-producing strokes of the piston.

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.)

Figure 1.6
Power Pulses From a 4-Cylinder Engine



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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 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 (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.

Of course, the power produced by the engine depends on fuel being present in the correct proportions. Air combines with fuel in the fuel metering device. This device automatically delivers fuel in the correct amount as determined by the air flow.

The classic fuel metering device was the carburetor, which is now virtually obsolete. In modern car engines, fuel injectors do the fuel metering. The amount of fuel delivered by a fuel injector is determined electronically in

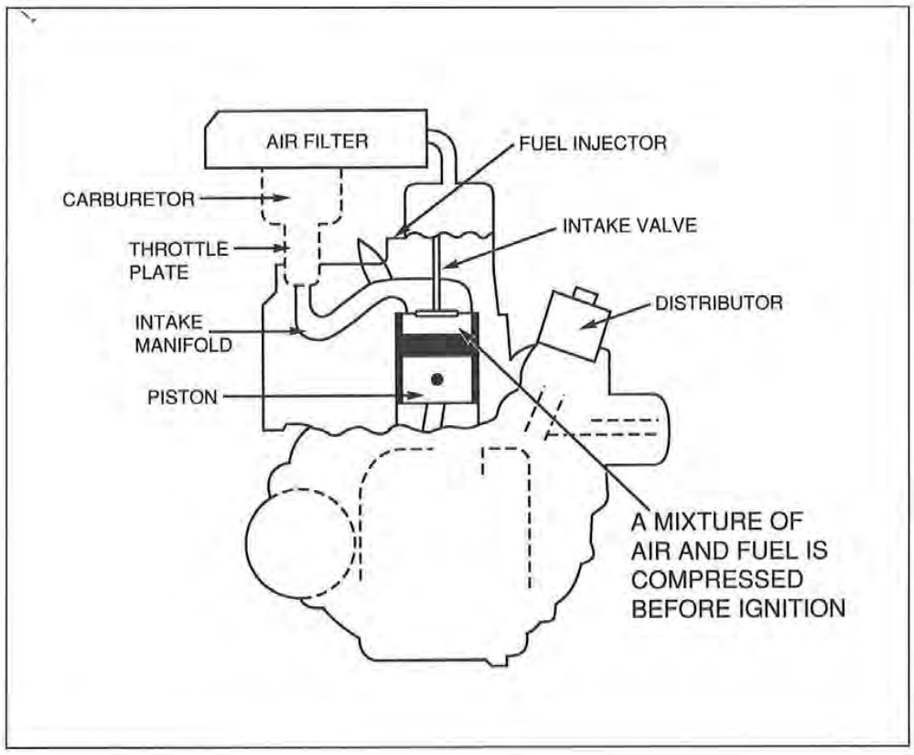


Figure 1.7 Intake Manifold and Fuel Metering

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accordance with the air flow in such a way as to minimize pollutants in the exhaust gas (see Chapter 5).

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. 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. 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.

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Figure 1.8
Spark Plug Configuration

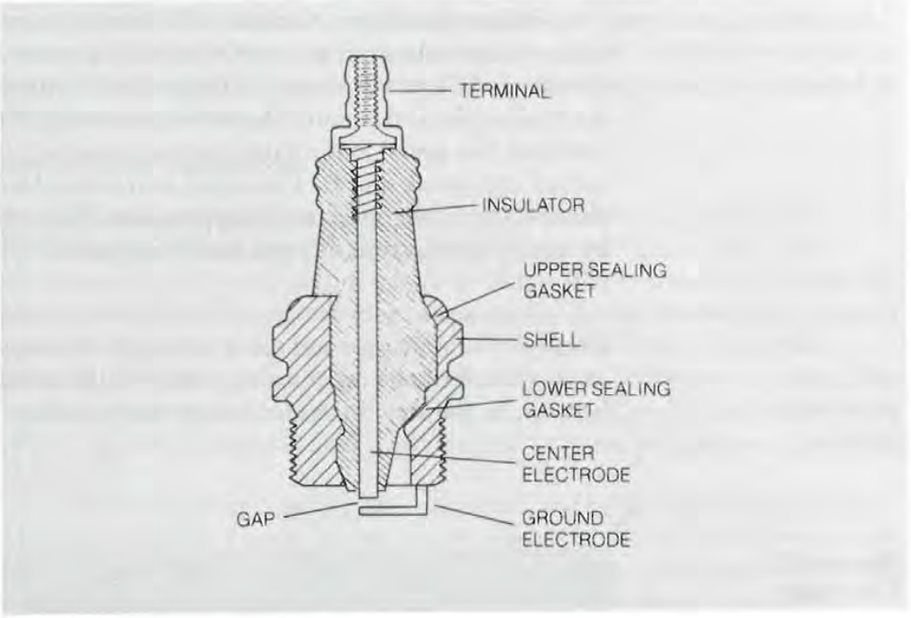
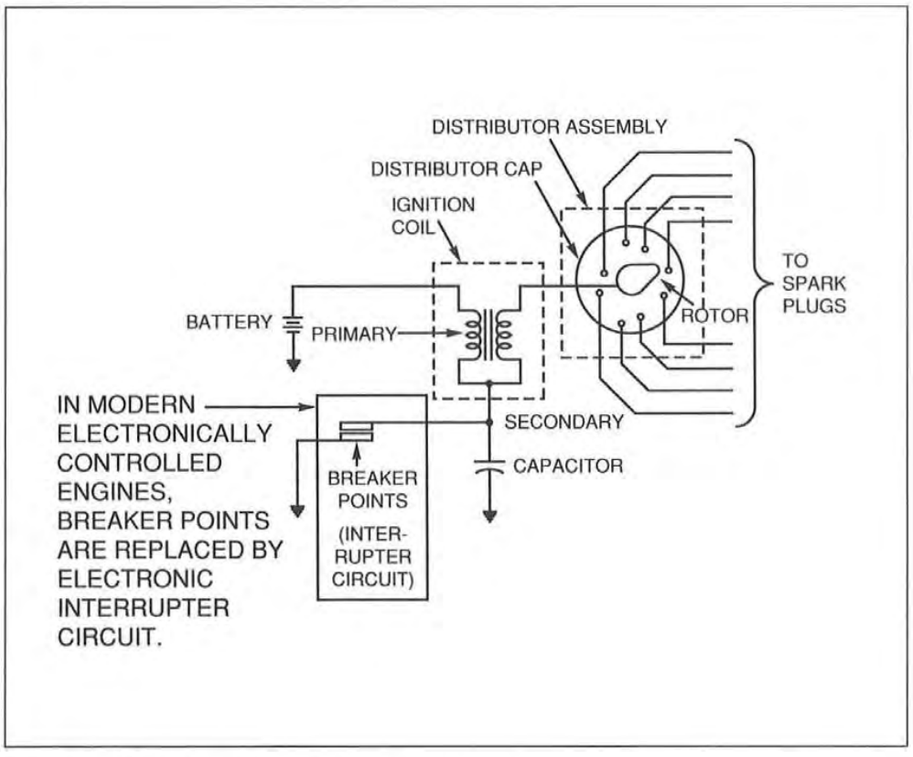


Figure 1.9
Schematic of the Ignition Circuit

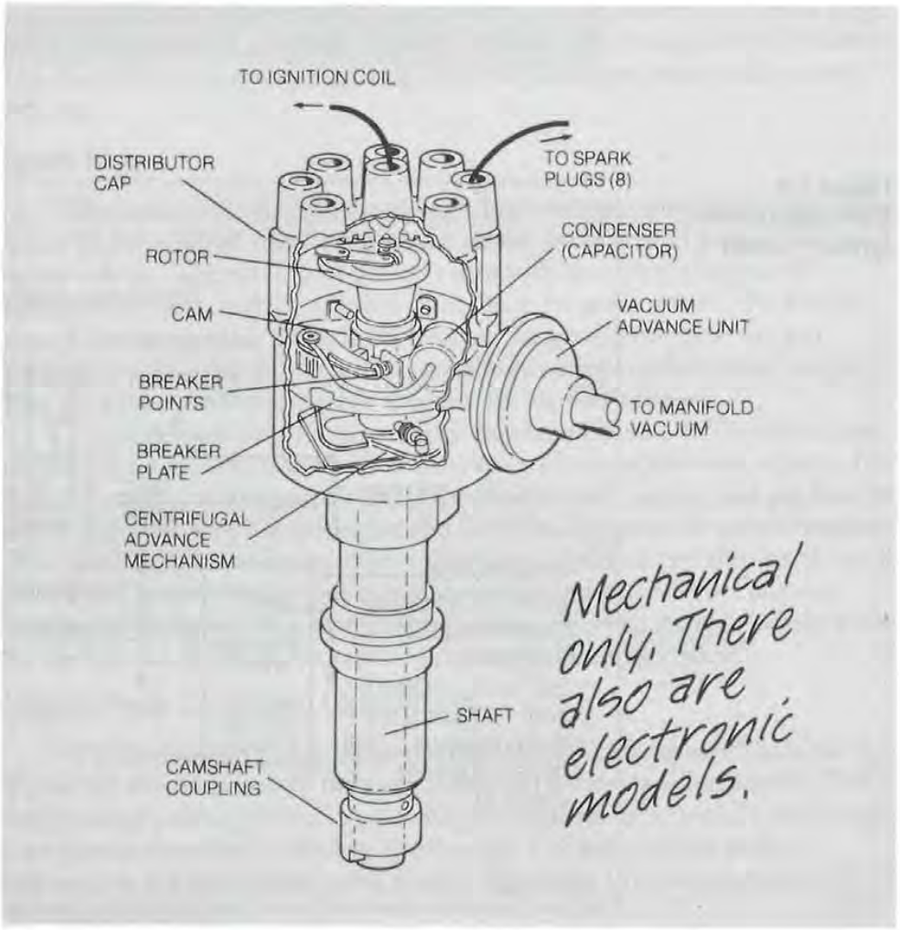


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Before the advent of modern electronic controls, the distribution of high-voltage pulses was accomplished with a rotary switch called the *distributor.* Figure 1.9 shows a schematic of a typical distributor; Figure 1.10 is a typical physical layout. 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, 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.

Figure 1.10
Distributor



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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 distribution 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;

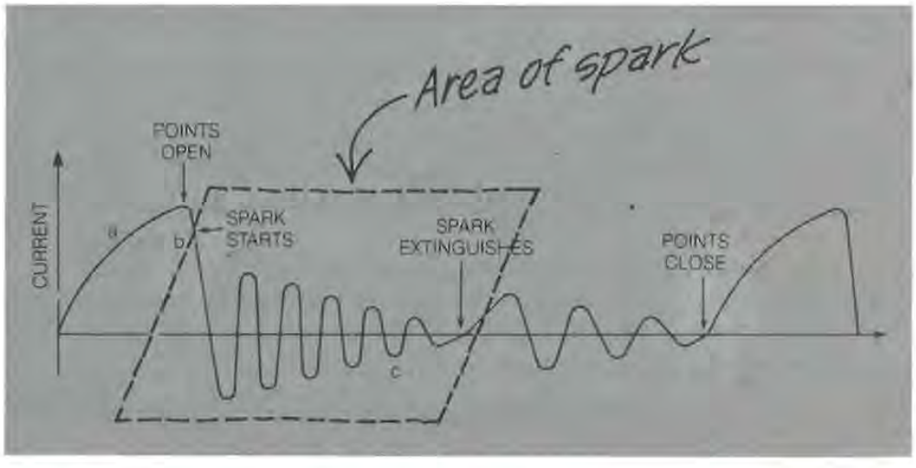


Figure 1.11 Primary Current Waveform

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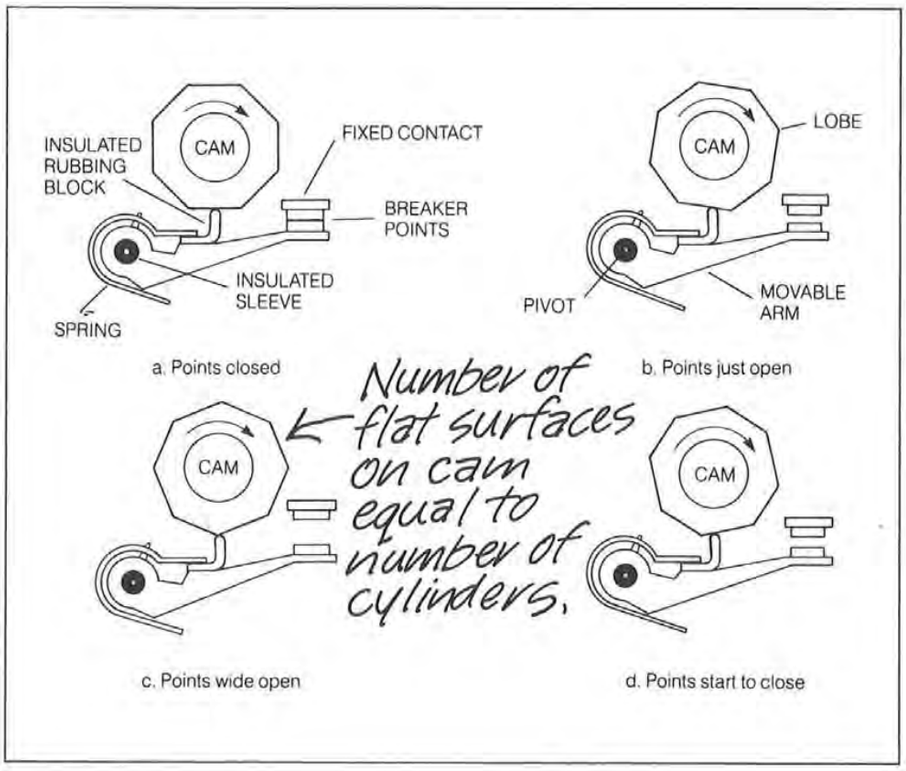
point *c*) because of the resonant circuit formed between the coil and capacitor.

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.

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, 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 and spark occurs.

Figure 1.12 Breaker Point Operation



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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.

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.

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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. Because their use in North American passenger cars is so low and because electronic diesel engine control is not widely used, it will not be further discussed in this book.

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.

Probably the most serious 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. After considerable research and development, a version of the 2-stroke/cycle engine is emerging that has great potential for displacing the 4-stroke/cycle engine in automotive applications. It remains to be seen what inroads the 2-stroke/cycle engine will make.

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

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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. Most automatic transmissions have three forward gear ratios, although a few have two and some have four. A properly used manual transmission 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 1.13). 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.*

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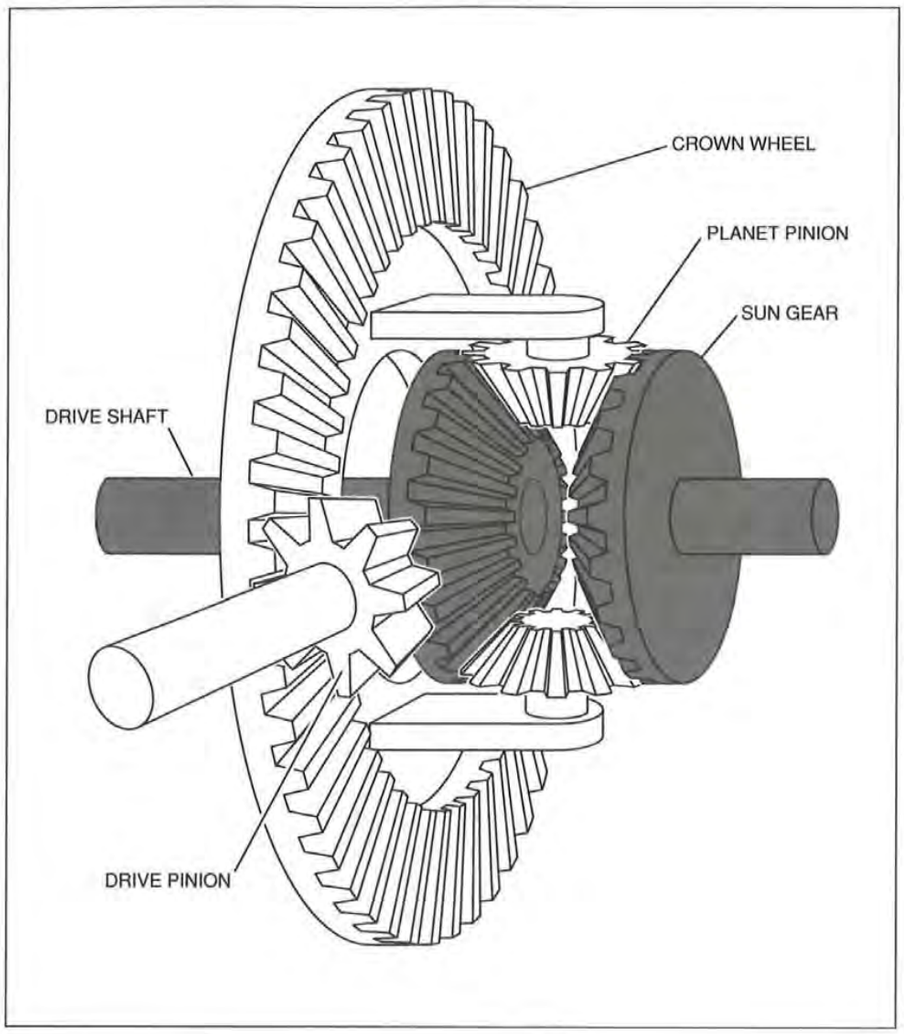


Figure 1.13 Schematic of a Differential

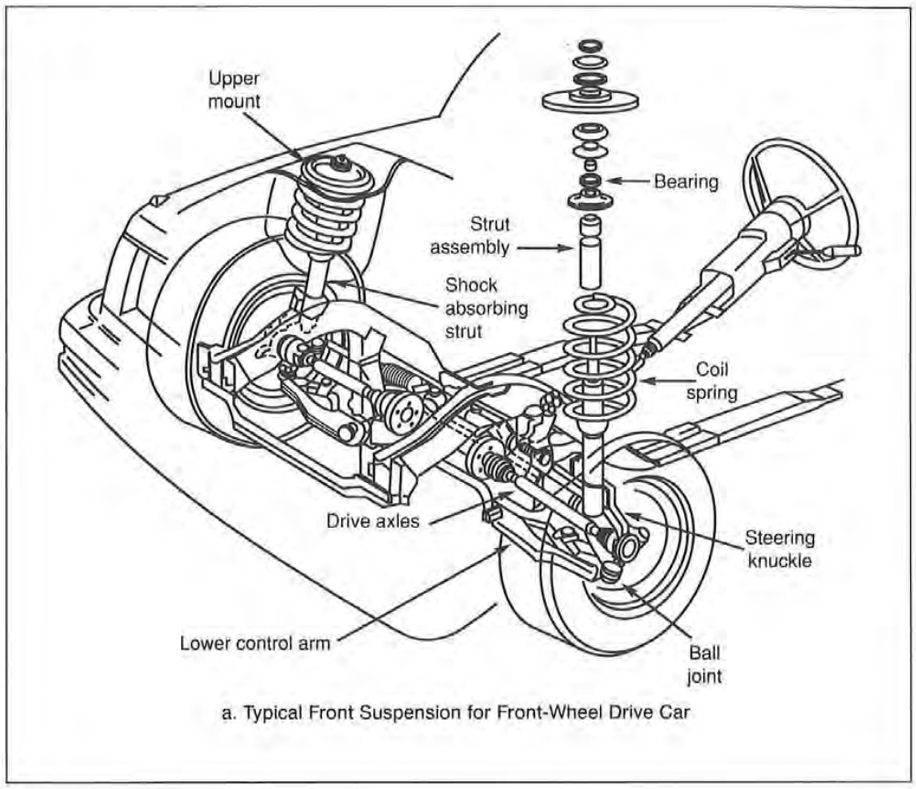
SUSPENSION

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 1.14, 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

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Figure 1.14
Major Components of a Suspension System



a. Typical Front Suspension for Front-Wheel Drive Car

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.

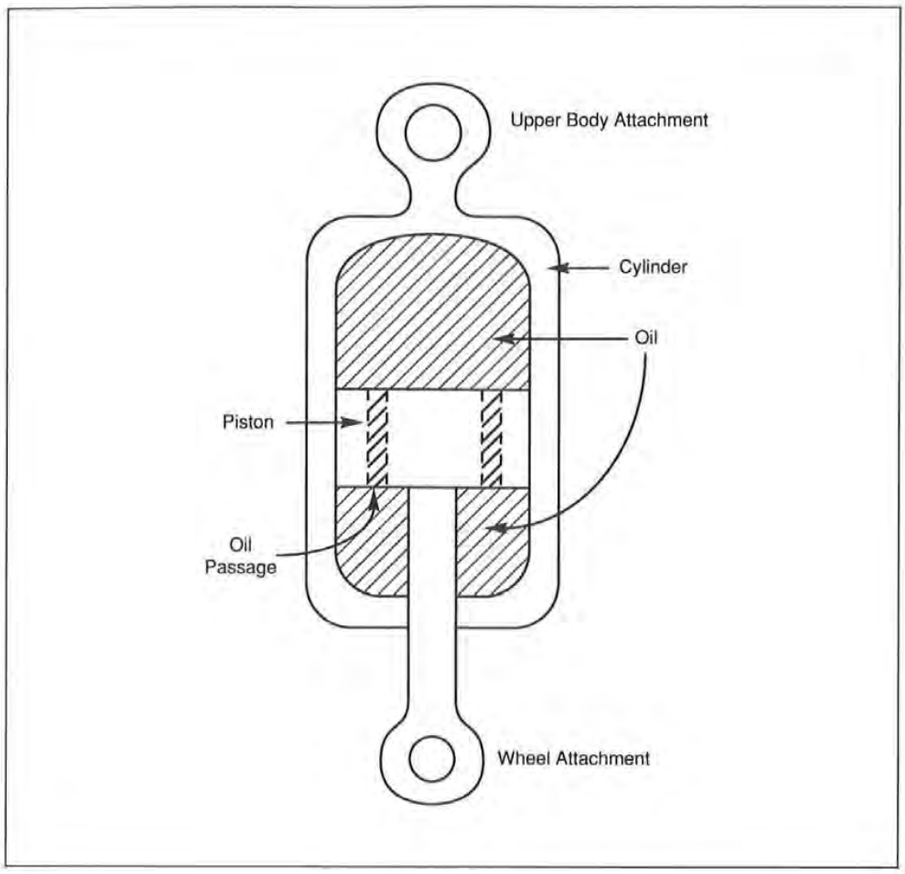
The mass of the car body is called the *sprung mass,* that is, the mass that is supported by springs. The mass of the wheel assemblies at the other end of the springs is called *unsprung mass.*

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.

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 1.15 is an illustration of a typical shock absorber.

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Figure 1.15
Shock Absorber Assembly



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.

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BRAKES

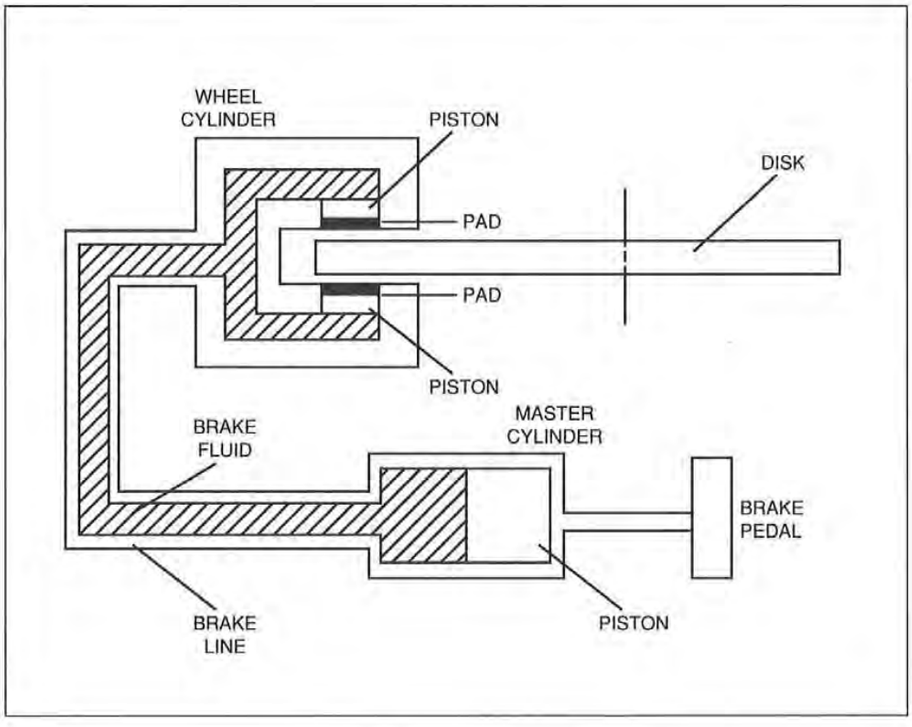
Brakes are as basic to the automobile as the engine drivetrain system and are responsible for slowing and stopping the vehicle. Most of the kinetic energy of the car is dissipated by the brakes during deceleration and stopping (with the other contributions coming from aerodynamic drag and tire rolling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

There are two major types of automotive brakes: drum and disk brakes. Drum brakes are an extension of the type 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 1.16. 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, 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.

Figure 1.16
Disk Brake System



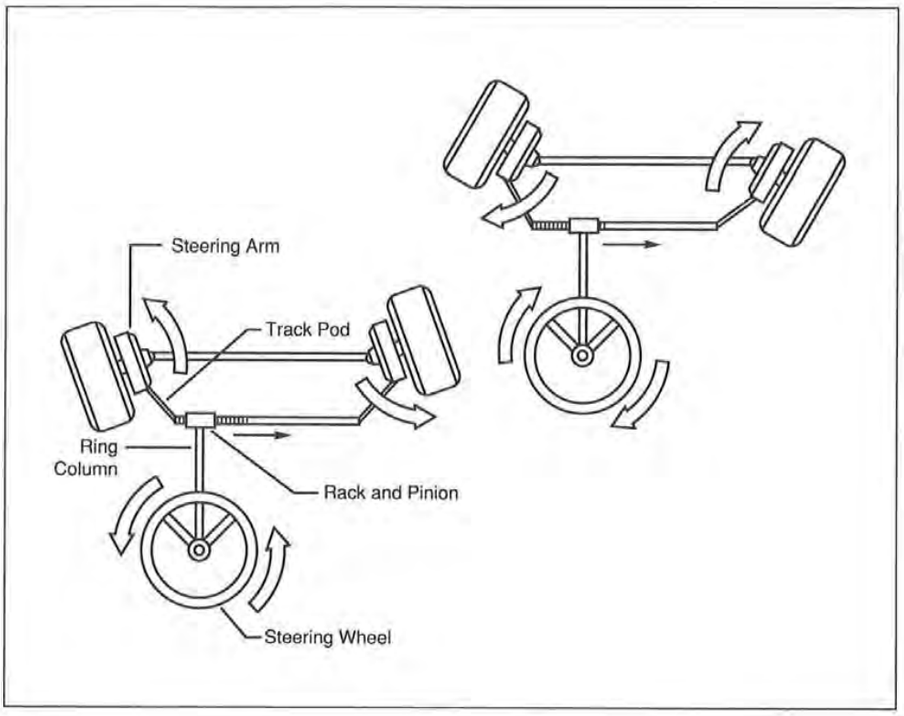
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Electronic control of braking benefits safety by improving stopping performance in poor or marginal braking conditions. Chapter 8 explains the operation of the so-called *antilock braking system* (ABS).

STEERING SYSTEM

A steering system is one of the major automotive subsystems required for operation of the car (see Figure 1.17). 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.

Figure 1.17
One Type of Steering Mechanism



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.

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When steering the car, the driver must provide sufficient torque to overcome the restoring torque. Because the restoring torque is proportional to 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 1.18.

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.

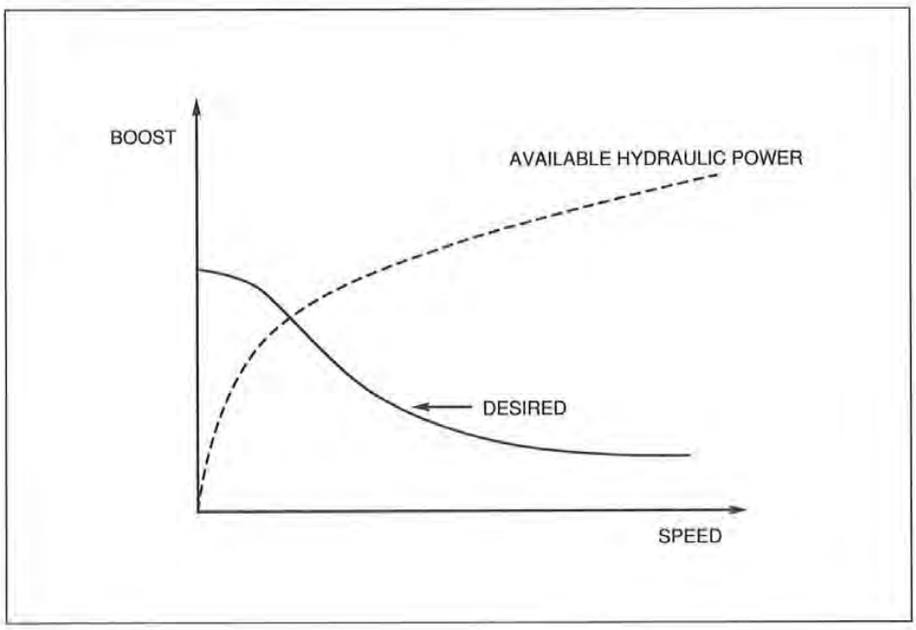


Figure 1.18
Desired Boost Versus Speed

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

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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

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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

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The Systems Approach to Control and Instrumentation

Generally speaking, electronic systems function to control, measure, or communicate. Automotive electronic systems fall generally into these same three application areas. The major categories of automotive electronic systems include

1. Engine/power train control
2. Ride/handling control
3. Cruise control
4. Braking/traction control
5. Instrumentation (instrument panel)
6. Power steering control
7. Occupant protection
8. Entertainment
9. Comfort control
10. Cellular phones

Historically, automotive electronics was confined primarily to communications, with the incorporation of AM radios and police-car two-way radio systems. These remained the only significant electronics applications throughout the 1930s and 1940s. This was an era in which vacuum tubes were the only important active electronic devices.

The development of solid-state electronics, beginning with the transistor in the late 1940s and evolving through high-performance integrated circuits, provided a technology that was compatible with the evolution of other automotive electronic systems such as ignition systems, turn signals, instrumentation, and a variety of other automotive subsystems. Perhaps the biggest evolutionary jump occurred in the 1970s with the advent of electronic fuel control systems, a step motivated primarily by government regulations (as we will show later). Since then the evolution of electronic systems in automobiles has seen spectacular growth, such that automotive electronics is now estimated to account for 10% to 25% of the cost of the vehicle, depending on feature content.

CHAPTER OVERVIEW

This book will discuss the application of electronics in automobiles, from the standpoint of electronic systems and subsystems. In a sense, the systems approach to describing automotive electronics is a way of organizing

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the subject into its component parts based on functional groups. This chapter will lay the foundation for a discussion by explaining the concepts of a system and a subsystem, and how such systems function. The means for characterizing the performance of any system will be explained so that the reader will understand some of the relative benefits and limitations of automotive electronic systems. This chapter will explain generally what a system is and, more precisely, what an electronic system is. In addition, basic concepts of electronic systems that are applicable to all automotive electronic systems, such as structure (architecture) and quantitative performance analysis principles, will be discussed.

Two major categories of electronic systems—analog or continuous time and digital or discrete time—will be explained. In most cases, it is theoretically possible to implement a given electronic system as either an analog or digital system. The relatively low cost of digital electronics coupled with the high performance achievable relative to analog electronics has led modern automotive electronic system designers to choose digital rather than analog realizations for new systems.

CONCEPT OF A SYSTEM

A *system* is a collection of components that function together to perform a specific task. Various systems are encountered in everyday life. It is common practice to refer to the bones of the human body as the skeletal system. The collection of highways linking the country's population centers is known as the interstate freeway system.

Electronic systems are similar in the sense that they consist of collections of electronic and electrical parts interconnected in such a way as to perform a specific function. The components of an electronic system include transistors, diodes, resistors, and capacitors, as well as standard electrical parts such as switches and connectors among others. All of these components are interconnected with individual wires or with printed circuit boards. In addition, many automotive electronic systems incorporate specialized components known as *sensors* or *actuators* that enable the electronic system to interface with the appropriate automotive mechanical systems.

Systems can often be broken down into subsystems. The subsystems also consist of a number of individual parts.

Any electronic system can be described at various levels of abstraction, from a pictorial description or a schematic drawing at the lowest level to a block diagram at the highest level. For the purposes of the present discussion, this higher-level abstraction is preferable. At this level, each functional subsystem is characterized by inputs, outputs, and the relationship between input and output. Normally only the system designer or maintenance technician would be concerned with detailed schematics and the internal workings of the system. Furthermore, the only practical way to cover the vast range of automotive electronic systems is to limit our discussion to this so-called system level of abstraction. It is important for the reader to realize that there are typically many different circuit configurations capable of performing a given function.

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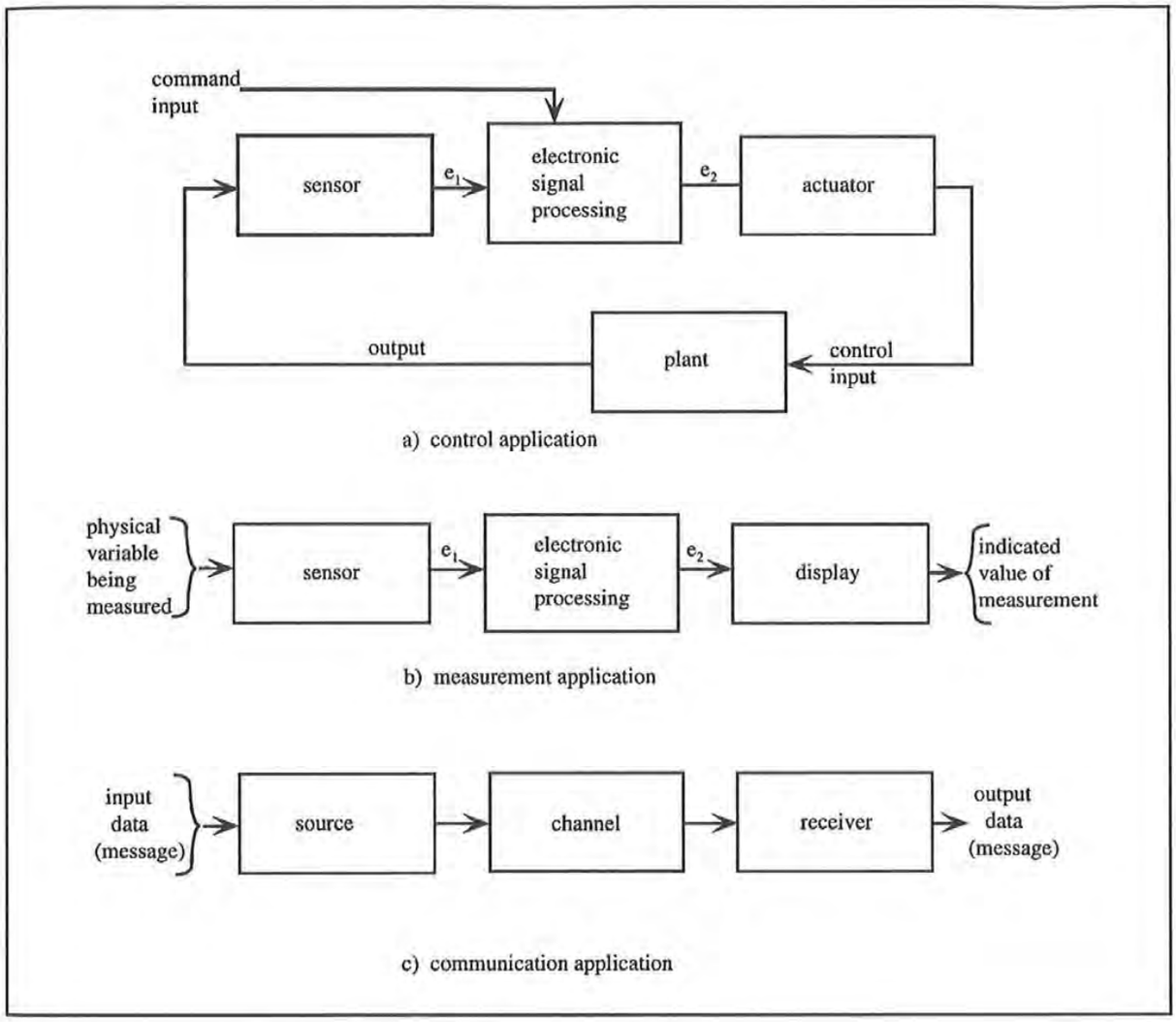
BLOCK DIAGRAM REPRESENTATION OF A SYSTEM

The designer of a system often begins with a block diagram, in which major components are represented as blocks.

At the level of abstraction appropriate for the present discussion, an electronic system will be represented by a block diagram. Depending on whether a given electronic system application is to (a) control, (b) measure or (c) communicate, it will have one of the three block diagram configurations shown Figure 2.1.

In block diagram architecture, each functional component or subsystem is represented by an appropriately labeled block. The inputs and outputs for each

Figure 2.1
Block Diagrams for Various System Applications



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block are identified. In electronic systems, these input and output variables are electrical signals, except for the system input and system output. One benefit of this approach is that the subsystem operation can be described by functional relationships between input and output. There is no need to describe the operation of individual transistors and components within the blocks.

Figure 2.1a depicts the architecture or configuration for a control application electronic system. In such a system, control of a physical subsystem (called the *plant*) occurs by regulating some physical variable (or variables) through an actuator. An actuator has an electrical input and an output that may be mechanical, pneumatic, hydraulic, chemical, or so forth. The plant being controlled varies in response to changes in the actuator output. The control is determined by electronic signal processing based on measurement of some variable (or variables) by a sensor in relationship to a command input by the operator of the system (i.e., by the driver in an automotive application).

In an electronic control system, the output of the sensor is always an electrical signal (denoted e_1 in Figure 2.1). The input is a physical variable in the plant being controlled. The electronic signal processing generates an output electrical signal (denoted e_2 in Figure 2.1) that operates the actuator. The signal processing is designed to achieve the desired control of the plant in relation to the variable being measured by the sensor. The operation of such a control system is described later in this chapter. At this point, we are interested only in describing the control system architecture. A detailed explanation of electronic control is presented later in this chapter.

The architecture for electronic measurement (also known as instrumentation) is similar to that for a control system in the sense that both structures incorporate a sensor and electronic signal processing. However, instead of an actuator, the measurement architecture incorporates a display device. A display is an electromechanical or electro-optical device capable of presenting numerical values to the user (driver). In automotive electronic measurement, the display is sometimes simply a warning light with a fixed message rather than a numeric display. Nevertheless, the architecture is as shown in Figure 2.1b. It should be noted that both control and instrumentation electronic systems use one or more sensors as well as electronic signal processing.

Figure 2.1c depicts a block diagram for a communication system. In such a system, data or messages are sent from a source to a receiver over a communication channel. This particular architecture is sufficiently general that it can accommodate all communication systems, from ordinary car radios to digital data buses between multiple electronic systems on cars. Communication systems are described in greater detail later in this chapter.

ANALOG SYSTEMS

Although digital electronic systems are rapidly replacing analog systems in automotive electronics, it is simpler to describe analog systems first since they can generally be understood more intuitively than digital systems. Considering control and instrumentation applications, the sensor converts the input variable

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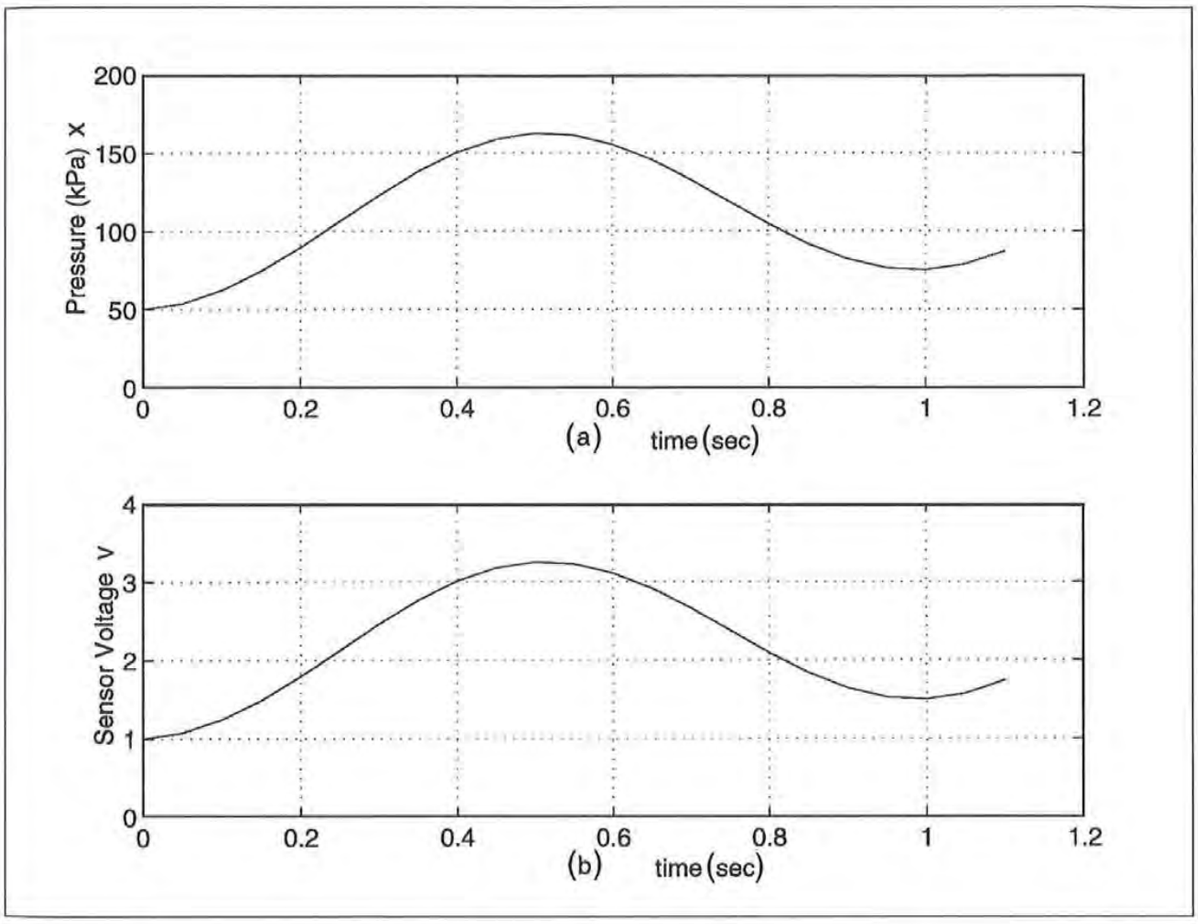
to a proportional electrical signal continuously. That is, as the input quantity varies, the sensor output voltage varies proportionately. In mathematical terms, letting x be the amplitude of the input quantity (e.g., pressure, displacement, or temperature), the output voltage of an ideal sensor (denoted v) is continuously proportional to x:

$$v = k_s x$$

In this expression, k_s represents the so-called *transducer gain* of the sensor.

Figure 2.2 illustrates the operation of an ideal pressure sensor, in which x is the pressure of a fluid and v is the sensor output voltage. The graph seen in Figure 2.2a shows this pressure as it varies with time; Figure 2.2b shows the corresponding ideal sensor output voltage. In this example, at every instant of

Figure 2.2
Ideal Pressure Sensor



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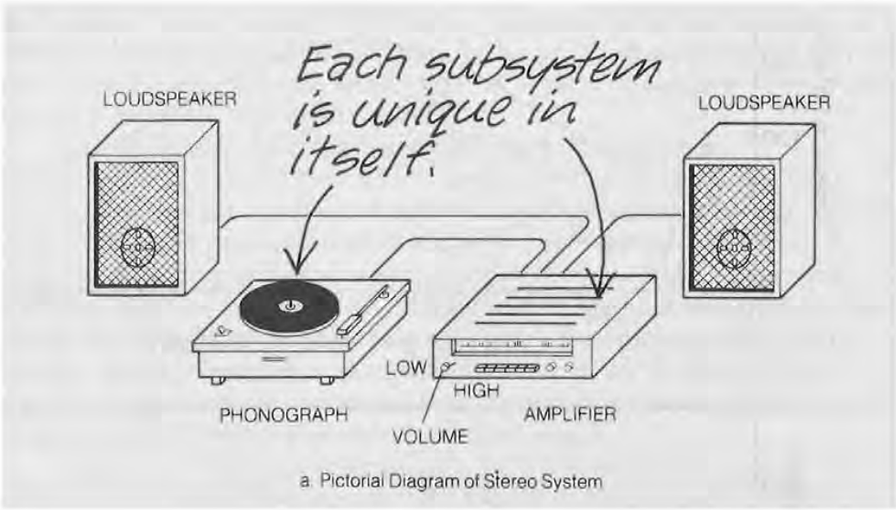
time the sensor output voltage is a multiple of the input pressure; the transducer gain is .02 volts/kPa.

In a control system using this sensor, the signal processing component should perform an operation on this voltage and generate an output e_2 to drive the actuator. The signal processing is designed to create the correct actuator voltage at each instant to achieve the desired control. There are many examples of such a system in automotive electronic systems. One of the most important points of this analog system is that the system functions continuously with time.

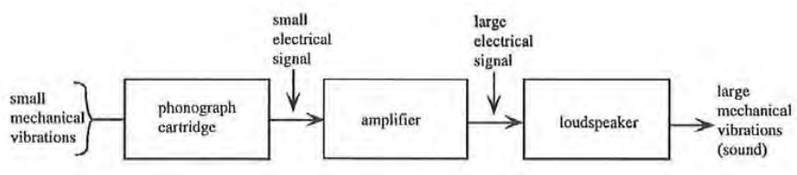
An Example Analog System

Perhaps the most familiar example of an analog electronic system is the home audio entertainment system. Figure 2.3 depicts such a system that includes a phonograph record. This example system incorporates a sensor, an electronic signal process, and an actuator. Although the phonograph has been replaced by other recording means, it is common enough to be familiar to most readers. Moreover, it is, perhaps, more easily understood than other recording media such as magnetic tape or compact discs.

Figure 2.3
Example of an Electronic System



a. Pictorial Diagram of Stereo System



b. System Diagram

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In this system, the input is the mechanical vibration of the phonograph needle as it tracks along the groove in the record. The sensor is the phonograph cartridge that converts these mechanical vibrations to an analog electrical signal. This electrical signal, which is too weak to drive the loudspeakers (the actuators in the present example) at an acceptable audio level, is amplified in the stereo amplifier. The amplifier increases the power level to a point at which it can drive the loudspeakers. In mathematical terms, if the power level input to the amplifier is P_i, then the power output to the speakers (denoted P_o) is an amplified version of the input:

$$P_o = GP_i$$

where G is the power gain of the amplifier. That is, the input power is continuously amplified by the amplifier by a factor of G.

CHARACTERISTICS OF A DIGITAL ELECTRONIC SYSTEM

In contrast to an analog electronic system that operates in continuous time, a digital system operates in discrete instants of time. This process of representing a continuous-time quantity at specific discrete times is called *sampling* and is illustrated in Figure 2.4.

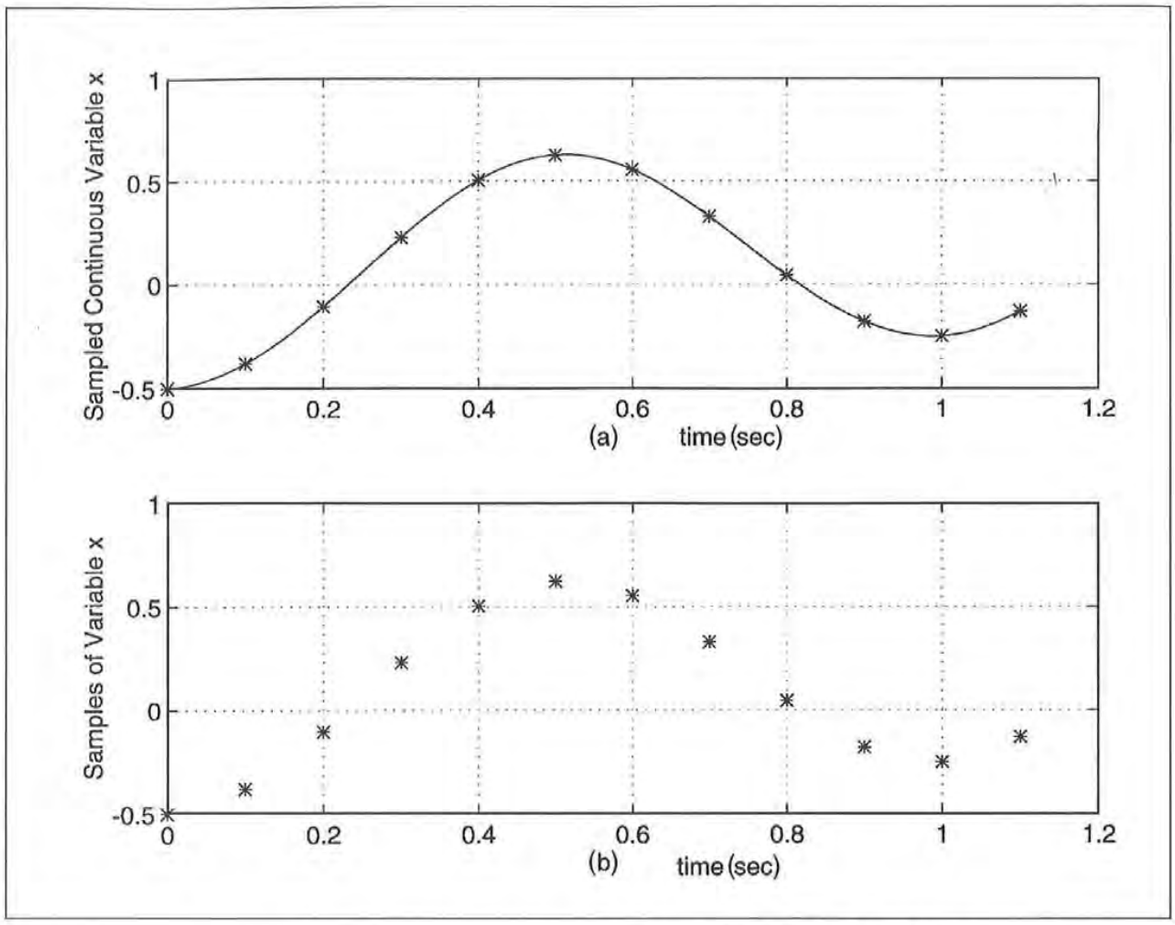
Figure 2.4a illustrates a continuously varying quantity that is denoted x (which might, for example, be intake manifold pressure). This continuous-time quantity is sampled electronically at times that are multiples of a basic sample period. Figure 2.4a depicts the sample points of the continuous pressure as asterisks. Each sample is the value of the continuous variable at a specific (discrete) time. A sequence of samples is presented to the signal processor at the corresponding sample times. The sequence of samples is shown in Figure 2.4b. In a digital electronic system, the signal processing is performed by some form of digital computer. This computer requires time to perform its computations. The time between samples provides an interval in which the necessary computations are performed.

The time between any successive samples is normally a constant known as *sample time.* Sample time is a critically important parameter for any digital system and is chosen with great care by the system designer. It must be sufficiently long to enable the computer to perform its computations on any given sample before the next sample is taken, or the computer cannot keep up with the data stream in real time. On the other hand, if the sample time is too long, then the input might change too much for the sampled data to adequately represent the continuous quantity being sampled. The time required for computation on each sample is influenced in part by the processor speed and by the efficiency of the program being used to perform the computations. This aspect of performance is discussed in greater detail in Chapter 4.

The sampled data illustrated in Figure 2.4b are in a sampled analog format. This format is not compatible with a digital system. One more step, called *quantization,* is required to convert the sampled analog data into data that can be read by the computer. In a digital electronic system, each sample is represented numerically by its magnitude. For example, a sequence of samples

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Figure 2.4
Sampling of a Continuous Variable

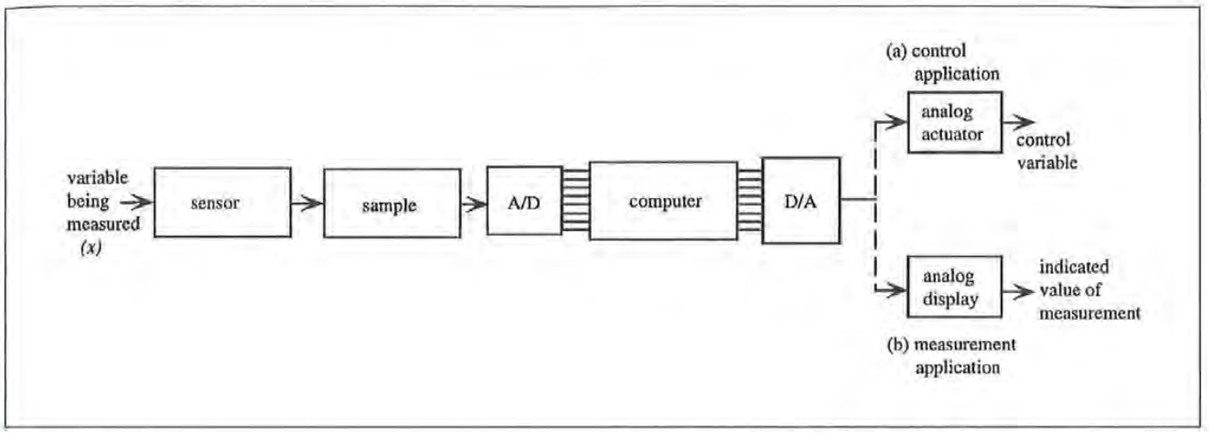


of a continuous quantity might be {0.9, 1.1, 1.6, 2.3, 1.5, 1.2, . . .}. However, computers don't use decimal number systems since there is no practical way to represent decimal digits. Rather, computers use a binary number system that is based on 2 rather than 10. In a binary number system, each numerical value is represented by a combination of ones or zeros. For example, the decimal number 11 is represented by 1011. This system will be described in greater detail in Chapter 3, but for the present, it is sufficient to understand that each sample is converted to a binary number in the form of combinations of one or zero. Chapter 3 will explain that this binary system is appropriate for a computer, in which ones and zeros correspond to transistors that are either "on" or "off," respectively. By having a sufficient number of transistors, it is possible to represent any possible numerical value.

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The circuit that converts sampled analog data to binary values is called an *analog-to-digital converter* (ADC). It is also sometimes called a *quantizer.* When the computer has finished calculations on a given sample, it outputs a numerical value to an external device in the form of a binary number. If that device is analog, as in the case of an actuator for a control system, the output binary number must be reconverted to analog format. This conversion is done in a device known as a *digital-to-analog converter* (DAC). The two types of converters are explained in detail in Chapter 4. Not all digital electronic systems require converters, because some sensors and actuators are digital already. Except for these cases, a digital electronic system for either control or instrumentation has a block diagram as depicted in Figure 2.5.

Figure 2.5
Digital Control (a) or Measurement (b) System Configuration



ELECTRONIC SYSTEM PERFORMANCE

The performance of an electronic system is evaluated by quantitative descriptions of how well it performs its intended task and inherently uses numerical representation (e.g., parameters and graphs). The home audio system, which has been mentioned previously as a familiar example of an electronic system, will serve as an example for performance analysis.

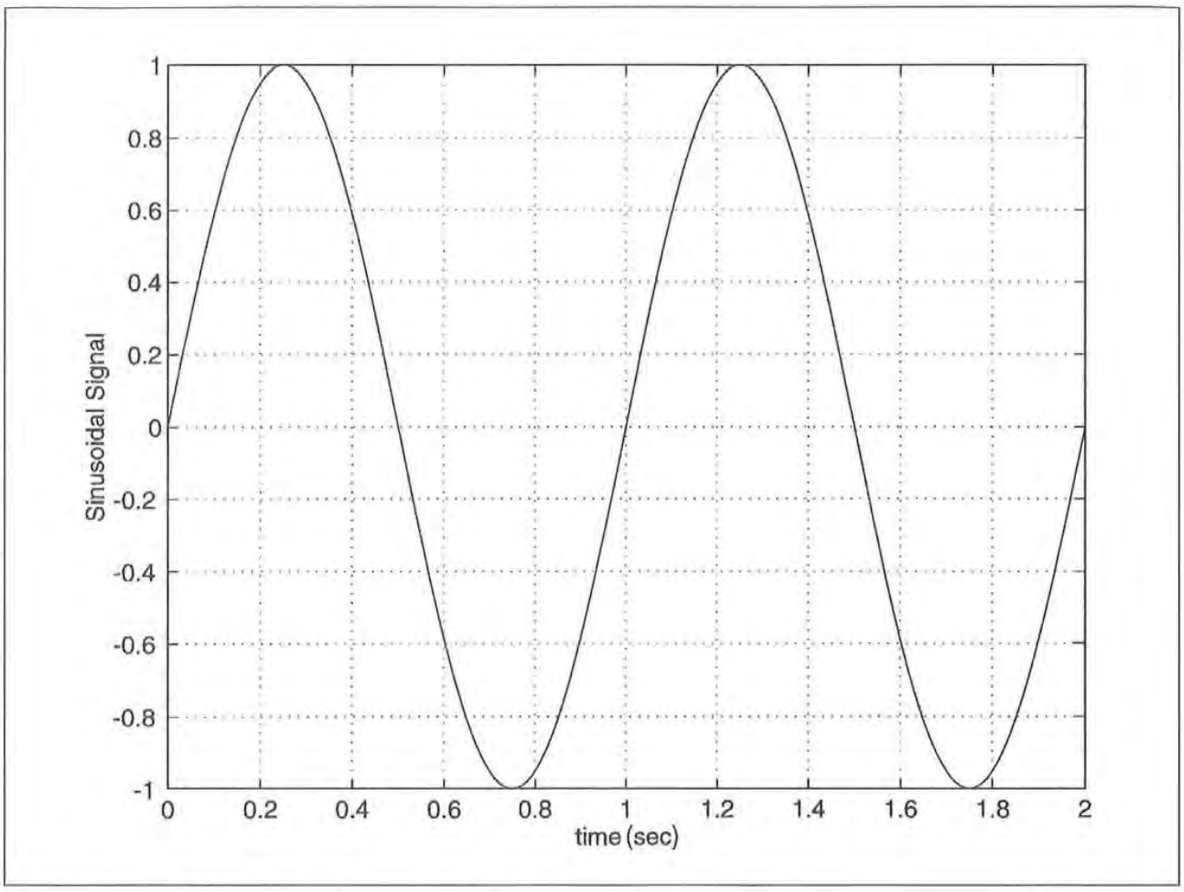
The performance of a high-fidelity home audio system is described by such characteristics as frequency response, maximum power level, harmonic distortion, and linearity (as well as other characterizations that are specific to an audio system). The "fidelity" of an audio system, which expresses how well it reproduces the sounds from the source, is best given by its frequency response. Unwanted distortion of the sound is characterized by harmonic distortion and linearity. Similar measures are also appropriate and useful for characterizing an electronic system.

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The performance of any electronic system (analog or digital) is determined by its various components—transistors, resistors, capacitors, sensors, actuators, displays, and so forth—as well as by the system architecture or interconnections of its components. For a digital electronic system, performance is further determined by the computer program (software) that is running in the associated computer. The system designer makes careful choices for the system structure as well as for the parameter values (e.g., resistance or capacitance) to tailor the specific system performance to the specifications of a given task.

Just as in the case of a hi-fi audio system, the fidelity of an automotive electronic system to dynamically changing inputs is given by its frequency response. Specifically, this is the response of the system to a standard input called a *sinusoid*. The standard input is a smoothly varying periodic quantity as illustrated by the graph in Figure 2.6.

Figure 2.6
Sinusoidal Signal



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The input fluctuates through a complete cycle beginning at zero, increasing positively to a maximum, then moving symmetrically negatively back to zero in T seconds. It then repeats periodically in intervals of T seconds. The frequency f of the input is the number of cycles in one second, or

$$f = 1/T$$

In mathematical terms, a sinusoidal input $x(t)$ is given by the following equation:

$$x(t) = X\sin(2\pi ft)$$

where

X = amplitude of the input
f = frequency
t = time

The output of an electronic system from a sinusoidal input is also sinusoidal at the same frequency, as depicted by the graphs in Figure 2.7, in which the solid curve is the input and the dashed curve the output.

The *frequency response* of an electronic system is defined as the ratio of the peak amplitude of the output (denoted Y) to the peak amplitude of the input (denoted X). Notice that there is a time delay in the response of the system relative to the input, corresponding to the difference in zero crossing of the input and output.

In formal mathematical terms, the output $y(t)$ is given by

$$y(t) = Y\sin[2\pi f(t - d)]$$

where

Y = amplitude of the output
d = time delay

The system frequency response, denoted H, is formally defined as follows:

$$H = Y/X$$

The delay is expressed as a fraction of the period, called the *phase*, and is usually denoted by the Greek letter phi (ϕ):

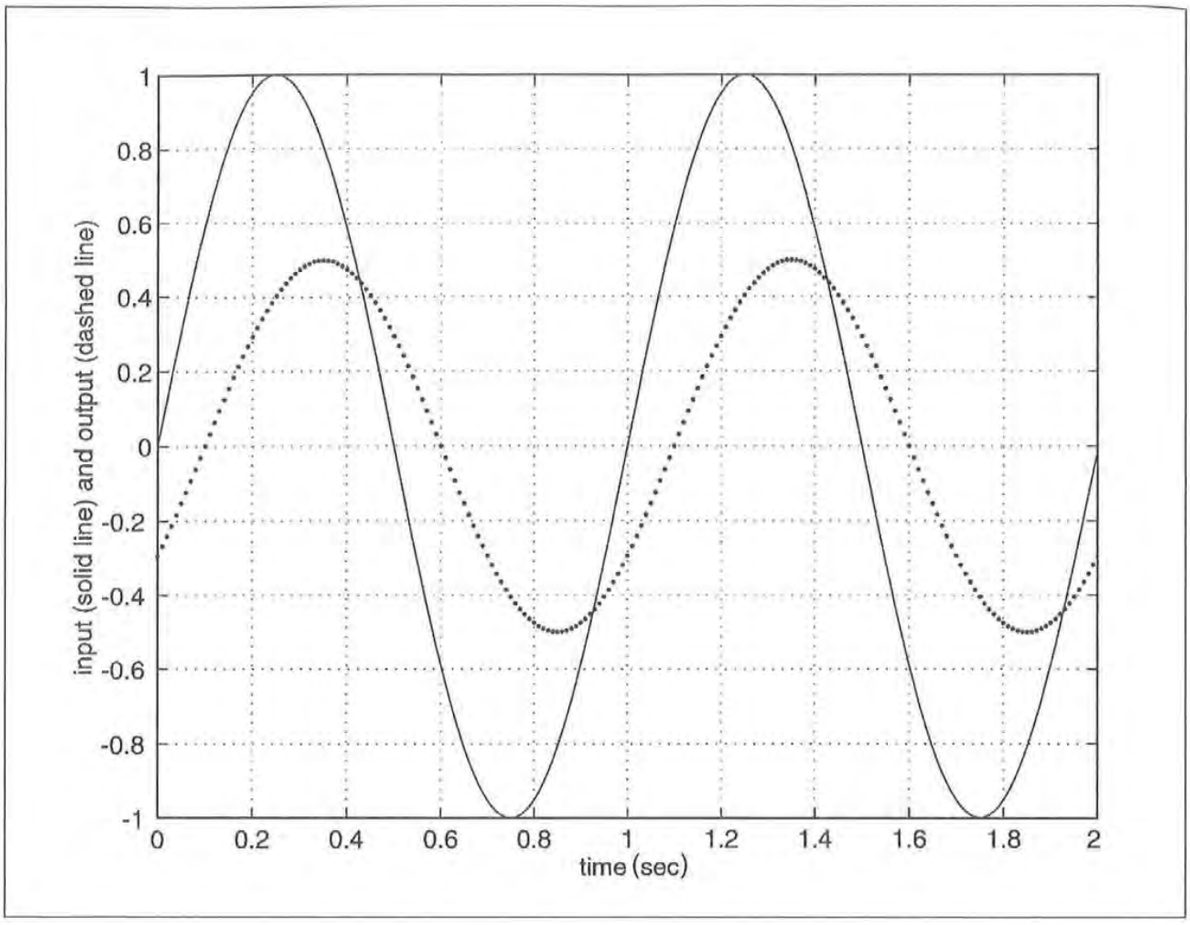
$$\phi = 2\pi\, d/T$$
$$= 2\pi fd$$

For an electronic system that is ideal with respect to its dynamic performance, the frequency response is a constant for all frequencies. In practice, the frequency response varies with frequency. A graph of the frequency response of a typical electronic system is shown in Figure 2.8.

In this example, the frequency response is close to ideal (i.e., constant) over a range of frequencies from frequency f_1 to f_2. For frequencies below f_1 or above f_2, the response drops off. In the example of a hi-fi amplifier, f_1 might be about 20 Hz and f_2 might be about 20 kHz. The range of frequencies over which the frequency response is nearly constant is called the system *bandwidth*. The

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Figure 2.7
Illustration of Steady-State Input and Output of a System

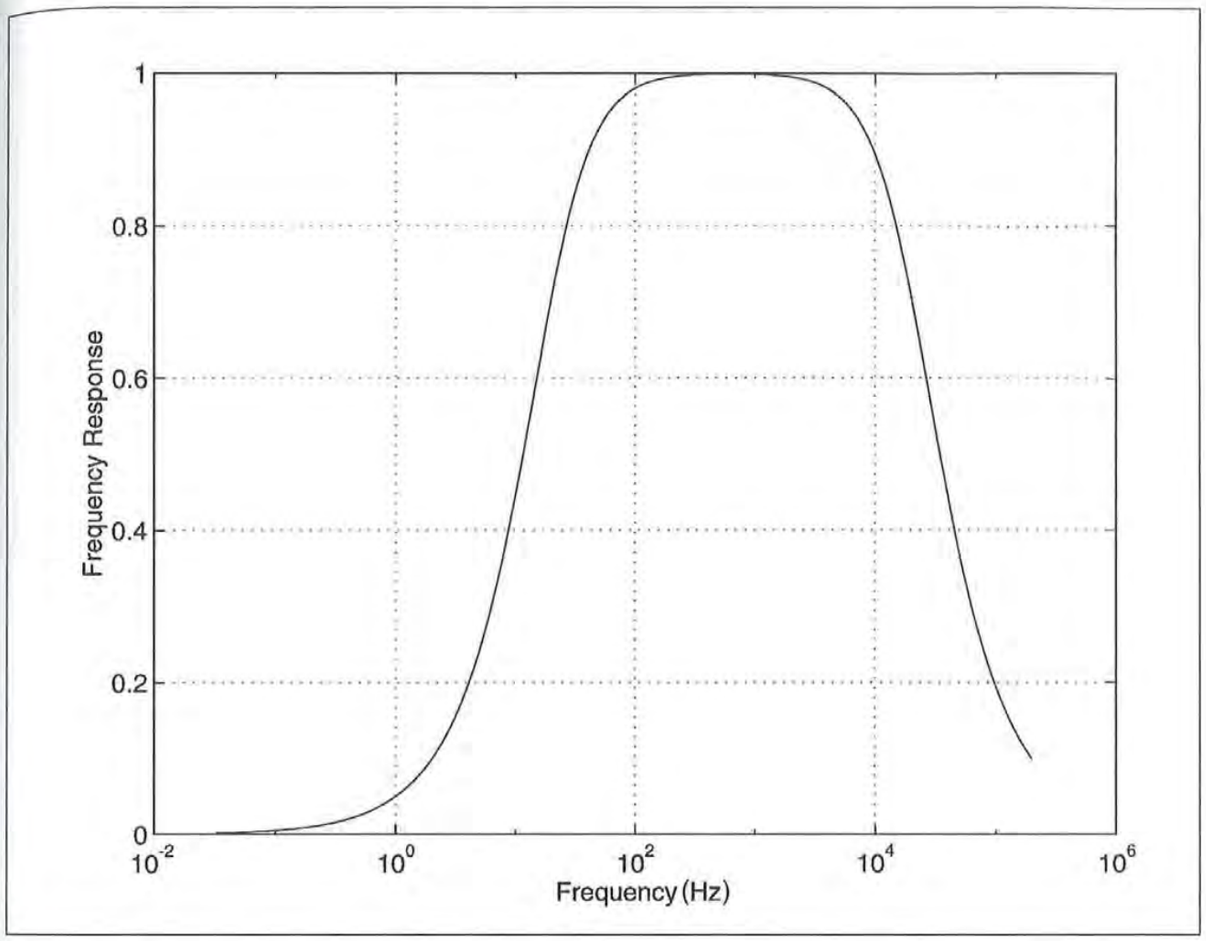


frequency response is said to be "flat" over this bandwidth. For example, in Figure 2.8 the frequency response is nearly constant from 10^2 (100) Hz to about 10^4 (10,000) Hz. In automotive electronic systems, this range of frequencies is determined by the system designer to be compatible with the corresponding range of input frequencies in normal systems operation. There are numerous references to the bandwidth of automotive electronic systems in later chapters.

The performance of any system can be evaluated from the response of the output to a sinusoidal input. Important properties of the system can be determined from this response, such as resonance, bandwidth, and response to rapid input changes.

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Figure 2.8
Frequency Response of an Example System



To illustrate this performance analysis method, consider the suspension system, which is an important automotive system. Figure 2.9 is a simplified representation of the suspension system at one wheel on a car. The car body (sprung mass M_s) is supported by a spring (depicted as K in Figure 2.9) and shock absorber (denoted as D in Figure 2.9). The unsprung mass (wheel and axle assembly) is displaced by force f, which is transmitted by the tire in response to a rough road. The response of this system is the displacement x of the unsprung mass relative to its rest position. The input to this system is a force that in mathematical terms we denote $F(t)$.

Perhaps the most important input for characterizing system performance is the sinusoid. In our example, we consider a sinusoidal force such as might

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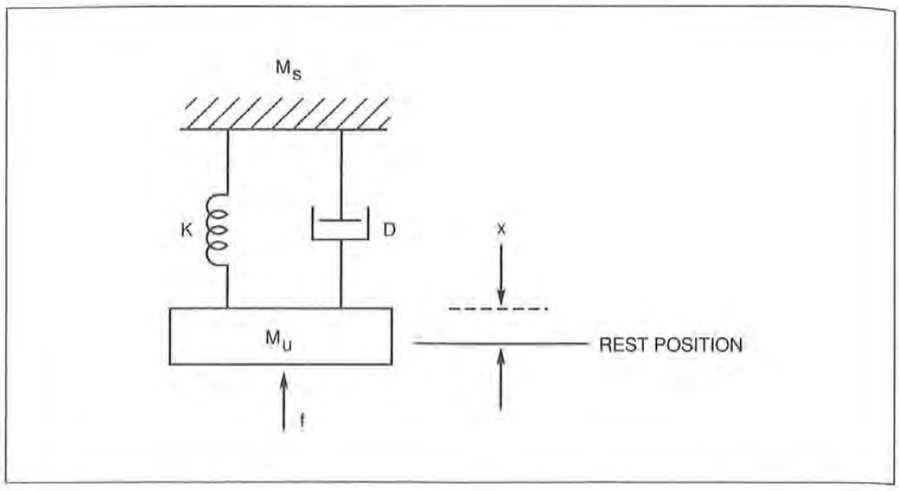


Figure 2.9 Simplified Suspension System

occur on a so-called washboard gravel road. The force transmitted by the tire to the unsprung mass, depicted by the solid curve in Figure 2.10, is represented by

$$F(t) = F_0 \sin\omega t$$

where

F_0 = amplitude of the force
$\omega = 2\pi f$
f = frequency or $(1/T)$
T = period

The displacement of the unsprung mass is represented by x (relative to the rest position) and is depicted by the dashed curve in Figure 2.10. This displacement is given mathematically by

$$x = X \sin(\omega t - \phi)$$

where ϕ equals phase, or $2\pi d/T$.

The performance of the example suspension system is given by the sinusoidal frequency response. For any system, the sinusoidal frequency response is the ratio of the amplitude of the response to the amplitude of the input. In our example, the response amplitude is X and the input amplitude is F, yielding

$$H = \frac{X}{F}$$

The sinusoidal frequency response of any system is a function of (i.e., depends on) frequency. In our example, the frequency of the rough road force due to the washboard road is proportional to the speed at which the car travels over the road. For the example suspension system, frequency response is depicted in

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Figure 2.10
Graph of Force Transmitted by the Tire

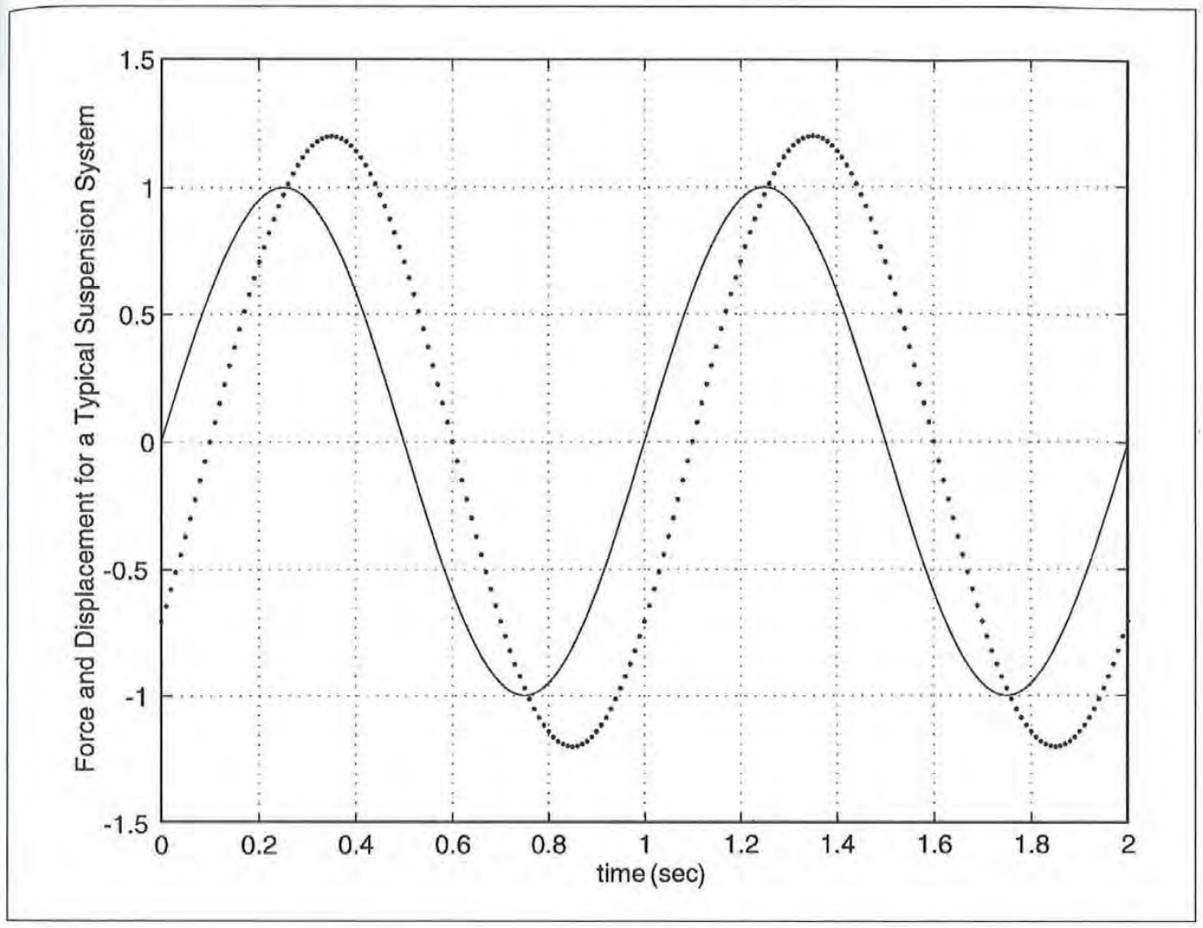


Figure 2.11. In this illustration, four separate responses are shown for four different shock absorber damping constants. For very low damping coefficient D (weak damping or defective shock absorber), the response becomes very large for frequencies near the resonant frequency (i.e., f_o):

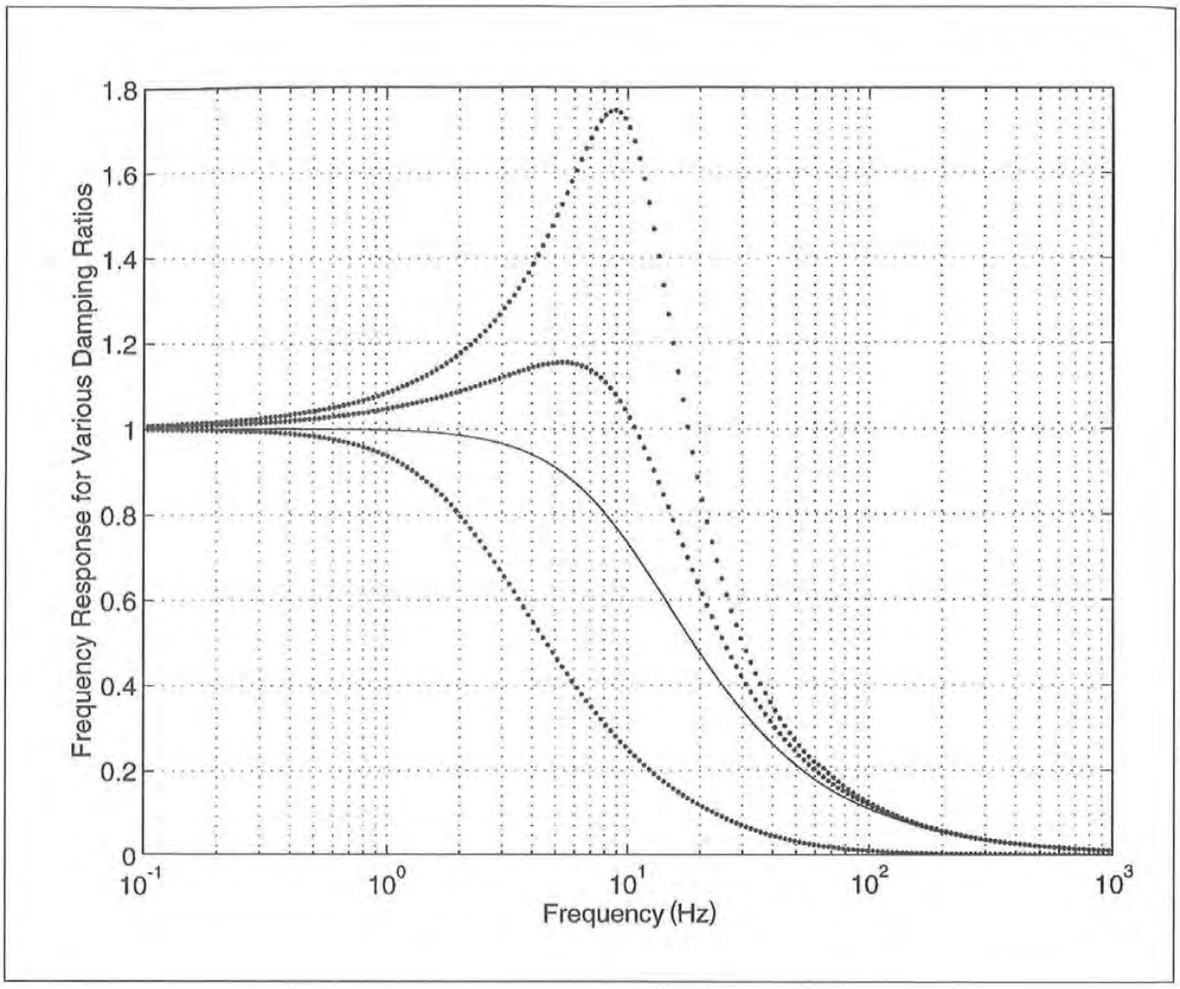
$$f_o = \sqrt{\frac{M_u}{K}}$$

This situation is depicted by the uppermost dotted curve in Figure 2.11.

For a somewhat larger damping, the response is large enough near resonance to absorb the road force, transmitting relatively little of this force to the car body.

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Figure 2.11
Frequency Response for Four Different Shock Absorber Damping Constants



A car with a so-called soft suspension yields relatively good ride characteristics. Unfortunately, a soft suspension tends to have relatively poor handling. The situation is depicted by the next highest dotted curve in Figure 2.11.

On the other hand, for very high damping coefficient, the response decreases sharply for frequencies greater than f_o. This circumstance corresponds to a very stiff suspension in which much of the road force is transmitted by the shock absorber to the car body, making for a rather rough ride. This situation is depicted by the lowest dotted curve in Figure 2.11.

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The response that is often optimum for many applications is called *critical damping* D_c:

$$D_c = \sqrt{M_u K}$$

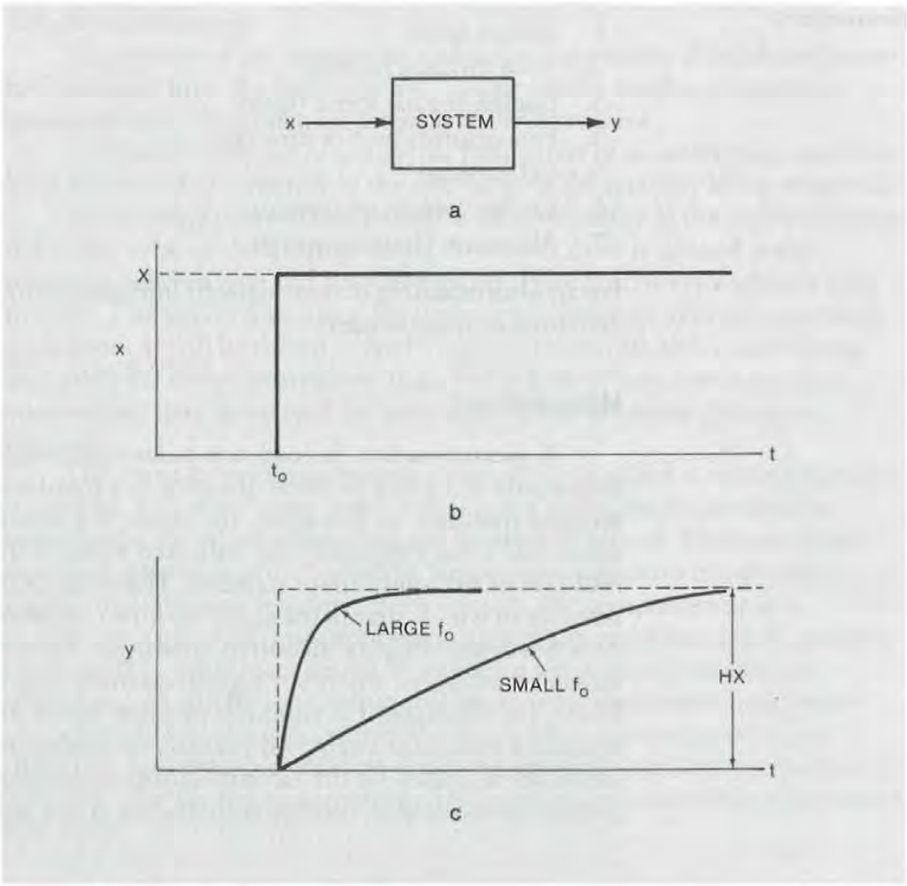
Critical damping gives the most uniform response for the greatest range of frequencies. This situation (which is normally the most desirable) is depicted by the solid curve in Figure 2.11.

Step Response

The step response characterizes the performance of a system.

The performance of a system is also represented by its time response which is closely related to its frequency response. Perhaps the most meaningful method of assessing the time response of a system is to examine its response to an input step. Figure 2.12 is a graph of a step input to the example system as well as the

Figure 2.12
Step Response of a System



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system response. The step input is an abrupt change occurring at time t_o. However, the output change is gradual relative to the input. The output asymptotically approaches a steady value *HX*.

The rate at which the output approaches the final value varies inversely with bandwidth, as illustrated in Figure 2.12 (where bandwidth is denoted f_o). Although the actual response of the system depends on the characteristics of the system, the response time of any system generally varies inversely with its bandwidth.

INSTRUMENTS

Instrumentation systems, whether electrical, mechanical, or a combination of both, measure a physical quantity and provide a report of that measurement.

An instrument (or instrumentation system) is a device for measuring some specific quantity. Automotive instruments have traditionally been mechanical, pneumatic, hydraulic, electrical, or combinations of these. However, modern automotive instrumentation is largely electronic. These electronic instruments or instrumentation systems are used to measure a variety of physical quantities, including

1. Vehicle speed
2. Total distance traveled
3. Engine angular speed (rpm)
4. Fuel quantity and/or flow rate
5. Oil pressure
6. Engine coolant temperature
7. Alternator charging current

For an understanding of measurement instrumentation, it is helpful to review a definition of measurement.

Measurement

A *measurement* is defined as a numerical comparison of an unknown magnitude of a given physical quantity to a standard magnitude of the same physical quantity. In this sense, the result of a measurement is normally a numerical value expressing the indicated value of the measurement as a multiple of the appropriate standard. However, other display devices are possible in which simple messages are given. Automotive instrumentation does not always display measured quantities. Rather, a warning lamp (or buzzer) is activated whenever a given quantity falls outside of allowed limits. For example, it is common practice not to provide a display of measured values for engine oil pressure or coolant temperature. Warning lamps are activated by the electronic instrumentation system whenever oil pressure is too low or coolant temperature is too high.

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Issues

In any measurement made with any instrument there are several important issues, including

1. Standards
2. Precision
3. Calibration
4. Accuracy
5. Errors
6. Reliability

Each of these issues has an important impact on the performance of the instrumentation.

The *standard* magnitudes of the physical variables measured by any instrument are maintained by the National Institute of Standards & Technology in the United States. These standard magnitudes and the fundamental relationships between physical variables determine the units for each physical quantity.

The *precision* of any instrument is related to the number of significant figures that is readable from the display device. The greater the number of significant figures displayed, the greater the precision of the instrument.

Calibration is the act of setting the parameters of an instrument such that the indicated value conforms to the true value of the quantity being measured.

The *accuracy* of any measurement is the conformity of the indicated value to the true value of the quantity being measured. *Error* is defined as the difference between true and indicated values. Hence, accuracy and error vary inversely. The required accuracy for automotive electronic systems varies with application, as will be shown in later chapters. In general, those instruments used solely for driver information (e.g., fuel quantity) have lower accuracy requirements than those used for such applications as engine control or diagnosis.

Systematic errors in the accuracy of instruments are due to known imperfections in an instrument; random errors are caused by outside disturbances.

The errors in any measurement are generally classified as either systematic or random. *Systematic* errors result from known variations in instrument performance, for which corrections can be made if desired. There are many sources of systematic error, including temperature variations in calibration, loading, and dynamic response. Since virtually any component in an instrument is potentially susceptible to temperature variations, great care must be exercised in instrument design to minimize temperature variations in calibration. As will be seen later in this book, most automotive instruments have relatively low precision requirements, so that temperature variations in calibration are negligible. *Random* errors are essentially random fluctuations in indicated value for the measurement. Most random measurement errors result from noise.

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Systematic *loading* errors are due to the energy extracted by an instrument when making a measurement. Whenever the energy extracted from a system under measurement is not negligible, the extracted energy causes a change in the quantity being measured. Wherever possible, an instrument is designed to minimize such loading effects. The idea of loading error can be illustrated by the simple example of an electrical measurement, as illustrated in Figure 2.13. A voltmeter M having resistance R_m measures the voltage across resistance R. The correct voltage (v_c) is given by

$$v_c = V\left(\frac{R}{R + R_l}\right)$$

However, the measured voltage v_m is given by

$$v_m = V\left(\frac{R_p}{R_p + R_l}\right)$$

where R_p is the parallel combination of R and R_m:

$$R_p = \frac{RR_m}{R + R_m}$$

Loading is minimized by increasing the meter resistance R_m to the largest possible value. For conditions where R_m approaches infinite resistance, R_p approaches resistance R, and v_m approaches the correct voltage. Loading is similarly minimized in measurement of any quantity by minimizing extracted energy. Normally, loading is negligible in modern instrumentation.

Another significant systematic error source is the *dynamic response* of the instrument. Any instrument has a limited response rate to very rapidly changing input, as illustrated in Figure 2.14. In this illustration, an input quantity to the instrument changes abruptly at some time. The instrument

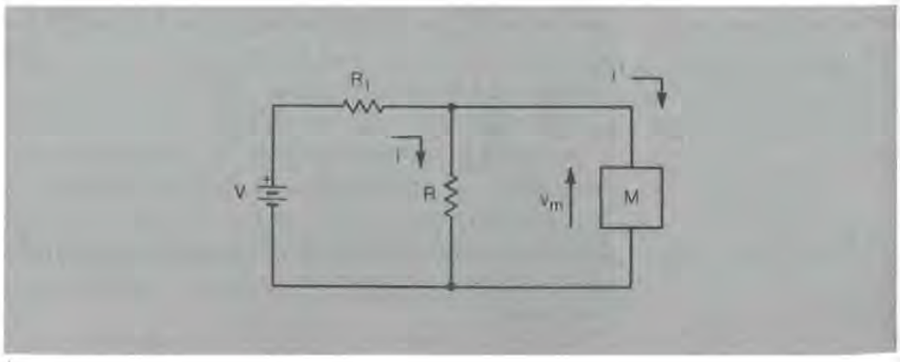


Figure 2.13 Illustration of Loading Error

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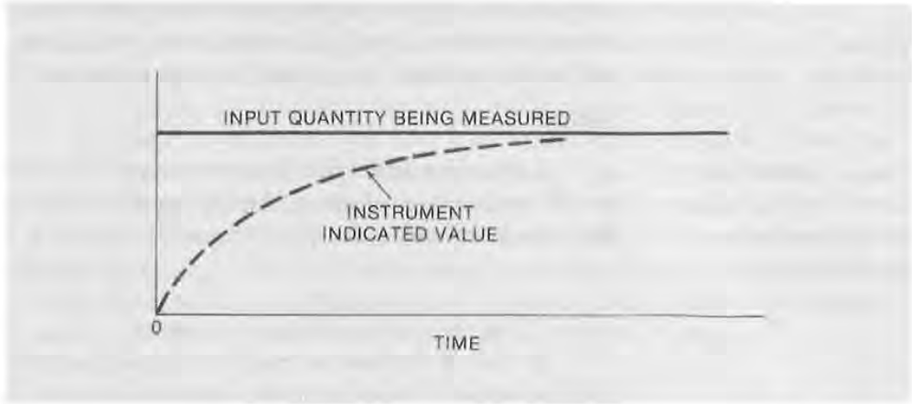


Figure 2.14
Instrument Dynamic Error

begins responding, but cannot instantaneously change and produce the new value. After a time, the indicated value approaches the correct reading (presuming correct instrument calibration). The greater the bandwidth of an instrument or instrumentation system, the more quickly it can follow rapid changes in the quantity being measured.

In many automotive instrumentation applications the bandwidth is purposely reduced to avoid rapid fluctuations in readings. For example, the type of sensor used for fuel quantity measurements actually measures the height of fuel in the tank with a small float. As the car moves, the fuel sloshes in the tank, causing the sensor reading to fluctuate randomly about its mean value. The signal processing associated with this sensor has an extremely low bandwidth so that only the average reading of the fuel quantity is displayed, thereby eliminating the undesirable fluctuations in fuel quantity measurements that would occur if the bandwidth were not restricted.

The *reliability* of an instrumentation system refers to its ability to perform its designed function accurately and continuously whenever required, under unfavorable conditions, and for a reasonable amount of time. Reliability must be designed into the system by using adequate design margins and quality components that operate both over the desired temperature range and under the applicable environmental conditions.

BASIC MEASUREMENT SYSTEM

The basic block diagram for an electronic instrumentation system has been given in Figure 2.1b. That is, each system has three basic components: sensor, signal processing, and display. Essentially, all electronic measurement systems incorporated in automobiles have this basic structure regardless of the physical variable being measured, the type of display being used, or whether the signal processing is digital or analog.

Understanding automotive electronic instrumentation systems is facilitated by consideration of some fundamental characteristics of the three functional

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components. Again it should be noted that the trend in automotive electronic systems is toward digital rather than analog realization. However, because both realizations are used, both types of components are discussed below.

Sensor

Sensors convert one form of energy, such as thermal energy, into electrical energy.

A *sensor* is a device that converts energy from the form of the measurement variable to an electrical signal. An ideal analog sensor generates an output voltage that is proportional to the quantity q being measured:

$$v_s = K_s q$$

where K_s is the sensor calibration constant.

By way of illustration, consider a typical automotive sensor—the throttle-position sensor. The quantity being measured is the angle (theta) of the throttle plate relative to closed throttle. Assuming for the sake of illustration that the throttle angle varies from 0 to 90 degrees and the voltage varies from 0 to 5 volts, the sensor calibration constant K_s is

$$K_s = \frac{5}{90^\circ} = .056 \text{ volt/degree}$$

Alternatively, a sensor can have a digital output, making it directly compatible with digital signal processing. For such sensors, the output is an electrical equivalent of a numerical value, using a binary number system as described earlier in this chapter. Figure 2.15 illustrates the output for such a sensor. There are N output leads, each of which can have one of two possible voltages, representing a 0 or 1. In such an arrangement, 2^N possible numerical values can be represented. For automotive applications, N ranges from 8 to 16, corresponding to a range of from 64 (2^8) to 256 (2^{16}) numerical values.

Of course, a sensor is susceptible to error just as is any system or system component. Potential error sources include loading, finite dynamic response, calibration shift, and nonlinear behavior. Often it is possible to compensate for these and other types of errors in the electronic signal processing unit of the instrument. If a sensor has limited bandwidth, it will introduce errors when

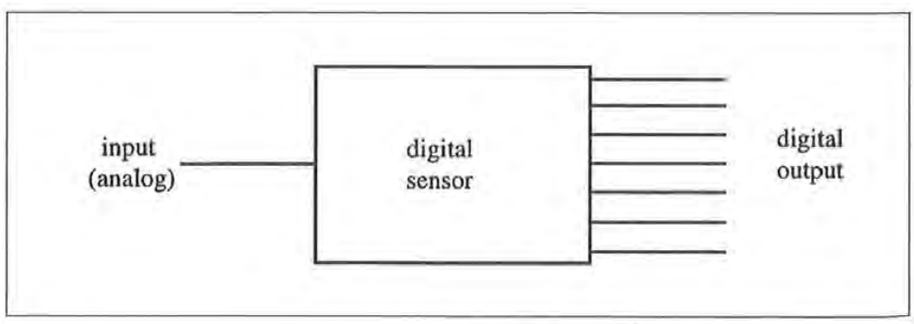


Figure 2.15 Digital Sensor Configuration

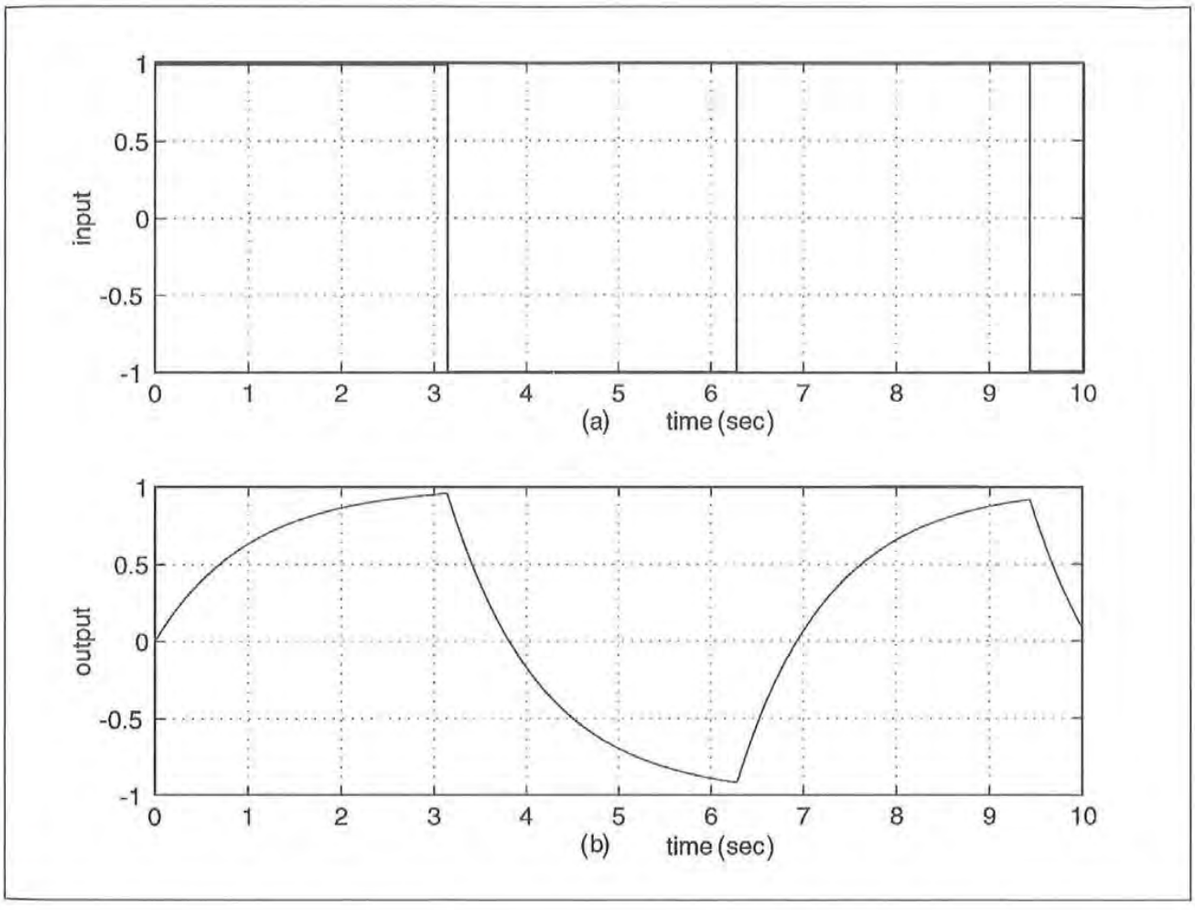
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measuring rapidly changing input quantities. Figure 2.16 illustrates such dynamic errors for an analog sensor measuring an input that abruptly changes between two values (this type of input is said to have a *square wave* waveform). Figure 2.16a depicts a square wave input to the sensor. Figure 2.16b illustrates the response that the sensor will have if its bandwidth is too small. Note that the output doesn't respond to the instantaneous input changes. Rather, its output changes gradually, slowly approaching the correct value.

Signal processing can be used to compensate for systematic errors of sensors.

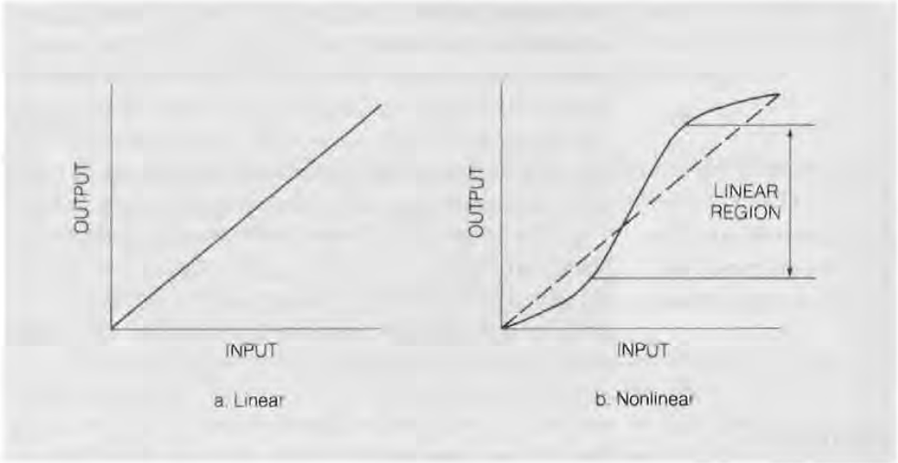
An ideal sensor has a *linear transfer characteristic* (or transfer function), as shown in Figure 2.17a. Thus, some signal processing is required to linearize the output signal so that it will appear as if the sensor has a straight line (linear) transfer characteristic, as shown in the dashed curve of Figure 2.17b.

Figure 2.16
Sensor Error Caused by Limited Dynamic Response of Sensor



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Figure 2.17
Sensor Transfer Characteristics



Sometimes a nonlinear sensor may provide satisfactory operation without linearization if it is operated in a particular "nearly" linear region of its transfer characteristic (Figure 2.17b).

Sensors are subject to random errors such as heat, electrical noise, and vibrations.

Random errors in electronic sensors are caused primarily by internal electrical noise. Internal electrical noise can be caused by molecular vibrations due to heat (thermal noise) or random electron movement in semiconductors (shot noise). In certain cases, a sensor may respond to quantities other than the quantity being measured. For example, the output of a sensor that is measuring pressure may also change as a result of temperature changes. An ideal sensor responds only to one physical quantity or stimulus. However, real sensors are rarely, perfect and will generally respond in some way to outside stimuli. Signal processing can potentially correct for such defects.

Displays and Actuators

Automotive display devices, typically analog or digital meters, provide a visual indication of the measurements made by the sensors.

To be useful for measurement purposes, an electronic instrumentation system must somehow make the results of measurement available to the user. This is done through the display, which yields numerical values to the user. As in other aspects of electronic systems, the display can be analog or digital. Both types of display are described in detail in Chapter 9.

Displays, like sensors, are energy conversion devices. They have bandwidth, dynamic range, and calibration characteristics, and, therefore, have the same types of errors as do sensors. As with sensors, many of the shortcomings of display devices can be reduced or eliminated through the imaginative use of signal processing.

Actuators convert electrical inputs to an action such as a mechanical movement.

An *actuator* is an energy conversion device having an electrical input signal and an output signal that is mechanical (e.g., force or displacement). Automotive actuators include electric motors and solenoid-controlled valves and switches. These are used, for example, in throttle positioners for cruise control.

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Signal Processing

Any changes performed on the signals between the sensor and the display is considered to be signal processing.

Signal processing, as defined earlier, is any operation that is performed on signals traveling between the sensor and the display. Signal processing converts the sensor signal to an electrical signal that is suitable to drive the display. In addition, it can increase the accuracy, reliability, or readability of the measurement. Signal processing can make a nonlinear sensor appear linear, or it can smooth a sensor's frequency response. Signal processing can be used to perform unit conversions such as converting from miles per hour to kilometers per hour. It can perform display formatting (such as scaling and shifting a temperature sensor's output so that it can be displayed on the engine temperature gauge either in centigrade or in Fahrenheit), or process signals in a way that reduces the effects of random system errors.

Signal processing can use either analog circuitry or digital circuitry, depending on the application.

Signal processing can be accomplished with either a digital or an analog subsystem. The trend in automotive electronic systems toward fully digital instrumentation means that the majority of automotive electronic signal processing is accomplished with a digital computer.

DIGITAL SIGNAL PROCESSING

The block diagram of a digital instrumentation system is shown in Figure 2.5. In this figure the sensor is assumed to be analog and is measuring a physical variable (which we call x in this figure). This continuously varying quantity is sampled (as described earlier) and quantized, yielding a sequence of binary-valued numbers (which we call x_n when $n = 1, 2, 3, \ldots$). In more formal mathematical terms, this sequence is given by

$$x_n = x(nT) \qquad n = 1, 2, 3, \ldots$$

where T is the sample period. That is, each x_n is the value of the input at discrete time nT. This sequence is the input to a digital computer that performs the digital signal processing (DSP). The output from the computer (which we call y_n) is a sequence of digital data that is input to the display. The display is assumed to be digital since such display devices are commonplace in automotive electronic instrumentation systems. It should be noted that in the event the sensor is digital, the sample and quantizer (ADC) are not required because the digital sensor output is in a form that can be read directly by the computer.

The actual signal processing computation is specific to a given application. Perhaps the most general statement that can be made concerning the DSP operation is that each output from the computer is made by a series of computations performed by the computer on one or more input samples. The mathematical formula or rule for these computations is called an *algorithm*. The number of inputs used to compute each output is specific to a given algorithm, which, in turn, is specific to a given application.

The DSP operates on the samples x_n under program control to perform arithmetic and logical operations (as explained in Chapter 4) and generate an output y_n for each input x_n. The set of steps performed on x_n to yield y_n is

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determined by the desired processing algorithm. Although there are a great many algorithms used in automotive electronics, it is possible to illustrate an important class of DSP algorithms with the following recursive digital filter algorithm:

$$y_n = \sum_{k=0}^{K} a_k x_{n-k} - \sum_{j=1}^{J} b_j y_{n-j}$$

In this algorithm, the coefficients a_k and b_j are constants. The variables x_{n-k} are previous inputs, beginning with the most recent (x_n) and ending with the oldest input used to find y_n(that is, x_{n-k}). Similarly y_{n-j} are previously computed outputs, beginning with y_{n-1} (the most recent) and ending with y_{n-j}. The microcomputer calculates each product (that is, $a_k x_{n-k}$ and $b_j y_{n-j}$) and sums the products for each k from 0 to K and for each j from 1 to J.

As an example of DSP application, consider a low pass filter. The digital equivalent of such a filter has a very simple algorithm,

$$y_n = ax_n - by_{n-1}$$

where a and b are constants that determine the dynamic response of the digital filter.

Throughout the remainder of this book, there will be specific examples given of DSP systems in which the signal processing operations are performed by computation in a microcomputer. The trend for virtually the entire spectrum of automotive electronics is for digital implementation of signal processing.

ANALOG SIGNAL PROCESSING

Although signal processing is mostly digital today, it is worthwhile to explain certain aspects of analog signal processing, as it is still the preferred method for low-cost signal processing involving simple functional operations.

The operational amplifier is the predominant analog signal processing building block.

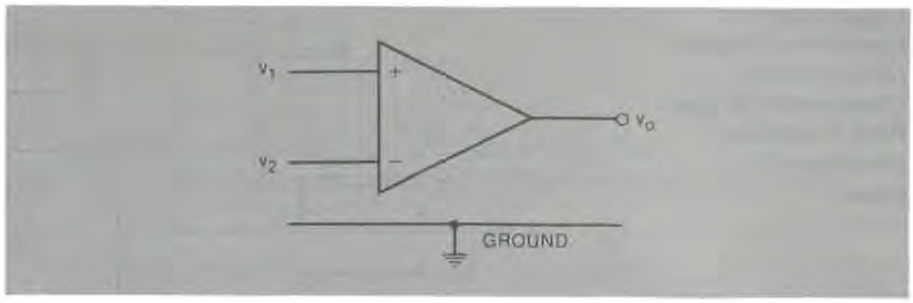
The primary building block of analog signal processing is the operational amplifier, which is depicted symbolically in Figure 2.18. An operational amplifier is a very high gain differential amplifier; that is, it amplifies the difference between the two input voltages. These voltages (relative to ground) are denoted v_1 and v_2. The input labeled + in Figure 2.18 is known as the *noninverting* input, and the one labeled – is called the *inverting* input. The output voltage v_o, relative to ground, is given by the following equation:

$$v_o = A(v_1 - v_2)$$

where A is the *open-loop gain.* For an ideal operational amplifier, the open-loop gain should be infinite. In practice it is finite, though very large (e.g., more than 100,000, typically).

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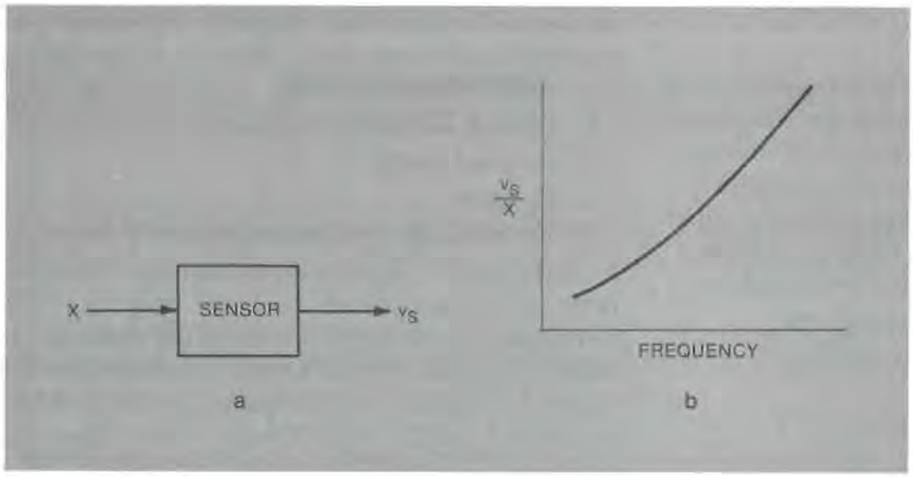
Figure 2.18
Operational Amplifier Diagram



As an example of the signal processing application of the operational amplifier, consider an instrument using a sensor that has an imperfect response. For the purpose of illustration, assume that the frequency response H for the sensor is as shown in Figure 2.19. The output voltage for a fixed-amplitude input increases linearly with frequency, as shown in the graph. An example of this type of frequency response is a magnetic angular speed sensor, described in Chapter 6.

A signal processing circuit that can compensate for the undesirable frequency response is shown in Figure 2.20. In this circuit, a parallel resistance–capacitance ($R_f C$) combination is connected in a so-called feedback path from the output to the inverting input. The frequency response for this circuit ($H_{sp} = v_o/v_s$) is shown graphically in Figure 2.21. Also shown in this illustration is the frequency response for the combination sensor and signal processor. For frequencies above about 2 Hz, the frequency response ($H = v_o/x$) for the combination is flat, as is desired. The characteristics and applications of operational amplifiers are discussed in greater detail in Chapter 3.

Figure 2.19
Example Sensor Frequency Response



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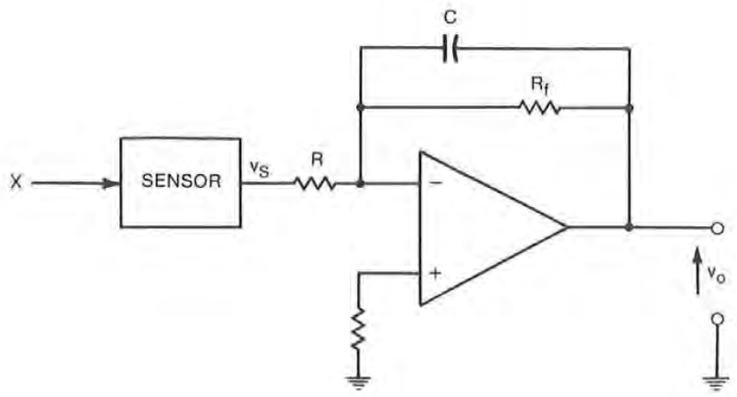


Figure 2.20 Operational Amplifier Circuit Used to Compensate for the Poor Frequency Response of a Sensor

CONTROL SYSTEMS

Control systems are systems that are used to regulate the operation of other systems. For this discussion, the system being controlled is known as the *system plant.* The controlling system is called an *electronic controller.*

In preparation for discussing the many electronic control systems in automobiles it is worthwhile to explain in detail what a control system is. A control system is described by its fundamental elements, which are the objectives of control, system components, and results or outputs. The objectives of a control system are the quantitative measures of the tasks to be performed by the system. These describe the desired values of a variable or of multiple variables and are normally specified by the user. The results are called outputs (or controlled variables). Typically, the objective of a control system is to regulate the values of the outputs in a prescribed manner by the (operator-determined) inputs through the elements (or components) of the control system.

Control systems, which are used to control the operation of other systems, are measured in terms of accuracy, speed of response, stability, and immunity from external noise.

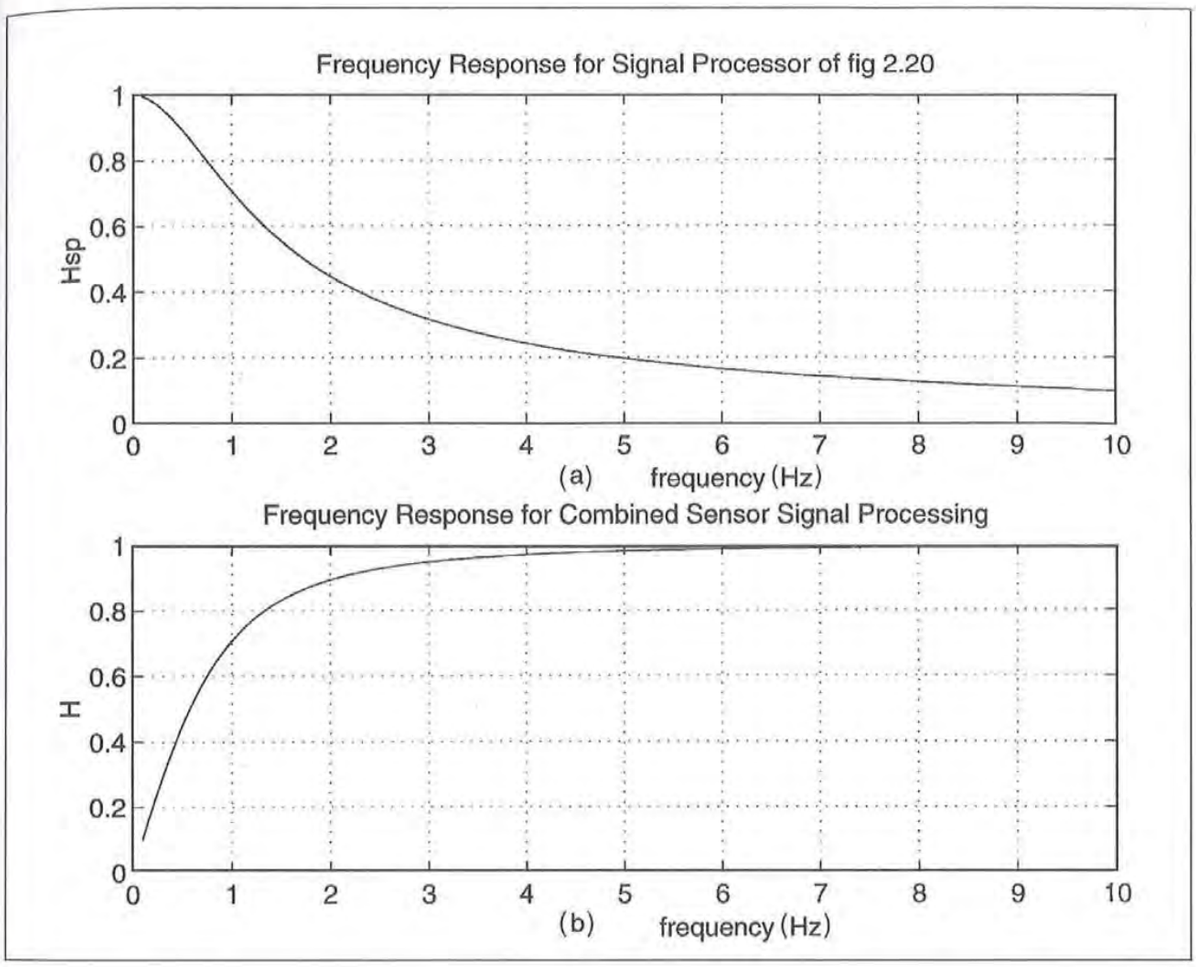
A control system should

1. Perform its function accurately.
2. Respond quickly.
3. Be stable.
4. Respond only to valid inputs (noise immunity).

A control system's accuracy determines how close the system's output will come to the desired output, with a constant-value input command. Quick response determines how closely the output of the system will track or follow a changing input command. A system's stability describes how a system behaves when a change, particularly a sudden change, is made by the input signal. Some unstable systems will oscillate wildly if uncontrolled. Others that are normally controlled may go out of control. Either case is undesirable, and a good controller design will minimize the chance of unstable operation. A system should maintain its

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Figure 2.21
Frequency Response for Operational Amplifier Circuit



accuracy by responding only to valid inputs. When noise or other disturbances threaten to change the system plant's output, good design will eliminate them from system performance as much as possible. The more this invalid response is eliminated, the more noise immunity the control system has. Accuracy, quick response, stability, and noise immunity are all determined by the control system configuration and parameters chosen for a particular plant.

The purpose of a control system is to determine the output of the system (plant) being controlled in relation to the input and in accordance with the operating characteristics of the controller. The relationship between the

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controller input and the desired plant output is called the *control law* for the system. The desired value for the plant output is often called the *set point.*

The behavior of the plant is influenced electronically by means of an electromechanical device called an *actuator.* Looking ahead to our discussion of automotive electronics, a specific actuator will be introduced, namely, an electrically activated fuel injector. Generally speaking, an actuator has input electrical terminals that receive electrical power from the control electronics. By a process of internal electromechanical energy conversion, a mechanical output is obtained that operates to control the plant. In the case of the fuel injector, the air–fuel mixture is controlled, which, in turn, controls the engine output.

Although electronic controllers can, in principle, be implemented with either analog or digital electronics, the trend in automotive control is digital. Since the purpose of this chapter is to discuss fundamentals of electronic systems, both continuous-time (analog) and discrete-time (digital) control systems are presented.

There are two major categories of control systems: open-loop (or feedforward) and closed-loop (or feedback) systems. There are many automotive examples of each, as we will show in later chapters. The architecture of an open-loop system is given in the block diagram of Figure 2.22.

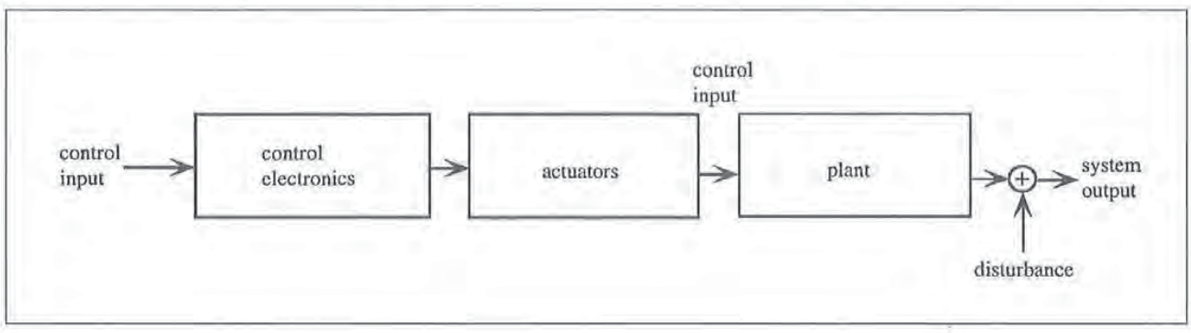
Open-Loop Control

The components of an open-loop controller include the electronic controller, which has an output to an actuator. The actuator, in turn, regulates the plant being controlled in accordance with the desired relationship between the reference input and the value of the controlled variable in the plant. Many examples of open-loop control are encountered in automotive electronic systems, such as fuel control in certain operating modes.

An open-loop control system never compares actual output with the desired value.

In the open-loop control system of Figure 2.22, the command input is sent to a system block, which performs a control operation on the input to generate an intermediate signal that drives the plant. This type of control is called open-loop control because the output of the system is never compared with the command input to see if they match.

Figure 2.22
Open-Loop Control System Block Diagram



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The control electronics generates the electrical signal for the actuator in response to the control input and in accordance with the desired relationship between the control input and the system output. The operation of the plant is directly regulated by the actuator (which might simply be an electric motor). The system output may also be affected by external disturbances that are not an inherent part of the plant but are the result of the operating environment.

One of the principal drawbacks to the open-loop controller is its inability to compensate for changes that might occur in the controller or the plant or for any disturbances. This defect is eliminated in a closed-loop control system, in which the actual system output is compared to the desired output value in accordance with the input. Of course, a measurement must be made of the plant output in such a system, and this requires measurement instrumentation.

Closed-Loop Control

It is the potential for change in an open-loop system that led to feedback, or closed-loop, control. In a closed-loop control system a measurement of the output variable being controlled is obtained via a sensor and fed back to the controller, as illustrated in Figure 2.23.

The measured value of the controlled variable is compared with the desired value for that variable based on the reference input. An error signal based on the difference between desired and actual values of the output signal is created, and the controller generates an actuating signal that tends to reduce the error to zero. In addition to reducing this error to zero, feedback has other potential benefits in a control system. It can affect control system performance by improving system stability and suppressing the effects of disturbances in the system. Later chapters will include numerous examples of closed-loop control, such as idle speed control.

The generic closed-loop control system illustrated in Figure 2.23 has some of the components found in an open-loop control system, including the

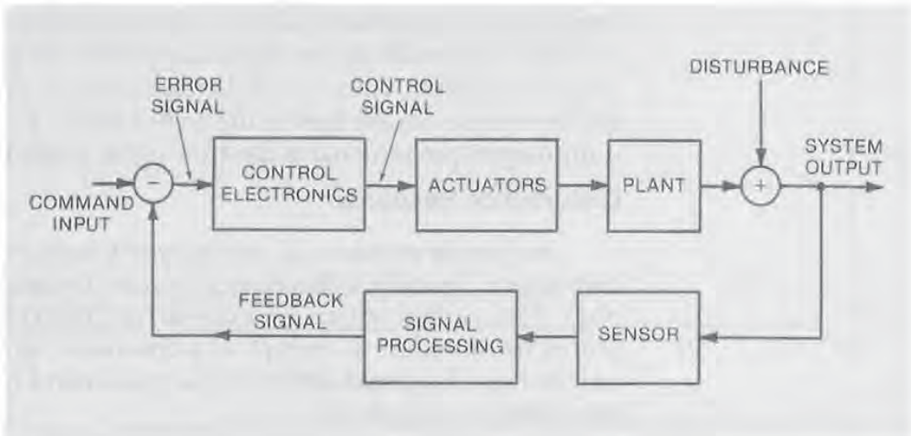


Figure 2.23
Closed -Loop Control Configuration

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plant to be controlled, actuator(s), and control electronics. In addition, however, this system includes one or more sensors and some signal-conditioning electronics. The signal conditioning used in a closed-loop control system plays a role similar to that played by signal processing in measurement instrumentation. That is, it transforms the sensor output as required to achieve the desired measurement of the plant output. Compensation for certain sensor defects (e.g., limited bandwidth) is possible, and in some cases necessary, to allow for the comparison of the plant output with the desired value. Electronic control systems are classified by the way in which the error signal is processed to generate the control signal. The major control systems include proportional, proportional integral, and proportional integral differential controllers.

PROPORTIONAL CONTROLLER

The component at the left of the block diagram of Figure 2.23, is the element in which the output is actually compared to the input. An error signal is obtained by electrically subtracting the feedback signal from the command input. The error signal is the input to the control electronics system, which, in turn, generates an output called a *control signal.* The control signal is applied to the actuator, and the actuator moves in such a direction as to reduce the error between the actual and desired output to zero.

In Figure 2.23, the sensor provides a measurement x_o of the plant output. The error signal e is obtained by subtracting x_o from the desired value x:

$$e = x - x_o$$

In a proportional control system, the error signal is amplified by an amplifier to yield an output v_c, which is the control signal:

$$v_c = Ge$$

where G is the amplifier gain.

The actuator causes the plant output y to increase in proportion to v_c. The operation of this control system is as follows. Assume arbitrarily that the plant output (x_o) is larger than its desired value. In this case the error signal e is negative. The amplified error signal is applied to the actuator, causing the plant output to decrease. Thus, x_o will decrease until $x_o = x$, at which point e is zero and the output remains fixed at the desired value. A controller that generates a control signal proportional to the error signal is called a *proportional controller.*

Disturbance Response

Any purely proportional control system has poor response to a disturbance. Typically, a disturbance is caused by factors that are outside of the plant or the control system. For example, in Chapter 8 in a discussion of cruise control, we introduce an example of a disturbance in which cruise control is activated on a level road. When the car encounters a hill, the change in load on the engine is a disturbance.

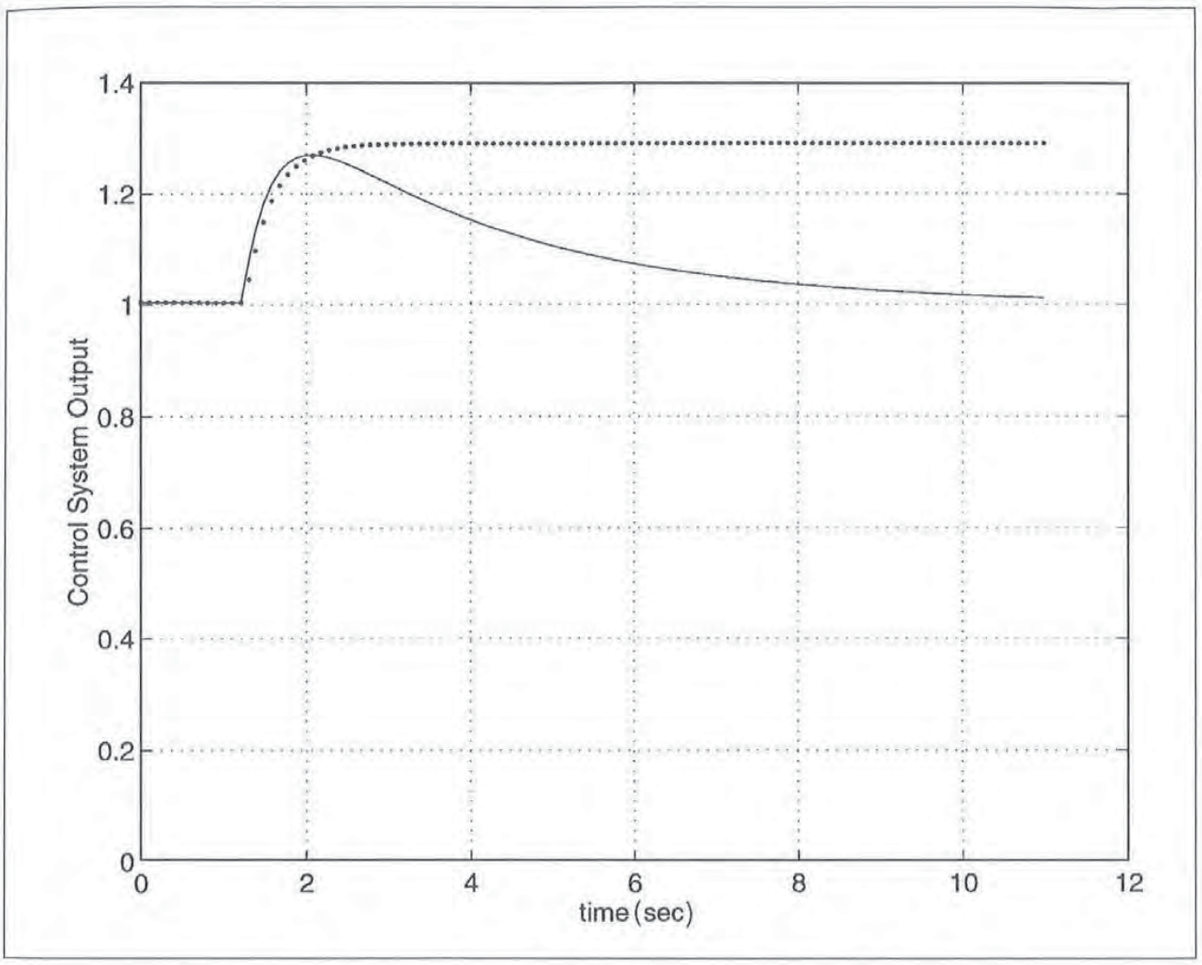
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The dotted curve in Figure 2.24 shows the response of a proportional control system to a disturbance d at time $t = 1$ sec. Instead of remaining at the set point x_0 following disturbance d, the system response changes to a steady error e, which is given by

$$e = \frac{d}{G}$$

In principle, the error for any given disturbance can be made as small as desired by raising the feedback gain. Unfortunately, the control system

Figure 2.24
Response of a Proportional Control System to a Disturbance



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dynamic response is also affected by G. Raising the gain too far will cause the system response to become oscillatory. Often if the gain is too large, the system becomes unstable. This property of having a steady error in response to a steady disturbance is fundamental to all control systems incorporating a proportional controller, but can be eliminated by use of a proportional-integral controller.

Concept of Integration

Before beginning the discussion of proportional integral (PI) control, it is worthwhile to discuss the concept of integration briefly. Of course those readers having a background in and familiarity with integral calculus can skip this discussion. The concept of an integrator can perhaps best be understood with reference to the block diagram of Figure 2.25a. In mathematical terms this system is denoted:

$$y = \int x dt$$

and the output y is said to be the integral of the input x with respect to time. In more practical terms the integrator can be thought of as a device that continuously "adds" or accumulates the input such that the input is the rate of change of the output.

A good practical example of an integrator is depicted in Figure 2.25b. In this figure the integrator is a storage tank into which fluid is flowing. The output for this example is the total volume of fluid that has accumulated at any time (until the tank is full). The input to this integrator is the volume flow rate x of fluid flowing into the tank. For example, if the volume flow rate into a tank were 10 gal/min then every minute the volume of fluid in the tank *(y)* would increase by 10 gallons, that is to say, the volume of fluid in the tank would be 10 multiplied by the time (from empty) that the fluid flows into the tank. This is a rather straightforward concept when the input is constant. However, if the input volume flow rate changes continuously, then the volume of fluid is given by the integral (with respect to time) of the input flow rate.

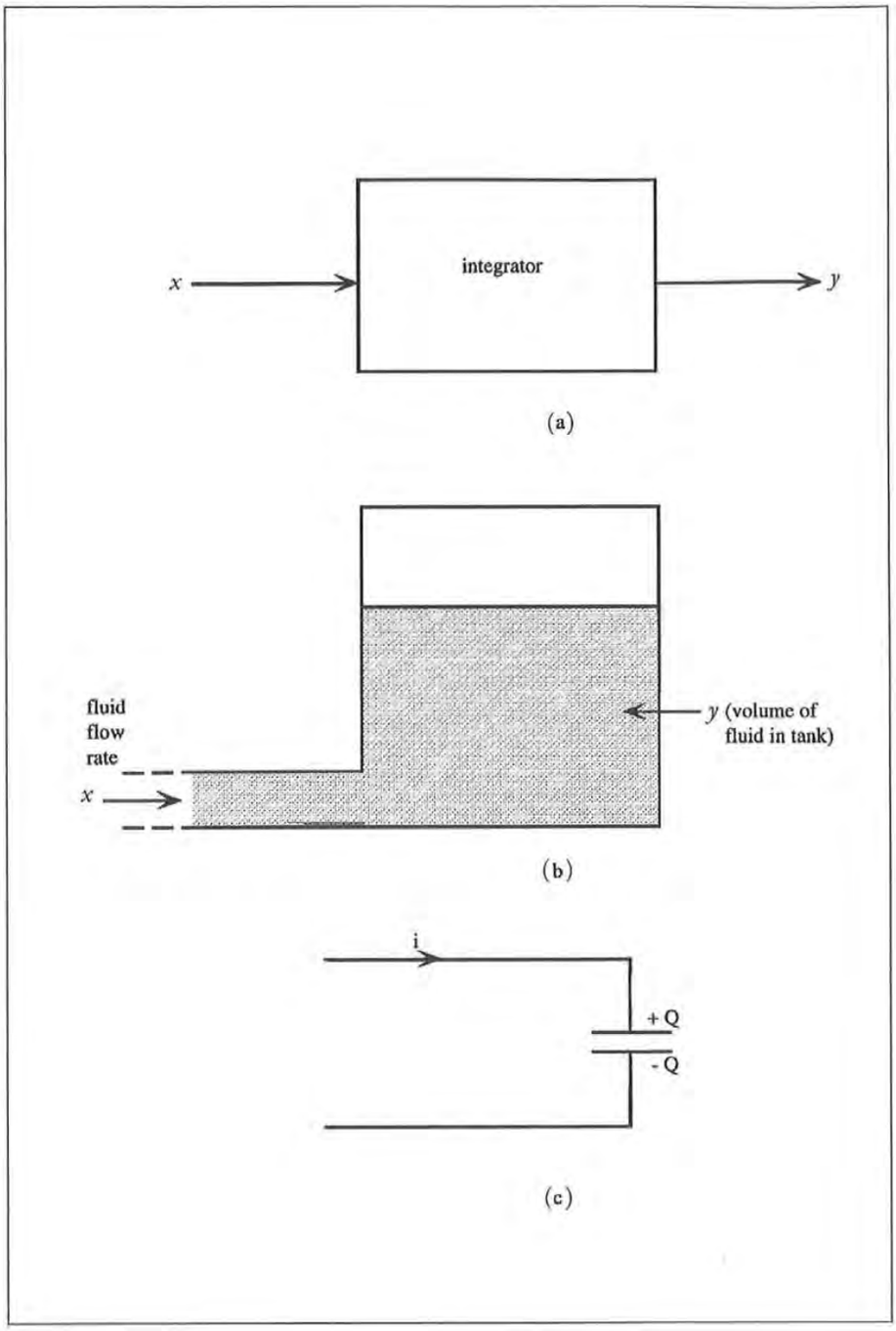
Another device that acts as an integrator is a capacitor into which a current is flowing, as depicted in Figure 2.25c. The charge stored in the capacitor Q is the integral with respect to time of the current:

$$Q = \int i dt$$

This property of a capacitor is used to implement the integral part of an analog proportional integral control system. (See the discussion in Chapter 3 of operational amplifiers.)

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Figure 2.25
Concept of Integration



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PROPORTIONAL INTEGRAL CONTROLLER

One way of avoiding the steady disturbance response error of a proportional (P) controller is to use a controller that is called a proportional integral (PI) controller. The proportional integral control corrects for a serious defect in a purely proportional controller. In the latter type, any steady disturbance leads to a steady error in the output regulation. The configuration for a PI controller is shown in Figure 2.26. This controller combines a term proportional to the error with the integral of the error.

The error signal for a PI controller is generated the same way as for the P controller. That is, the error e is the difference between the desired and actual values:

$$e = x - x_0$$

The controller then generates the integral of the error,

$$\int e dt$$

electronically. The control signal that is applied to the plant includes a part that is proportional to the error as well as a part that is proportional to the integral of the error. The resulting control signal is the sum of these two parts:

$$v_c = Ge + k\int e dt$$

where G is the proportional gain and k is the integral gain. The proportional part of the control signal acts the same as in a P controller, that is, it drives the plant so as to reduce the error to zero.

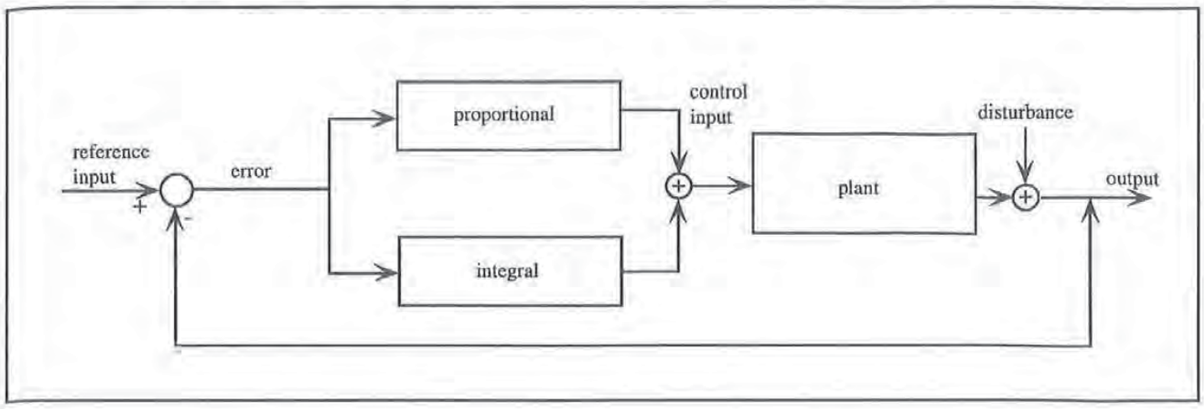
However, consider the case of a disturbance to the system that tends to produce a steady error in a P controller. In a PI controller, the integral part continues to increase (since the integral of a steady error continuously increases until the error itself is zero). This integral part of the control signal drives the plant in a direction to reduce the error due to disturbance to zero.

The disturbance rejection of a PI and P controller are illustrated in Figure 2.24. Here a steady disturbance occurs at time $t = 0$. The P controller response is shown in the dotted curve, which depicts the steady error. The PI controller response is shown by the solid curve, for which the error eventually is reduced to zero. This ability to reduce errors due to disturbance to zero is a fundamental property of PI controllers.

In principle a PI controller could be implemented in a purely mechanical control system. However, in practice the only feasible implementation of an integral is electronic (where integration can be implemented by means of a capacitor in a simple electronic circuit). Integrals can also be implemented with

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Figure 2.26
Block Diagram for Proportional Integral Controller



digital controllers. The relative ease and low cost of implementing PI controllers is part of the motivation for the trend toward electronic control in automotive systems.

A good example of the performance of a PI controller is given in Chapter 8. The accuracy of speed regulation for a PI controller in the presence of disturbance (hills) is superior to that of a P controller. It is worthwhile to summarize that a PI controller will, in general, reduce the error in response to disturbances to exactly zero, whereas the P controller will always have a residual output error.

Digital PI Controller

A PI control can also be implemented via a digital control system in which the control signal is generated with a special-purpose digital computer. Such a system operates in discrete time by representing the variables at sample times.

In a digital PI controller, the control electronics samples the error signal at multiples of the sample period. The control signal includes two parts: a proportional part and an integral part. The proportional part is proportional to the most recent sample of the error. The integral part includes a sum of several previous samples. If there is no disturbance to the system, the sum is zero (or at least very small). If there is a disturbance, the sum of previous errors can become very large. The sum of previous errors in the control signal is applied to the actuator in such a way as to force the controlled system to reduce the error caused by disturbance toward zero.

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In mathematical terms, the control signal at sample time t_k, which we denote v_k, is given by

$$v_k = -Ge_k - K\sum_{m=1}^{M} e_{k-m}$$

where

e_k is the most recent sample
e_{k-m} is the mth oldest sample ($m = 1, 2, \ldots, M$)
G is proportional gain
K is integral gain

The dynamic properties of a PI controller with the above control law are determined by the sizes of the proportional (G) and integral (K) gains as well as the number (M) of error samples included in the sum (Σ).

PROPORTIONAL INTEGRAL DIFFERENTIAL CONTROLLER

Still another control type that finds wide application in practice is the proportional integral differential (PID) controller. In a PID controller, the control signal is given by

$$v_k = -Ge_k - K\sum_{m=1}^{M} e_{k-m} - D[(e_k - e_{k-1})/T]$$

The final term in this expression for the control signal involves the difference between the two most recent samples of the error. This term represents the rate of change of the error, and its inclusion in the control law often improves dynamic response greatly. For the corresponding analog (continuous-time) controller, the control signal is given by

$$v_c = Ge + k\int e\,dt + D\frac{de}{dt}$$

CLOSED-LOOP LIMIT-CYCLE CONTROL

In a proportional control system the control signal is proportional to the error between desired and actual output.

The control electronics in the previous example provided what is called proportional control because the control signal is proportional to the error signal. Other combinations of control electronics are possible, and it is a challenge to the system designer to develop imaginative types of control electronics to improve the performance of a given plant.

Another type of control that is used in automotive applications is limit-cycle control. Limit-cycle control is a type of feedback control that monitors the system's output and responds only when the output goes beyond preset

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limits. Limit-cycle controllers often are used to control plants with nonlinear or complicated transfer functions.

Limit-cycle control responds only when the error is outside a pair of limits.

An example of a limit-cycle controller is the temperature-controlled oven depicted in Figure 2.27. The temperature inside the oven is controlled by the length of time the heating coil is energized. The temperature of the oven is measured with a temperature probe, and the corresponding electrical signal is fed back to the command to obtain an error signal. The control electronics checks the error signal against the temperature control dial to determine if one of the following two conditions exists:

1. Oven temperature is below minimum setting of command input.
2. Oven temperature is above maximum setting of command input.

The control electronics responds to error condition 1 by closing the relay contacts to energize the heating element. This causes the temperature in the oven to increase until the temperature rises above a maximum limit, producing error condition 2. In this case, the control electronics opens the relay contacts and the heat is turned off. The oven gradually cools until condition 1 again occurs and the cycle repeats. The oven temperature varies between the upper

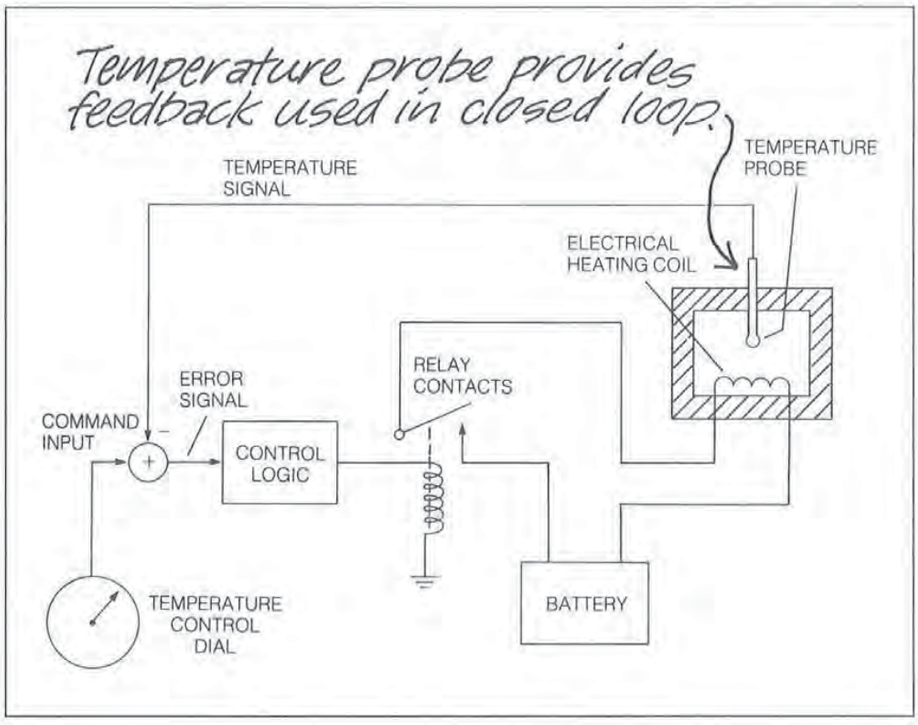


Figure 2.27 Limit-Cycle Controller to Control Oven Temperature

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and lower limit, and the variations can be graphed as a function of time, as shown in Figure 2.28.

The amplitude of the temperature variations, called the *differential*, can be decreased by reducing the difference between the maximum and minimum temperature limits. As the limits get closer together, the temperature cycles more rapidly (frequency increases) to hold the actual temperature much closer to the desired constant temperature. Thus, the limit-cycle controller controls the system to maintain an average value close to the command input. This type of controller has gained popularity due to its simplicity, low cost, and ease of application. Fuel control, one of the most important automotive electronic control systems is, at least partially, a limit-cycle control system (see Chapter 5).

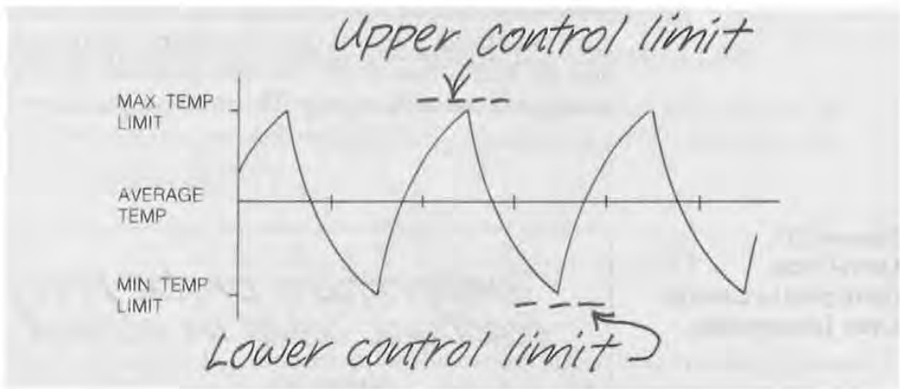


Figure 2.28
Oven Temperature Graph

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Quiz for Chapter 2

1. Which of the following are examples of systems?
   - **a.** clock
   - **b.** electric dishwasher
   - **c.** communication network
   - **d.** society
   - **e.** all of the above
2. Block diagrams are developed in what type of analysis?
   - **a.** physical
   - **b.** quantitative
   - **c.** qualitative
3. Specific system parameters are determined in what type of analysis?
   - **a.** physical
   - **b.** quantitative
   - **c.** qualitative
4. What is a sensor used for?
   - **a.** to convert a nonelectrical input to an electrical output
   - **b.** to convert an electrical input to a mechanical output
   - **c.** to reduce the effects of noise and other disturbances on the measured quantity
   - **d.** all of the above
5. What does an actuator do?
   - **a.** converts a nonelectrical input to an electrical output
   - **b.** converts an electrical input to an action
   - **c.** reduces the effects of noise and other disturbances on the measured quantity
   - **d.** all of the above
6. What does signal processing do?
   - **a.** converts a mechanical input to an electrical output
   - **b.** converts an electrical input to a mechanical output
   - **c.** reduces the effects of noise and other disturbances on the measured quantity
   - **d.** all of the above
7. An error amplifier is used to compare which of the following two signals?
   - **a.** the output of a sensor and the input to a signal processor
   - **b.** the output of a system and the command input of a system
   - **c.** the output of a signal processor and the output of a system
   - **d.** none of the above
8. A basic instrumentation system consists of which of the following components?
   - **a.** sensor
   - **b.** actuator
   - **c.** signal processor
   - **d.** all of the above
9. A control system may contain which of the following components?
   - **a.** error amplifier
   - **b.** control logic
   - **c.** plant
   - **d.** all of the above

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10. Which of the following are examples of a plant?

- **a.** automotive drivetrain
- **b.** high-temperature oven
- **c.** an airplane navigation system
- **d.** all of the above

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Electronics Fundamentals

This chapter is for the reader who has little knowledge of electronics. It is intended to provide an overview of the subject so that discussions in later chapters about the operation and use of automotive electronics control systems will be easier to understand.

The chapter discusses electronic devices and circuits having applications in electronic automotive instrumentation and control systems. Topics include semiconductor devices, analog circuits, digital circuits, and fundamentals of integrated circuits.

SEMICONDUCTOR DEVICES

Semiconductor (or solid-state) devices are basic building blocks for electronic circuits. Semiconductor devices are commonly called solid-state devices because they are made from a solid material. This material in pure form is neither a good conductor nor a good insulator. Therefore, this material (also called semiconductor material) and devices made from it are solid-state semiconductor devices.

There are many types of semiconductor devices, but transistors and diodes are two of the most important in automotive electronics. Furthermore, these devices are the fundamental elements used to construct nearly all modern integrated circuits. Therefore, the discussion of semiconductor devices will be centered on these two.

Semiconductor devices are made from silicon or germanium that is purposely contaminated with impurities that change the conductivity of the material. Transistors are semiconductor devices that are used as active devices in electronic circuits.

The earliest transistors were made from germanium, but today silicon is by far the most commonly used semiconductor material for making diodes, transistors, and other semiconductor devices. Semiconductor material is made to conduct better by diffusing an impurity into it. Boron and phosphorus often are used as impurity source materials to alter the conductivity of silicon. When boron is used, the semiconductor material becomes a so-called p-type semiconductor. When phosphorus is used, the semiconductor material becomes an n-type semiconductor. It is not necessary for the purposes of this book to understand the differences between p-type and n-type semiconductors. However, the interested reader can consult any of the standard introductory references on the theory of semiconductor devices for further information.

Semiconductor devices such as diodes and transistors are quite different from common linear components such as resistors, capacitors, inductors, and transformers. The following discussion presents an explanation of the operation of these devices.

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Diodes

A diode acts much like a one-way valve, allowing current to flow in only one direction.

A diode is a two-terminal electrical device having one electrode that is called the *anode* (a p-type semiconductor) and another that is called the *cathode* (an n-type semiconductor). A solid-state diode is formed by the junction between the anode and the cathode. Diodes can be thought of as one-way resistors or current check valves because they allow current to flow through them in only one direction, depending on the polarity of voltage (bias) across the anode and cathode. When current flows in the forward (conducting) direction with a plus voltage on the anode, diodes have low resistance (typically a few ohms). This is called the *forward biased condition.* (The conventional current flow direction of positive to negative is used in this book.) When the current flows in the reverse (nonconducting) direction with a plus voltage on the cathode, diodes have a very high resistance (typically a few million ohms). This is called the *reverse biased condition.*

Figure 3.1a shows the schematic symbol for a diode, and Figure 3.1b is a graph of the actual and ideal voltage and current transfer characteristics for a typical diode. Notice on the ideal curve that the diode doesn't start conducting until the voltage across it exceeds V_d volts; then, for small increases in voltage, the current increases very rapidly. For silicon diodes, V_d is about 0.7 volt. For germanium diodes, V_d is about 0.3 volt. Even for the actual curve, the change in current is quite steep for 0.1 volt changes in the voltage across the diode after V_d has been exceeded.

When designing or analyzing circuits, V_d is often ignored in relatively high-voltage circuits in which V_d is a very small percentage of the total voltage; however, in low-voltage and low-level signal circuits, V_d may be a significant factor.

Rectifier Circuit

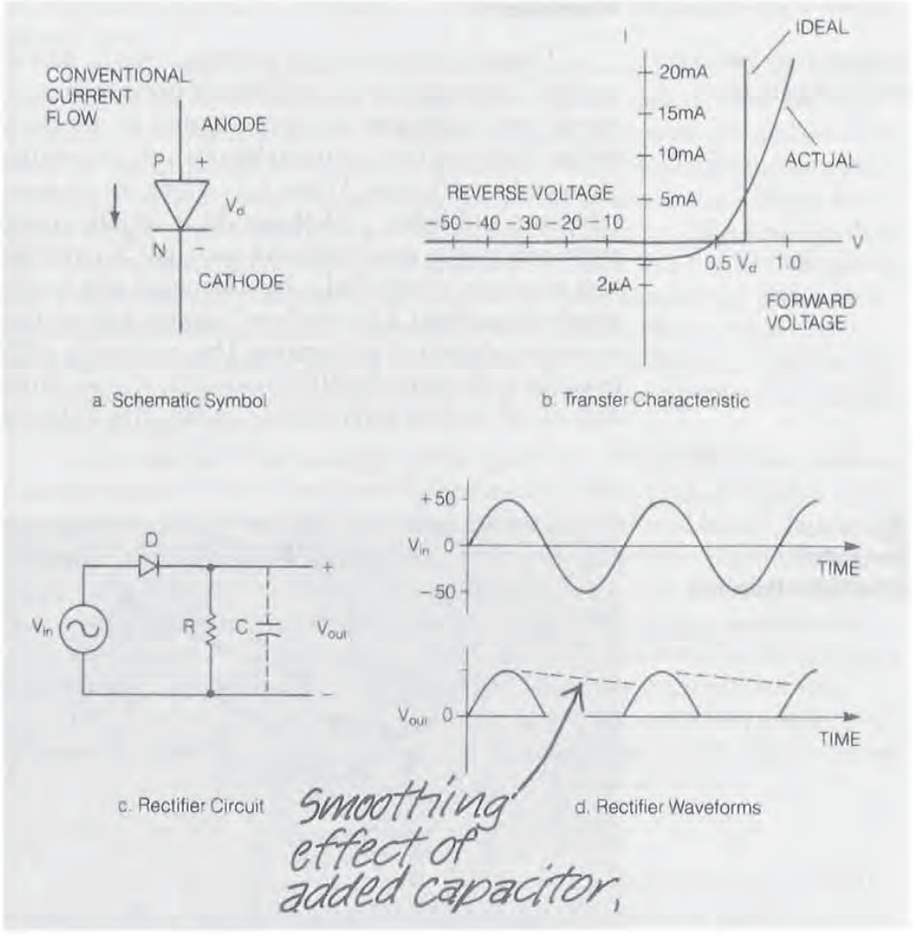
A diode has low resistance when forward biased and high resistance when reverse biased.

The circuit in Figure 3.1c, a very common diode circuit, is called a *half-wave rectifier circuit* because it effectively cuts the ac (alternating current) waveform in half. Consider the circuit first without the dotted-in capacitor. The alternating current voltage source is a sine wave with a peak-to-peak amplitude of 100 volts (50 volt positive swing and 50 volt negative swing). Waveforms of the input voltage and output voltage plotted against time are shown as the solid lines in Figure 3.1d. Notice that the output never drops below 0 volts. The diode is reverse biased and blocks current flow when the input voltage is negative, but when the input voltage is positive, the diode is forward biased and permits current flow. If the diode direction is reversed in the circuit, current flow will be permitted when the input voltage is negative and blocked when the input voltage is positive.

The half-wave rectifier is used to convert an ac voltage into a dc (direct current) voltage that stays either above 0 volts or below 0 volts, depending on which way the diode is installed. Rectifier circuits are commonly used to

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Figure 3.1 Diode Characteristics



The use of a capacitor to store charge and resist voltage changes smooths the rippling or pulsating output of a half-wave rectifier.

convert the ac voltage into a dc voltage for use with automotive alternators to provide dc current for battery charging.

The input voltage V_{in} of Figure 3.1c is ac; the output voltage V_{out} has a dc component and a time-varying component, as shown in Figure 3.1d. The output voltage of the half-wave rectifier can be smoothed by adding a capacitor, which is represented by the dotted lines in Figure 3.1c. Since the capacitor stores a charge and opposes voltage changes, it discharges (supplies current) to the load resistance R when V_{in} is going negative from its peak voltage. The capacitor is recharged when V_{in} comes back to its positive peak and current is supplied to the load by the V_{in}. The result is V_{out} that is more nearly a smooth, steady dc voltage, as shown by the dotted lines between the peaks of Figure 3.1d.

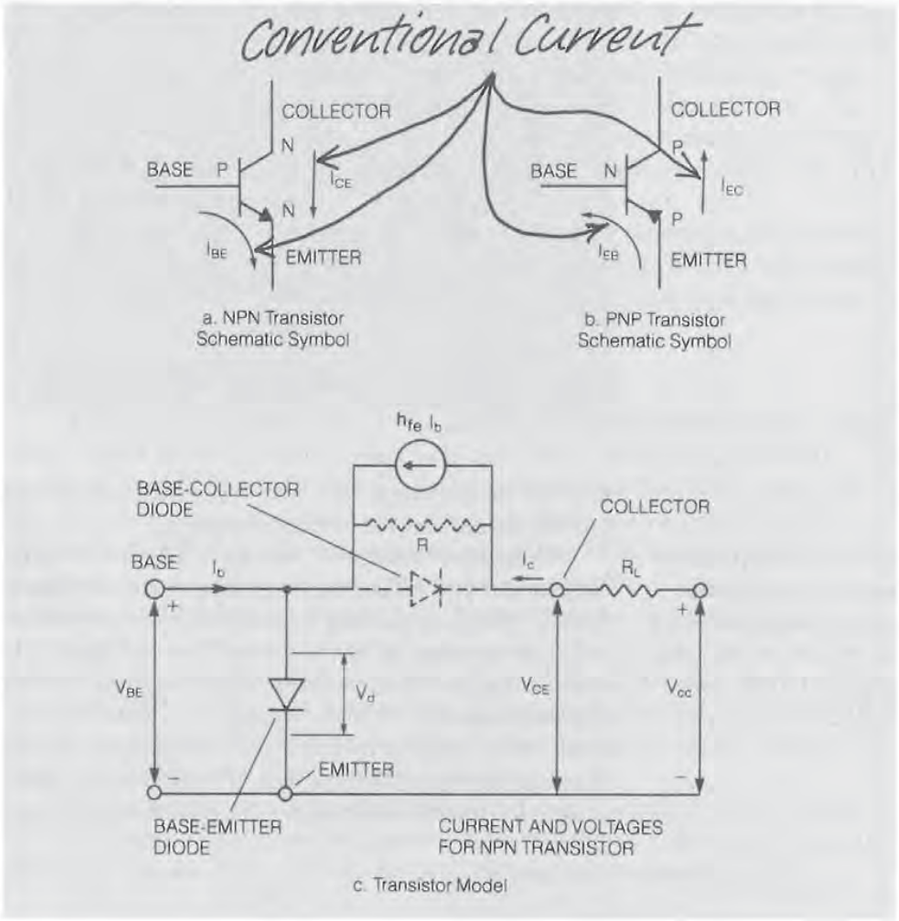
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Transistors

Transistors are useful as amplifying devices.

Diodes are static circuit elements; that is, they do not have gain or store energy. Transistors are active elements because they can amplify or transform a signal level. Transistors are three-terminal circuit elements that act like current valves. There are two common bipolar (i.e., consisting of n-type and p-type semiconductors) types. Figure 3.2a shows the schematic symbol for an NPN transistor, and Figure 3.2b shows the schematic symbol for a PNP transistor. P represents p-type semiconductor material; N represents n-type material. The area where the p-type and n-type materials join is called a *PN junction* (or simply a junction). Current flows into the base and collector of an NPN transistor and out of the emitter. The currents in a PNP transistor flow exactly opposite to those in the NPN transistor; that is, current flows into the emitter and out of the base and collector. In fact, this is the only difference between the

Figure 3.2 Transistor Schematic Symbols



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PNP transistor and NPN transistor. Their functions as amplifiers and switches are the same.

During normal operation, current flows from the base to the emitter in an NPN transistor. The collector-base junction is reverse biased, so that only a very small amount of current flows between the collector and the base when there is no base current flow.

The base-emitter junction of a transistor acts like a diode. Under normal operation for an NPN transistor, current flows forward into the base and out the emitter, but does not flow in the reverse direction from emitter to base. The arrow on the emitter of the transistor schematic symbol indicates the forward direction of current flow. The collector-base junction also acts as a diode, but supply voltage is always applied to it in the reverse direction. This junction does have some reverse current flow, but it is so small (1×10^{-6} to 1×10^{-12} amperes) that it is ignored except when operated under extreme conditions, particularly temperature extremes. In some automotive applications, the extreme temperatures may significantly affect transistor operation. For such applications, the circuit may include components that automatically compensate for changes in transistor operation.

Under normal linear (analog) circuit operation, the collector-base junction is reverse biased as mentioned previously; however, when used as a switch in the on condition, the collector-base junction can become forward biased. In normal operation, the current that flows through the collector-emitter terminals is controlled by the current flowing through the base terminal. Relatively small base currents control relatively large collector currents through a complicated physical process that is beyond the scope of this book. However, for the purposes of the present discussion, it is correct to think of the transistor as a current-amplifying device in which the base current controls the collector current. The current amplification of a typical transistor is on the order of 100. That is, a base current controls a collector current that is about 100 times larger.

Transistor Model

To aid in circuit analysis, Figure 3.2c shows the diagram of a commonly used transistor model for an NPN transistor. The base-emitter diode is shown in solid lines in the circuit, while the collector-base diode is shown in dotted lines because generally it can be ignored.

The base-emitter diode does not conduct (there is no transistor base current) until the voltage across it exceeds V_d volts in the forward direction. If the transistor is a silicon transistor, V_d equals 0.7 volt just as with the silicon diode. The collector current I_c is zero until the base-emitter voltage V_{BE} exceeds 0.7 volt. This is called the *cutoff condition*, or the off condition when the transistor is used as a switch.

When V_{BE} rises above 0.7 volt, the diode conducts and allows some base current I_b to flow. The collector current I_c is equal to the base current I_b times the transistor current gain h_{fe}. The current gain (h_{fe}) can range from 10 to 200 depending on the transistor type. It is represented by a current generator in the collector circuit of the model. This condition is called the *active region* because the transistor is on and amplifying. It also is called the *linear region* because collector current is (approximately) linearly proportional to base current. The

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dotted resistance in parallel with the collector-base diode represents the leakage of the reverse biased junction, which is normally neglected, as discussed previously.

A transistor is saturated when a large increase in the base-to-emitter current results in only a small increase in the collector current.

A third condition known as the *saturation condition* exists under certain conditions of collector-emitter voltage and collector current. In the saturation condition, large increases in the transistor base current produce little increase in collector current. When saturated, the voltage drop across the collector-emitter is very small, usually less than 0.5 volt. This is the on condition for a transistor switching circuit. This condition occurs in a switching circuit when the collector of the transistor is tied through a resistor R_L to a supply voltage V_c as shown in Figure 3.2c. Enough base current is supplied to the transistor to drive the transistor into the saturated condition, in which the output voltage (voltage drop from collector to emitter) is very small and the collector-base diode may become forward biased. Having briefly described the behavior of transistors, it is now possible to discuss circuit applications for them.

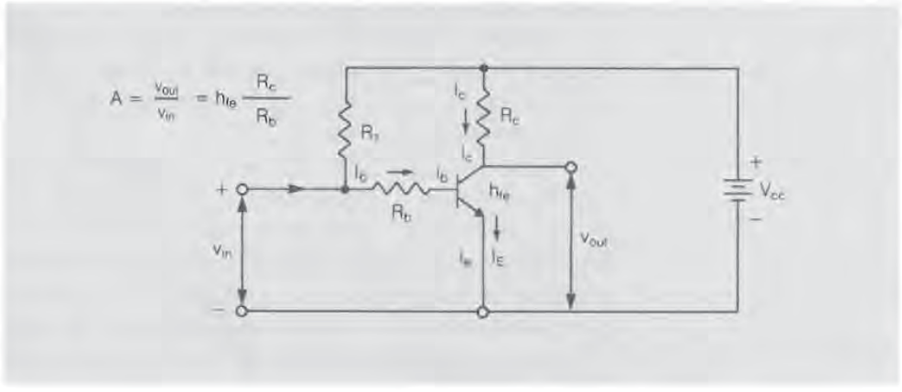
TRANSISTOR AMPLIFIERS

In a transistor amplifier, a small change in base current results in a corresponding larger change in collector current.

Figure 3.3 shows a transistor amplifier. The ac voltage source, V_{in}, supplies a signal current to the base-emitter circuit. The transistor is biased to operate in the linear region at some steady state I_b and I_c. The voltage source, V_{cc}, supplies the steady-state dc currents I_b and I_c and any signal current change i_c to the collector-emitter circuit. The small signal voltage V_{in} varies the base current around the steady dc operating point. This small current change is i_b, and it causes a corresponding but larger change in collector current i_c around the steady-state operating current I_c. The small signal current change causes a V_{out} change across the load resistor R_c. The small signal voltage gain of the circuit is as shown in Figure 3.3:

$$A = \frac{V_{out}}{V_{in}} = h_{fe}\frac{R_c}{R_b}$$

Figure 3.3 Transistor Amplifier Circuit



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This is found by using the model and the equations $V_{out} = i_c R_c$, $i_c = h_{fe} i_b$, and $i_b = V_{in}/R_b$, where h_{fe} is the small signal current gain.

Transistor amplifiers are commonly used in analog circuits, including those in automotive systems.

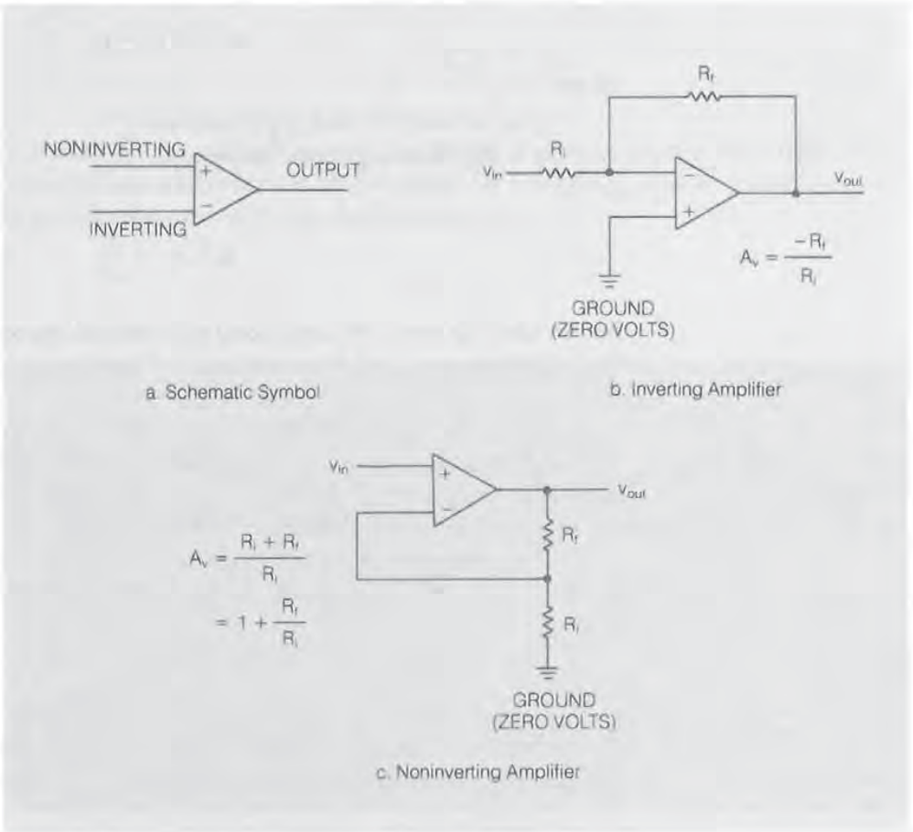
Circuits such as those depicted in Figure 3.3 are combined to make many types of amplifiers that are used in a variety of applications. Such circuits, especially when made in one package with integrated circuit technology (to be discussed later), are called *linear circuits* or *analog circuits.*

OPERATIONAL AMPLIFIERS

An op amp is a very high gain differential amplifier.

An operational amplifier (op amp) is another standard building block of integrated circuits and has many applications in analog electronic systems. It is normally connected in a circuit with external circuit elements (e.g., resistors and capacitors) that determine its operation. An op amp typically has a very high voltage gain of 10,000 or more and has two inputs and one output (with respect to ground), as shown in Figure 3.4a. A signal applied to the inverting input (–) is amplified and inverted at the output. A signal applied to the noninverting input (+) is amplified but is not inverted at the output.

Figure 3.4 Operational Amplifier Circuit



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Use of Feedback in Op Amps

The op amp is normally not operated at maximum gain, but feedback techniques can be used to adjust the gain to the value desired, as shown in Figure 3.4b. Some of the output is connected to the input through circuit elements (resistors, capacitors, etc.) to oppose the input changes. In the example of Figure 3.4b, the feedback path consists of resistor R_f. The gain is adjusted by the ratio of the two resistors and is calculated by the following equation:

$$A_v = -\frac{R_f}{R_i} = \frac{V_{out}}{V_{in}}$$

As indicated by applying the signal to the (–) terminal, the minus sign in the equation means signal inversion from input to output; that is, if the input goes positive, the output goes negative.

Since the op amp amplifies the voltage difference between its two inputs, it can be used as a differential amplifier as well as a single-input amplifier.

It is interesting to consider the inputs to the op amp in the inverting mode configuration (Figure 3.4b). The output voltage v_o is given by

$$v_o = A\,(v_1 - v_2)$$

where

v_1 is the noninverting input voltage

v_2 is the inverting input voltage

or

$$v_1 - v_2 = \frac{v_o}{A}$$

For an ideal op amp, the open-loop gain should approach infinity. In this case, the input voltages should become equal. That is, $v_1 - v_2 = 0$ for the ideal case, or $v_1 = v_2$.

The inverting amplifier of Figure 3.4b has the noninverting input at ground potential, that is, $v_1 = 0$. Consequently, the inverting input is (ideally) also at ground potential. In fact, the feedback path provides a current that holds the inverting input at so-called virtual ground. Furthermore, as the inverting input is held at ground potential, the input impedance of the op amp circuit of Figure 3.4b presented to input voltage V_{in} is the resistance of R_i:

$$\frac{V_{in}}{i_{in}} = R_i$$

By contrast, the input impedance presented to the input voltage V_{in} by the noninverting op amp configuration (Figure 3.4c) is ideally infinite. This very

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high input impedance is one of the primary features of the noninverting op amp configuration.

A noninverting amplifier is also possible, as shown in Figure 3.4c. The input signal is connected to the noninverting (+) terminal, and the output is connected through a series connection of resistors to the inverting (–) input terminal. The gain, A_v, in this case is

$$A_v = \frac{V_{out}}{V_{in}} = 1 + \frac{R_f}{R_i}$$

Besides adjusting gain, negative feedback also can help to correct for the amplifier's nonlinear operation and distortion.

Summing Mode Amplifier

One of the important op amp applications is summing of voltages. Figure 3.5 is a schematic drawing of a summing mode op amp circuit. In this circuit, a pair of voltages v_a and v_b (relative to ground) are connected through resistances R to the inverting input. The output voltage v_o is proportional to the sum of the input voltages:

$$v_o = \frac{-R_f(V_a + V_b)}{R}$$

For example, a compatible stereo broadcast system incorporating a right channel and a left channel characterized by voltages v_R and v_L, respectively, transmits the sum v_S of the channel voltages:

$$v_S = v_R + v_L$$

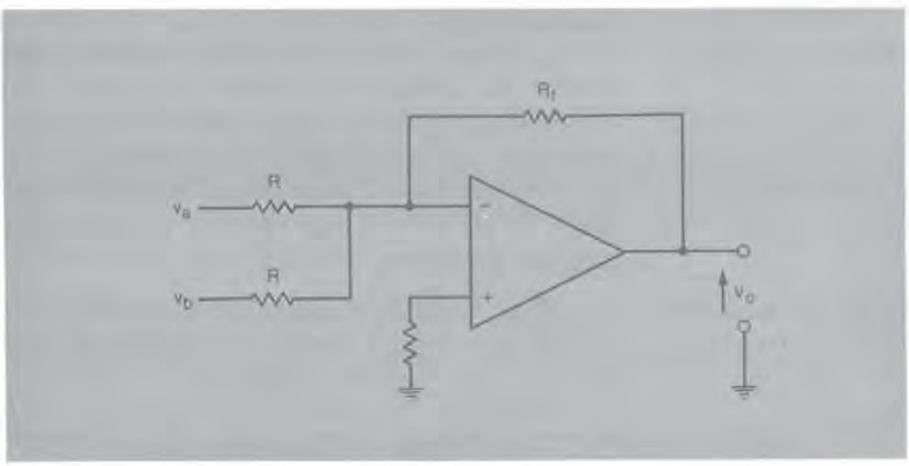


Figure 3.5 Summing Amplifier

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At the same time, the difference voltage v_D is transmitted on a subcarrier:

$$v_D = v_R - v_L$$

The right-channel voltage can be separated from the sum and difference voltages using the circuit of Figure 3.5. Replacing voltages V_a and V_b by v_S and V_D, respectively, yields an output:

$$v_o = \frac{-R_f}{R}(v_R + v_L + v_R - v_L)$$

$$= \left(\frac{-2R_f}{R}\right)v_R$$

A simple extension of this circuit permits similar separation of the left-channel voltage.

Analog Computers

Analog computers, like those used to simulate the performance of automotive systems, are constructed with operational amplifiers.

The op amp is the basic building block for analog computers. Analog computers are used to simulate the behavior of other systems. Virtually any system that can be described in a block diagram using standard building blocks can be duplicated on an analog computer. If a control system designer is building an automotive speed controller and does not want to waste a lot of time and money testing prototypes on a real car, he or she can program the analog computer to simulate the car's speed electronically. By varying amplifier gains, frequency responses, and resistor, capacitor, and inductor values, system parameters can be varied to study their effect on system performance. Such system studies help to determine the parts needed for a system before any hardware is built.

The main problem with analog circuits and analog computers is that their performance changes with changes in temperature, supply voltage, signal levels, and noise levels. While most of these problems are eliminated when digital circuits are used, analog computers are much more cost effective when dealing with relatively simple systems. However, analog computers have effectively been replaced in all practical applications by a corresponding digital computer.

DIGITAL CIRCUITS

Binary circuits can operate in only one of two states (on or off).

Digital circuits, including digital computers, are formed from binary circuits. Binary digital circuits are circuits whose output can be only one of two different states. Each state is indicated by a particular voltage or current level. An example of a simple binary digital system is a door-open indicator on a car. When a car door is opened, a light comes on. When it is closed, the light goes

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out. The system's output (the light from the bulb) is either on or off. The on state means the door is open; the off state means it is shut.

Digital circuits also can use transistors. In a digital circuit, a transistor is in either one of two modes of operation: on, conducting at saturation; or off, in the cutoff state.

In electronic digital systems, a transistor is used as a switch. Remember that the transistor has three operating regions: cutoff, active, and saturation. If only the saturation or cutoff regions are used, the transistor acts like a switch. When in saturation, the transistor is on and has very low resistance; when in cutoff, it is off and has very high resistance. In digital circuits, the control input to the transistor switch must be capable of either saturating the transistor or turning it off without allowing operation in the active region. In Figure 3.2c, the on condition is indicated by a very low collector-to-emitter voltage and the off condition by a collector-to-emitter voltage equal to the supply voltage.

Binary Number System

Combinations of digital circuits are capable of representing numbers in a binary number system.

Digital circuits function by representing various quantities numerically using a binary number system. In a binary number system, all numbers are represented using only the symbols 1 (one) and 0 (zero) arranged in the form of a place position number system. Electronically, these symbols can be represented by transistors in either saturation or cutoff. Before proceeding with a discussion of digital circuits, it is instructive to review the binary number system briefly.

The binary number system uses only two digits, 0 or 1, and is called a base 2 system. The decimal system uses 10 digits, 0 through 9, and is called a base 10 system. In the decimal system, numbers are grouped from right to left with the first digit representing the ones' place (10^0), the second digit the tens' place (10^1), the third digit the hundreds' place (10^2), and so on. Each place increases in value by a power of 10.

In the binary system, numbers are also grouped from right to left. The rightmost digit is in the ones' place (2^0) and, because only the numbers 0 and 1 can be represented, the second digit must be the twos' place (2^1), the third digit the fours' place (2^2), the fourth digit the eights' place (2^3), and so on. Each place increases in value by a power of 2. Table 3.1 shows a comparison of place

Table 3.1 Comparison of Place values

	Decimal (Base 10)				Binary (Base 2)				
Place (also called digit position)	4	3	2	1	5	4	3	2	1
Value	1000	100	10	1	16	8	4	2	1
Power of base	3	2	1	0	4	3	2	1	0

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values. Table 3.2 shows the binary equivalent for some decimal numbers. For example, the binary number 0010 is read as "zero, zero, one, zero"—not "ten."

To convert from binary to decimal, just multiply each binary digit by its place value and add the products. For instance, the decimal equivalent of the binary number 1010 is given by

$$\begin{aligned}(1010)_2 &= (1 \times 8) + (0 \times 4) + (1 \times 2) + (0 \times 1) \\ &= 8 + 2 \\ &= 10_{10}\end{aligned}$$

1010_2 means that the number is a base 2, or binary, number. 10_{10} means the number is a base 10, or decimal, number. Normal notation eliminates the subscripts 2 and 10 if the number system is clear from the context.

Table 3.2 Comparison of Numbers in Different Bases

Decimal (Base 10)	Binary (Base 2)
0	0000
1	0001
2	0010
3	0011
4	0100
5	0101
6	0110
7	0111
8	1000
9	1001
10	1010
11	1011
12	1100
13	1101
14	1110
15	1111
16	10000
255	11111111
256	100000000

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Converting from decimal to binary can be accomplished by finding the largest number that is a power of 2 (divisor) that will divide into the decimal number (dividend) with a 1 as a quotient, putting a 1 in its place, and subtracting the divisor (the number used to divide with) from the decimal number (dividend) to get a remainder. The operation is repeated by dividing with the next lower number that is a power of 2 until the binary ones' place has been tested. Any time the dividend is less than the divisor, a 0 is put in that place and the next power of 2 divisor is tried. For instance, to find the binary equivalent for the decimal number 73, the largest number that is a power of 2 and that will divide into 73 with a quotient of 1 is 64 (2^6):

(2^6)	73/64	= 1 remainder (73 – 64) = 9
(2^5)	9/34	= 0
(2^4)	9/16	= 0
(2^3)	9/8	= 1 remainder (9 – 8) = 1
(2^2)	1/4	= 0
(2^1)	1/2	= 0
(2^0)	1/1	= 1

Therefore,

73 = 1001001

LOGIC CIRCUITS (COMBINATORIAL)

Digital computers can perform *b*inary dig*it* (bit) manipulations very easily by using three basic logic circuits or gates: the NOT gate, the AND gate, and the OR gate. Digital gates operate on logical variables that can have one of two possible values (e.g., true/false, saturation/cutoff, or 1/0). As was previously explained, numerical values are represented by combinations of 0 or 1 in a binary number system.

As mentioned earlier, digital circuits operate with transistors in one of two possible states—saturation or cutoff. Since these two states can be used to represent the binary numbers 1 or 0, combinations of transistors that are in one of these two states can be used to represent multiple-digit binary numbers. The input and output voltages for such digital circuits will be either "high" or "low," corresponding to 1 or 0. High voltage means that the voltage exceeds a high threshold value that is denoted V_H. Symbolically, the high-voltage condition corresponding to logical 1 is written

$$V > V_H$$

meaning V exceeds V_H. Similarly, low voltage means that voltage V is given by

$$V < V_L$$

meaning V is less than V_L, where V_L denotes the low threshold value. The actual values for V_H and V_L depend on the technology for implementing the circuit. Typical values are V_H = 2.4 volts and V_L = 0.8 volt.

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Digital circuit operation is represented in terms of logical variables that are denoted here with capital letters. For example, in the next few sections A, B, and C represent logical variables that can have a value of either 0 or 1.

NOT Gate

A NOT gate inverts input 1 to 0 and input 0 to 1.

The NOT gate is a logic inverter. If the input is a logical 1, the output is a logical 0. If the input is a logical 0, the output is a logical 1. It changes zeros to ones and ones to zeros. The transistor inverting amplifier of Figure 3.3 performs the same function if operated from cutoff to saturation. A high base voltage (logical 1)* produces a low collector voltage (logical 0) and vice versa. Figure 3.6a shows the schematic symbol for a NOT gate. Next to the schematic symbol is what is called a *truth table.* The truth table lists all of the possible combinations of input A and output B for the circuit. The logic symbol is shown also. The logic symbol is read as "NOT A."

AND Gate

An AND gate requires all input signal levels to be high for the output signal to be high.

The AND gate is slightly more complicated. The AND gate has at least two inputs and one output. The one shown in Figure 3.6 has two inputs. The output is high (1) only when both (all) inputs are high (1). If either or both inputs are low (0), the output is low (0). Figure 3.6b shows the truth table, schematic symbol, and logic symbol for this gate. The two inputs are labeled A and B. Notice that there are four combinations of A and B, but only one results in a high output.

OR Gate

The output signal of an OR gate is high when any one of its input signal levels is high.

The OR gate, like the AND gate, has at least two inputs and one output. The one shown in Figure 3.6 has two inputs. The output is high (1) whenever one or both (any) inputs are high (1). The output is low (0) only when both inputs are low (0). Figure 3.6c shows the schematic symbol, logic symbol, and truth table for the OR gate.

NAND and NOR

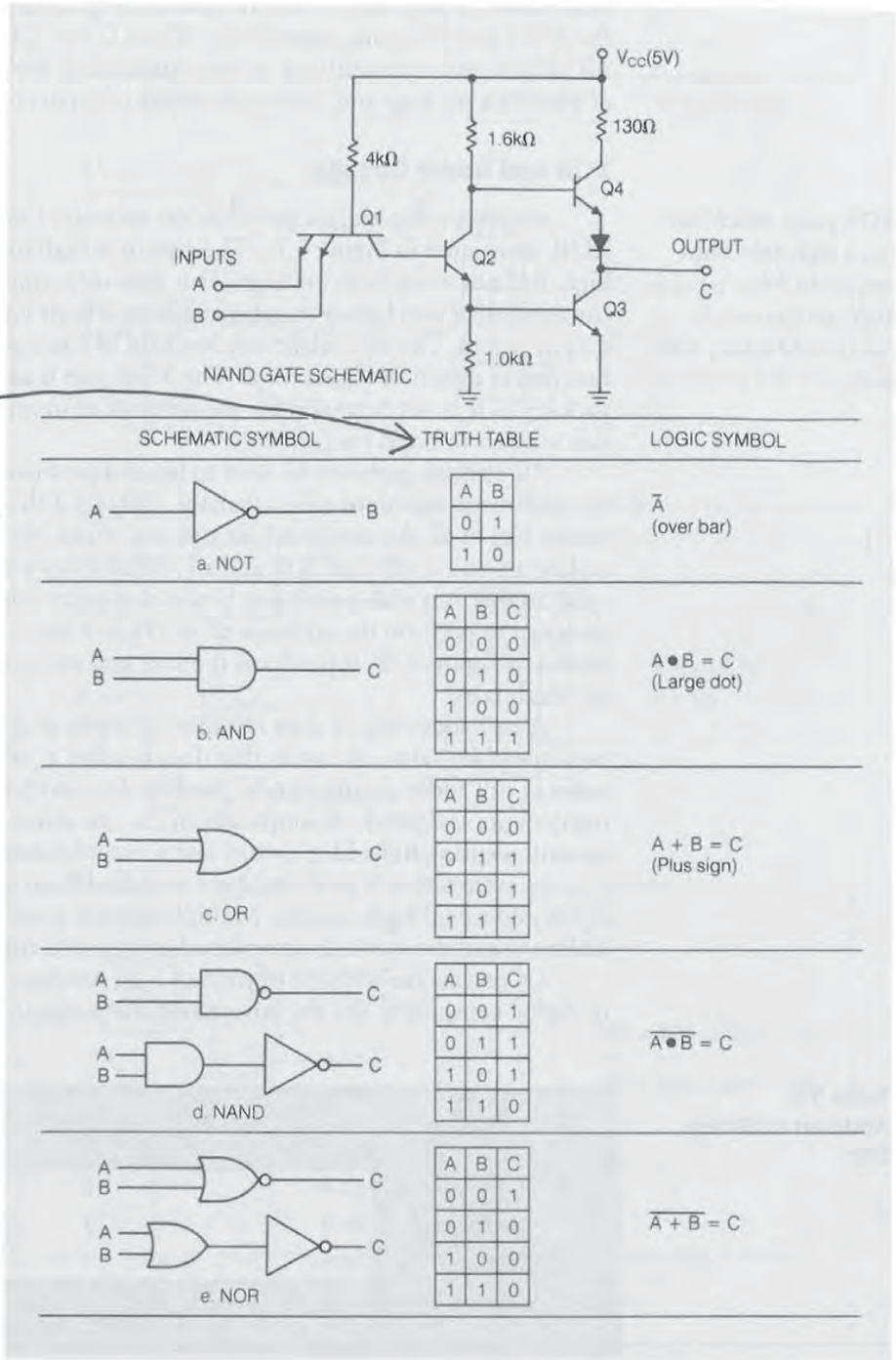
NAND and NOR gates may be constructed by combining AND, OR, and NOT gates.

Other logic functions can be generated by combining these basic gates. An inverter can be placed after an AND gate to produce a NOT-AND gate. When the inverter is an integral part of the gate, the gate is called a NAND gate. The same can be done with an OR gate; the resultant gate is called a NOR gate. The truth tables and schematic symbols for both of these gates are shown in Figure 3.6. Notice that the NOT function is indicated on the schematic symbol by a small circle at the output of each gate. The small circle is the schematic symbol for NOT, whereas the overbar is the logic symbol for NOT. Notice also that the

*Positive logic defines the most positive voltage as logical 1. Negative logic defines the most positive voltage as logical 0. Positive logic is used throughout this book.

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Figure 3.6
Basic Logic Gates



Provides output conditions for all combinations of inputs.

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truth table outputs for the NAND and NOR gates are the reverse of those for the AND and OR gates, respectively. Where C was 1, it is now 0 and vice versa. All of these gates are available in integrated circuit form with various quantities of gates in a package and various numbers of inputs per gate.

XOR and Adder Circuits

XOR gates, which output a high only when one or the other input is high, are commonly used to add binary numbers.

Another complex gate performs the exclusive OR function, abbreviated as XOR, illustrated in Figure 3.7a. The output is high only when one input is high, but not when both are high. This gate very commonly is used for comparison of two binary numbers because if both inputs are the same, the output is zero. The equivalent combination of basic gates to perform this function is shown in Figure 3.7a. The XOR gate is also available in an integral package so it is not necessary for the designer to interconnect separate gates in this manner to build the function.

All of these gates can be used to build digital circuits that perform all of the arithmetic functions of a calculator. Table 3.3 shows the addition of two binary bits in all the combinations that can occur. Note that in the case of adding a 1 to a 1, the sum is 0, and a 1, called a *carry*, is placed in the next place value so that it is added with any bits in that place value. A digital circuit designed to perform the addition of two binary bits is called a *half adder* and is shown in Figure 3.7b. It produces the sum and any necessary carry, as shown in the truth table.

A half adder circuit does not have an input to accept a carry from a previous place value. A circuit that does is called a *full adder* (Figure 3.7c). A series of full adder circuits can be combined to add binary numbers with as many digits as desired. A simple electronic calculator performs all arithmetic operations using full adder circuits and a few additional logic circuits. In such circuits, subtraction is performed as a modified form of addition by using some of the additional logic circuits. Multiplication is accomplished by repeated addition, and division is accomplished by repeated subtraction.

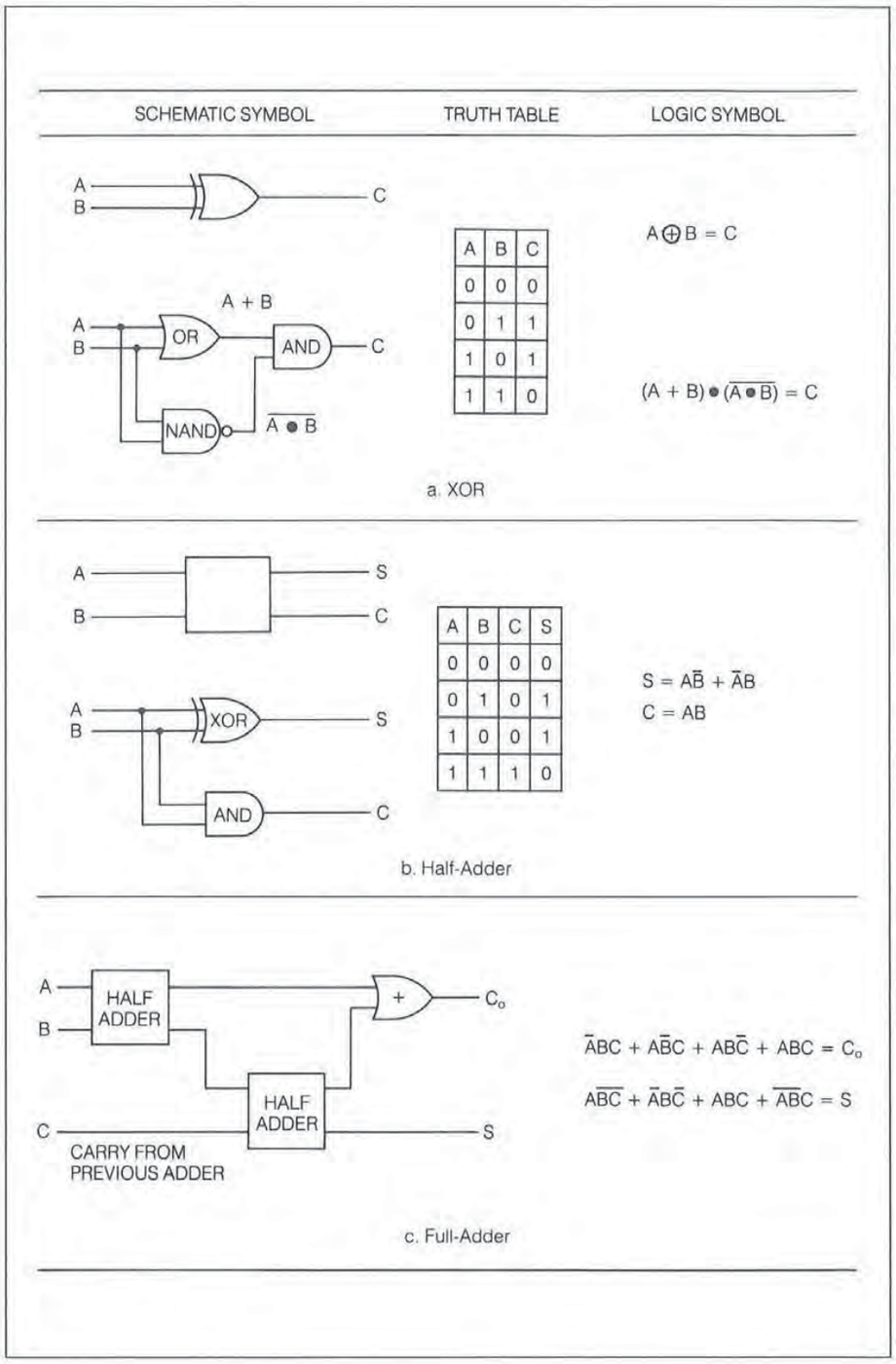
Of course, the addition of pairs of 1-bit numbers has no major application in digital computers. On the other hand, the addition of multiple-bit numbers

Table 3.3 Addition of Binary Bits

Bit *A*	0	0	1	1
Bit *B*	0	1	0	1
Sum	0	1	1	10

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Figure 3.7
XOR and Adders



A	B	C
0	0	0
0	1	1
1	0	1
1	1	0

A	B	C	S
0	0	0	0
0	1	0	1
1	0	0	1
1	1	1	0

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is of crucial importance in digital computers. The 1-bit full adder circuit can be expanded to form a multiple-bit adder circuit. By way of illustration, a 4-bit adder is shown in Figure 3.8. Here the 4-bit numbers in place position notation are given by

$$A = a_4\ a_3\ a_2\ a_1$$

$$B = b_4\ b_3\ b_2\ b_1$$

where each bit is either 1 or 0. The sum of two 4-bit numbers has a 5-bit result, where the fifth bit is the carry from the sum of the most significant bits. Each block labeled FA is a full adder. The carry out (C) from a given FA is the carry in (C') of the next-highest full adder. The sum S is denoted (in place position binary notation) by

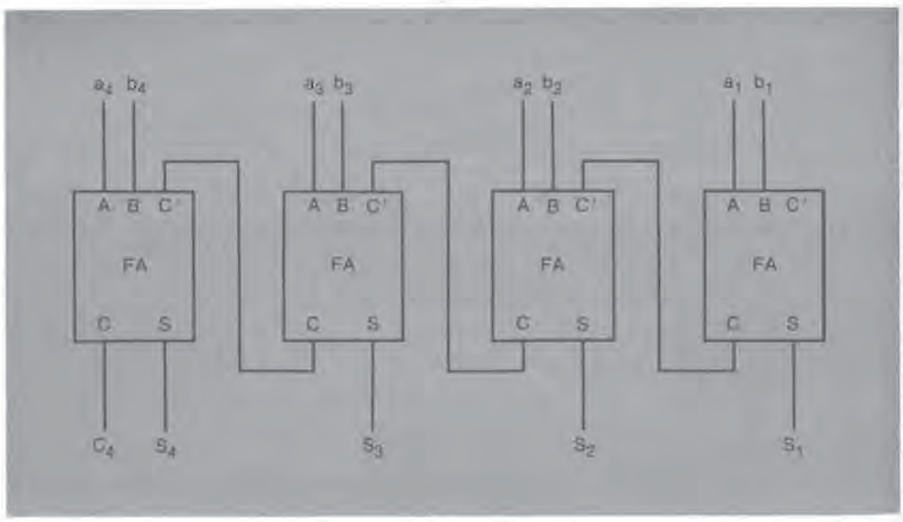
$$S = C_4\ S_4\ S_3\ S_2\ S_1$$

LOGIC CIRCUITS WITH MEMORY (SEQUENTIAL)

Sequential logic circuits have the ability to store, or remember, previous logic states. Sequential logic circuits are the basis of computer memories.

The logic circuits discussed so far have been simple interconnections of the three basic gates NOT, AND, and OR. The output of each system is determined only by the inputs present at that time. These circuits are called *combinatorial logic* circuits. There is another type of logic circuit that has a memory of previous inputs or past logic states. This type of logic circuit is called a sequential logic circuit because the sequence of past input values and the logic states at those times determine the present output state. Because *sequential logic* circuits hold or store information even after inputs are removed, they are the basis of semiconductor computer memories.

Figure 3.8
A 4-Bit Digital Adder



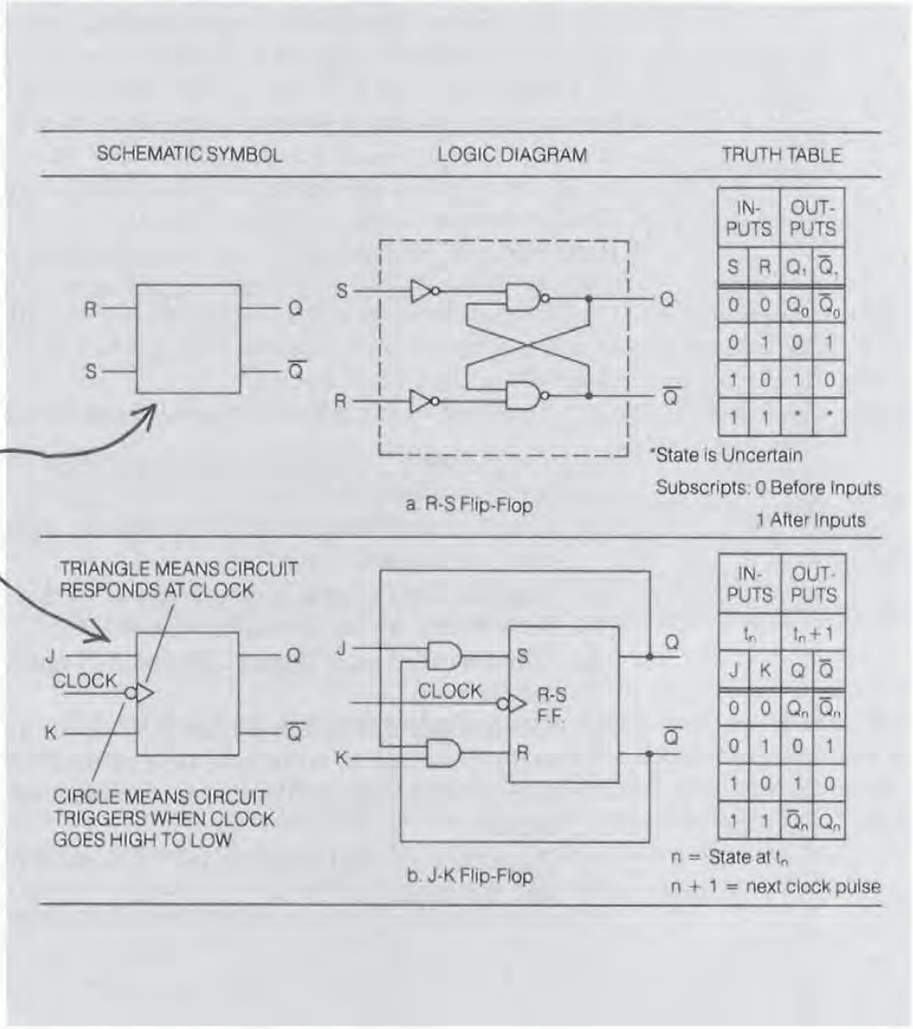
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R-S Flip-Flop

An R-S flip-flop circuit can be set into either state. It will remain latched in that state until it is set to the opposite state by the presence of opposing logic signals on its two inputs.

A very simple memory circuit can be made by interconnecting two NAND gates, as in Figure 3.9a. A careful study of the circuit reveals that when S is high (1) and R is low (0), the output Q is set high and remains high regardless of whether S is high or low at any later time. The high state of S is said to be *latched into* the state of Q. The only way Q can be unlatched to go low is to let R go high and S go low. This resets the latch. This type of memory device is called a *Reset-Set* (R-S) *flip-flop* and is the basic building block of sequential logic circuits. The term "flip-flop" describes the action of the logic level changes at Q. Notice from the truth table that R and S must not be 1 at the same time. Under this condition, the two gates are bucking each other and the final state of the flip-flop output is uncertain.

Figure 3.9
Flip-Flops



The basic memory building blocks.

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J-K Flip-Flop

The J-K flip-flop circuit is superior to the R-S flip-flop circuit because it resolves ambiguities resulting from simultaneous inputs.

A flip-flop where the uncertain state of simultaneous inputs on R and S is solved is shown in Figure 3.9b. It is called a *J-K flip-flop* and can be obtained from an R-S flip-flop by adding additional logic gating, as shown in the logic diagram. When both J and K inputs are 1, the flip-flop changes to a state other than the one it was in. The flip-flop shown in this case is a synchronized one. That means it changes state at a particular time determined by a timing pulse, called the *clock*, being applied to the circuit at the terminal marked by a triangle. The little circle at the clock terminal means the circuit responds when the clock goes from a high level to a low level. If the circle is not present, the circuit responds when the clock goes from a low level to a high level.

Synchronous Counter

Figure 3.10 shows a four-stage synchronous counter. It is synchronous because all stages are triggered at the same time by the same clock pulse. It has four stages; therefore, it counts 2^4 or 16 clock pulses before it returns to a starting state. The timed waveforms appearing at each Q output are also shown. It is easy to see how such circuitry can be used for counting, for generating other timing pulses, and for determining timed sequences. One can easily visualize how such stages can be lined up to store the digits of a binary number. If the storage is temporary, then such a combination of stages is called a *register*. If storage is to be more permanent, it is called *memory*.

Digital counter circuits can easily be arranged to develop circuits that are used in digital clocks.

Digital clocks, as well as circuits that convert binary numbers to decimal numbers so they can be displayed and read by humans, are made up of many stages of such counting circuits.

To review what has been discussed about digital circuits:

1. They operate with signals at discrete levels rather than with signals whose level varies continuously.
2. High and low voltage levels are commonly used to represent the binary numbers 1 and 0, respectively.
3. Combinations of ones and zeros can be used as codes to represent numbers, letters, symbols, conditions, and so forth.
4. Circuits called gates (Figures 3.6 and 3.7) can be combined to make logical decisions.
5. Circuits called flip-flops (Figure 3.9) can be used to store ones and zeros. They can be set or reset into particular binary sequences to produce or store digital information, to count, or to produce timed digital signals.
6. Transistors are used in the on and off condition in circuits to form gates and flip-flops.

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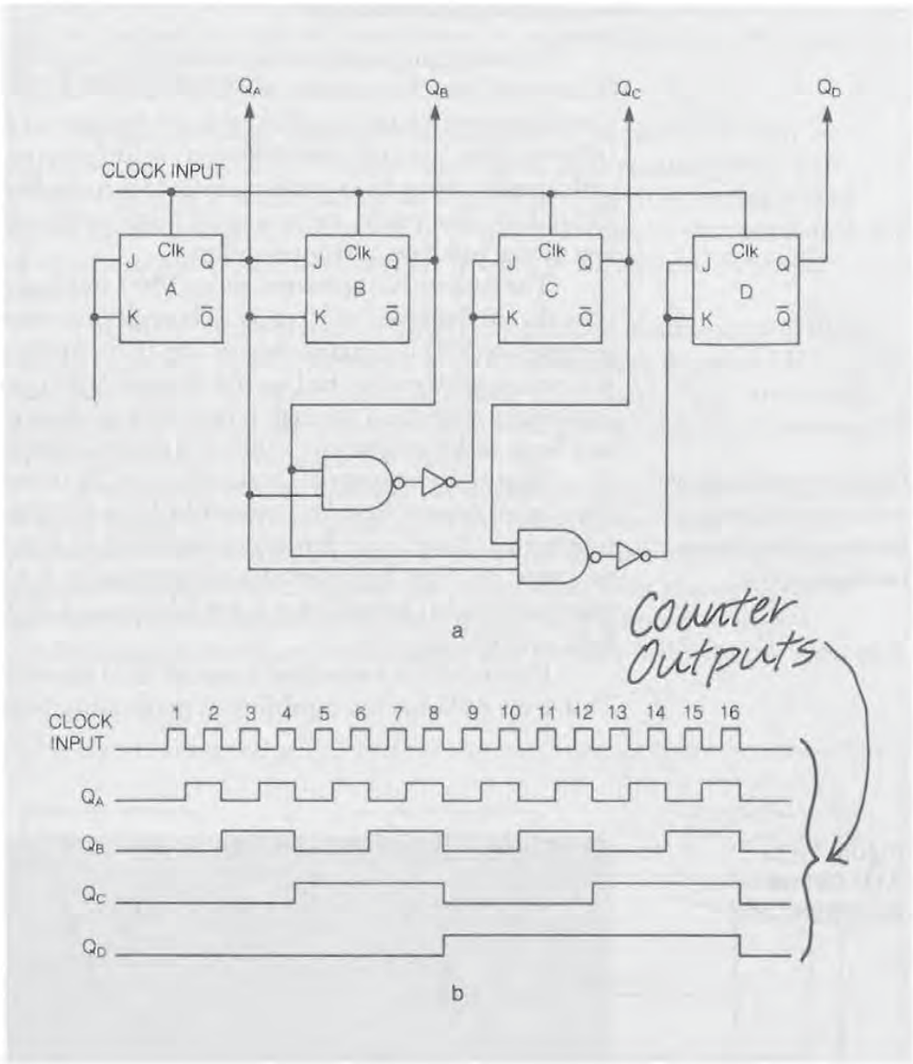


Figure 3.10
A Four-Stage Synchronous Counter

Integrated circuits are ideal for digital circuits because the digital circuits consist of many interconnected identical gates.

Digital electronic systems send and receive signals made up of ones and zeros in the form of codes. The digital codes represent the information that is moved through the digital systems by the digital circuits. Digital systems are made up of many *identical* logic gates and flip-flops interconnected to do the function required of the system. As a result, digital circuits are ideal for implementation in integrated circuits (ICs) because all components can be made at the same time on a small silicon area.

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INTEGRATED CIRCUITS

By using integrated circuit technology, all of the counters, registers, and binary-to-decimal converters are produced at the same time on a tiny piece of silicon semiconductor material by the techniques of photolithography (photographic printing) and diffusion (modifying one material by combining it with another using high temperature). This is the heart of integrated circuit technology. The results are very small, high-performance circuits that use very low power and have a high reliability.

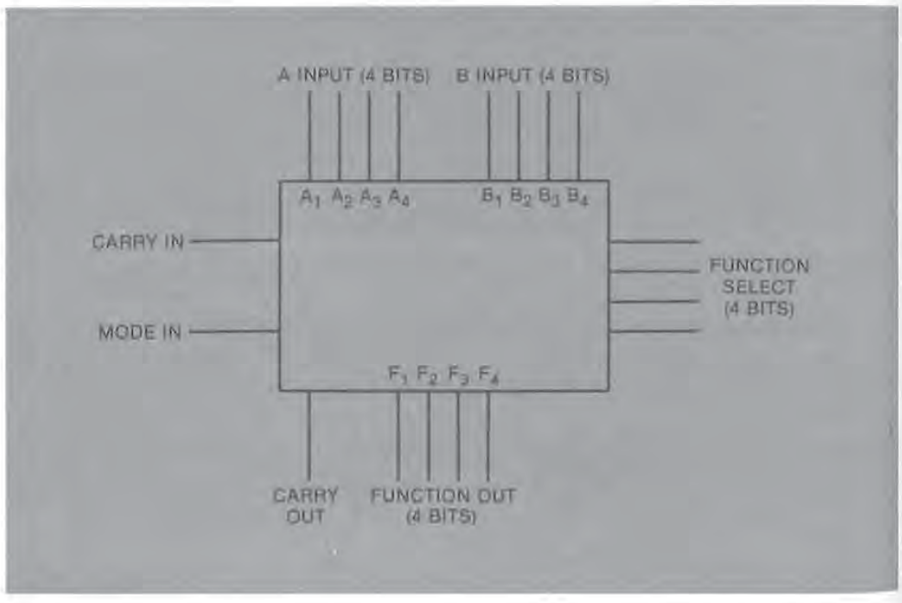
The earliest ICs appeared about 1960 and had relatively few gates, typically on the order of 10 to 12. Those devices were known as small-scale integration (SSI) integrated circuits. By 1970, medium-scale integration (MSI) ICs were available; they had on the order of 1,000 gates. The evolution of technology continued through phases of large-scale integration (LSI) ICs to very large scale integration (VLSI) ICs that had 5,000 or more gates.

Digital circuits are now available as electronic systems or subsystems packaged as ICs.

One of the important consequences of IC technological progress has been that digital circuits have become available (in IC form) as electronic systems or subsystems. That is, the functional capability of digital circuits in single IC packages, or chips, has spectacularly increased in the past 30 years. One of the important digital systems that is available as an LSI IC is the arithmetic and logic unit (ALU).

Figure 3.11 is a sketch of a typical ALU showing the various connections. This 4-bit ALU has the capability of performing 16 possible logical or

Figure 3.11 ALU Circuit Configuration



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arithmetic operations on two 4-bit inputs, A and B. Table 3.4 summarizes these various operations using the logical notation explained earlier in this chapter.

The Microprocessor

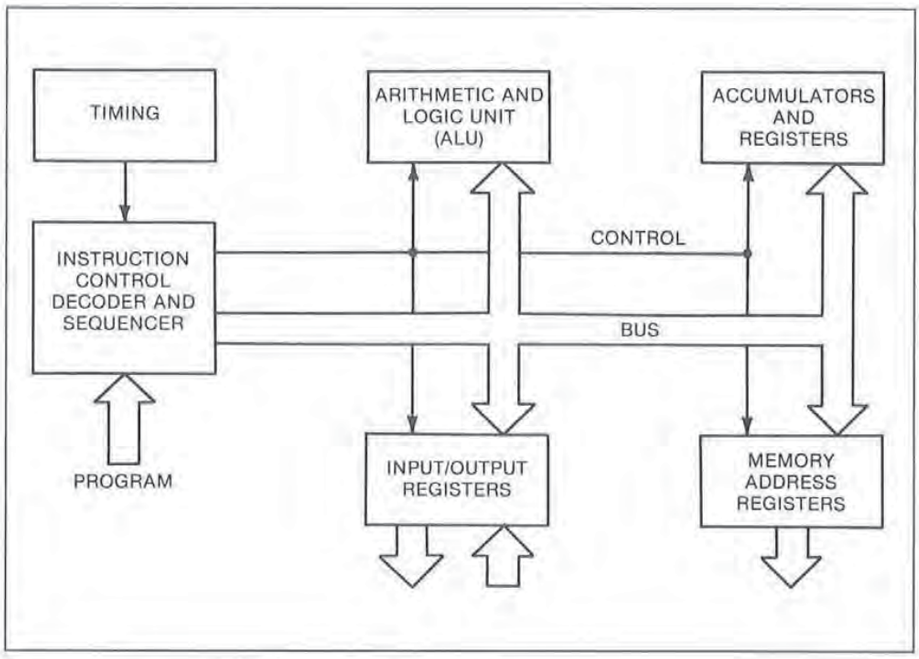
Perhaps the single most important digital IC to evolve has been the microprocessor (MPU). This important device, incorporating more than 250,000 gates in an area of about $^1/_4$-inch square, has truly revolutionized digital electronic system development. A microprocessor is the operational core of a microcomputer and has broad application in automotive electronic systems.

The MPU incorporates a relatively complicated combination of digital circuits including an ALU, registers, and decoding logic. A typical MPU block diagram is shown in Figure 3.12. The double lines labeled "bus" are actually sets of conductors for carrying digital data throughout the MPU. Common IC MPUs use 8, 16, or 32 conductor buses.

The microprocessor in combination with memory and other circuits under program control can accomplish very complex tasks.

A microprocessor by itself can accomplish nothing. It requires additional, external digital circuitry as explained in the next chapter. One of the tasks performed by the external circuitry is to provide instructions in the form of digitally encoded electrical signals. For example, an 8-bit microprocessor operates with 8-bit instructions. There are 28 (or 256) possible logical combinations of 8 bits, corresponding to 256 possible MPU instructions, each

Figure 3.12
MPU Block Diagram



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Table 3.4 Arithmetic Logic Functions

		Arithmetic Function, $M = 0$	
Select S Input	Logic Function, $M = 1$	$C_n = 1$	$C_n = 0$
0000	$F = \overline{A}$ (NOT)	$F = A$	$F = A$ Plus 1
0001	$F = \overline{A + B}$ (NOR)	$F = A + B$	$F = (A + B)$ Plus 1
0010	$F = \overline{A}\,B$	$F = A + \overline{B}$	$F = (A + \overline{B})$ Plus 1
0011	$F = 0$	$F =$ Minus 1 (2's Complement)	$F = 0$
0100	$F = \overline{AB}$ (NAND)	$F = A + A\overline{B}$	$F = (A + A\overline{B})$ Plus 1
0101	$F = \overline{B}$ (NOT)	$F = (A + B)$ Plus $A\overline{B}$	$F = (A + B)$ Plus $A\overline{B} + 1$
0110	$F = AB + B\overline{A}$ (Exclusive OR)	$F = (A - B)$ Minus 1	$F = A$ Minus B
0111	$F = A\overline{B}$	$F = A\overline{B}$ Minus 1	$F = \overline{AB}$
1000	$F = \overline{A} + B$ (Implication)	$F = A + AB$	$F = (A + B)$ Plus 1
1001	$F = \overline{AB} + AB$ (NOT exclusive OR)	$F = A + B$	$F = (A + B)$ Plus 1
1010	$F = B$	$F = (A + \overline{B})$ Plus AB	$F = (A + \overline{B})$ Plus $A + 1$
1011	$F = AB$ (AND)	$F = AB$ Minus 1	$F = AB$
1100	$F = 1$	$F = A$ Plus A^*	$F = (A + A)$ Plus 1
1101	$F = A + \overline{B}$	$F = (A + B)$ Plus A	$F = (A + B)$ Plus $A + 1$
1110	$F = A + B$ (OR)	$F = (A + \overline{B})$ Plus A	$F = (A + \overline{B})$ Plus $A + 1$
1111	$F = A$	$F = A$ Minus 1	$F = A$

**Each bit is shifted to the next more significant position.*

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causing a specific operation. A complete summary of these operations and the corresponding instructions (called microinstructions) is beyond the scope of this book. A few of the more important instructions are explained in the next chapter, which further expands the discussion of this important device.

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Quiz for Chapter 3

1. Forward conventional current flows in a diode circuit from
   - **a.** anode to cathode
   - **b.** anode to anode
   - **c.** cathode to anode
   - **d.** cathode to cathode
2. Forward conventional current for a PNP transistor flows from
   - **a.** base to ground
   - **b.** base to emitter
   - **c.** emitter to base
   - **d.** collector to base
3. The op amp is what type of circuit?
   - **a.** digital
   - **b.** analog
   - **c.** logic gate
   - **d.** none of the above
4. The AND gate is what type of circuit?
   - **a.** digital
   - **b.** analog
   - **c.** amplifier
   - **d.** inverter
5. Which conditions cause the output of an XOR gate to be high?
   - **a.** both inputs are low
   - **b.** both inputs are high
   - **c.** either input is high but not both
   - **d.** both inputs are zero
6. An R-S latch is what type of digital logic?
   - **a.** combinational logic
   - **b.** sequential logic
   - **c.** Fortran
   - **d.** J-K
7. Flip-flops are used in what type of logic systems?
   - **a.** memories
   - **b.** counters
   - **c.** data registers
   - **d.** all of the above
8. Integrated circuits are used in automotive electronic systems because they have
   - **a.** excellent functional performance
   - **b.** high reliability
   - **c.** small size
   - **d.** low cost
   - **e.** all of the above
9. Digital circuits operate with voltages representing
   - **a.** an analog of a physical quantity being measured
   - **b.** the electrical equivalent of 1 or 0
   - **c.** proportional currents
   - **d.** none of the above
10. A half adder circuit can be made from
    - **a.** an operational amplifier
    - **b.** three NOT gates
    - **c.** two OR gates
    - **d.** an XOR gate in combination with an AND gate
11. A full adder can be made from
    - **a.** a half adder with carry in
    - **b.** two half adder circuits with carry in
    - **c.** an R-S flip-flop
    - **d.** all of the above

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12. Which of the following devices require the use of semiconductors?
- **a.** transistors
- **b.** diodes
- **c.** integrated circuits
- **d.** all of the above

13. In which of the following circuits is a diode used?
- **a.** filter
- **b.** rectifier
- **c.** resistor
- **d.** capacitor

14. What device is used to smooth out the bumpy output of the rectifier circuit?
- **a.** capacitor
- **b.** resistor
- **c.** diode
- **d.** transistor

15. In which type of circuits are transistors used?
- **a.** amplifiers
- **b.** op amps
- **c.** logic gates
- **d.** all of the above

16. Which of the following conditions cause the output of an OR gate to be low?
- **a.** both inputs are high
- **b.** only one input is high
- **c.** both inputs are low

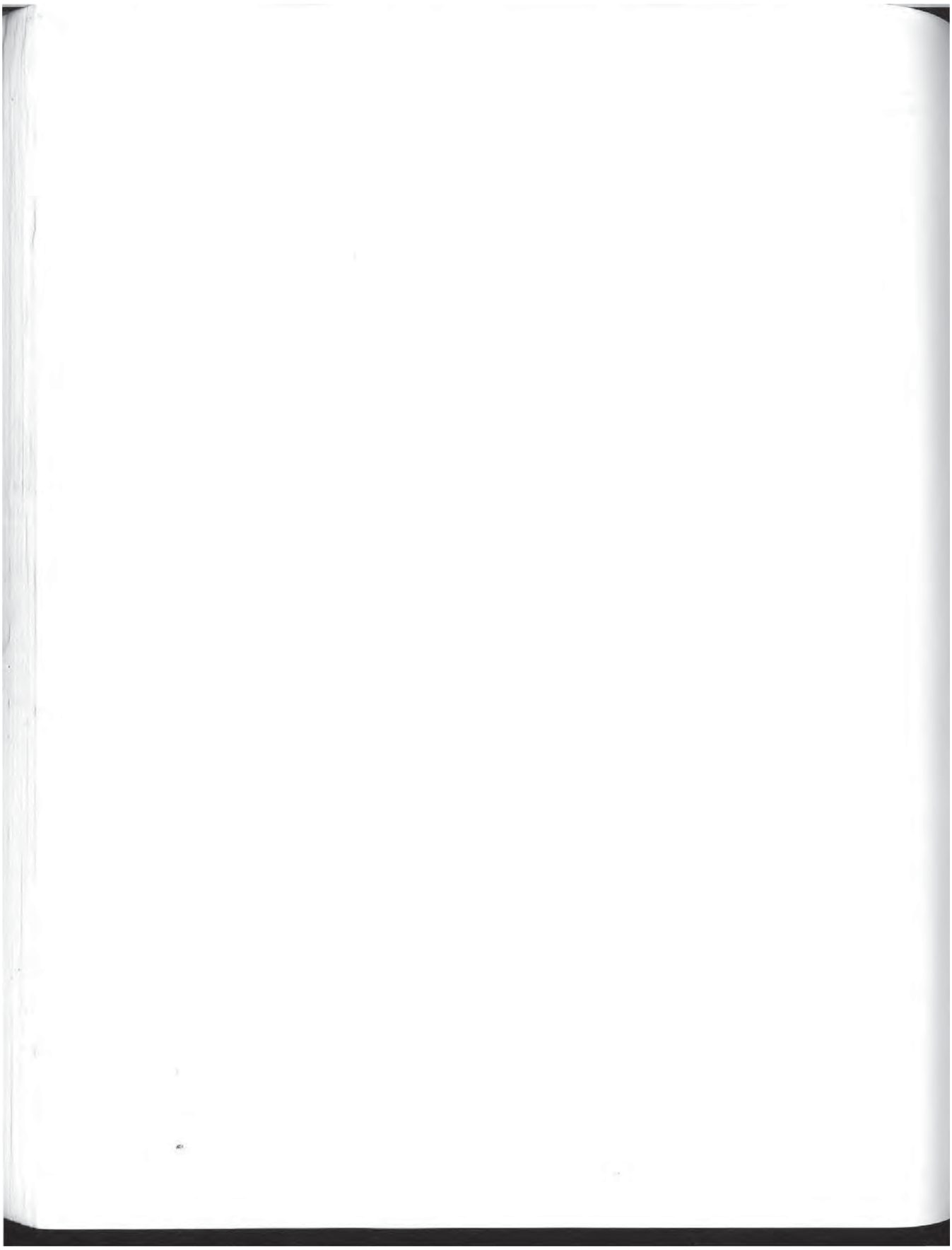
17. Which of the following conditions cause the outputs of an AND gate to be high?
- **a.** both inputs are low
- **b.** both inputs are high
- **c.** one input is low
- **d.** at least one input is low

18. What decimal number does the binary number 0110 represent?
- **a.** 4
- **b.** 3
- **c.** 110
- **d.** 6

19. What binary number does the decimal number 10 represent?
- **a.** 0010
- **b.** 0101
- **c.** 1010
- **d.** 1000

20. The binary addition of 0110 and 0010 produces what binary sum?
- **a.** 1000
- **b.** 0111
- **c.** 1111
- **d.** 1010

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Microcomputer Instrumentation and Control

This chapter explains microcomputers and how they are used in instrumentation and control systems. Topics include microcomputer fundamentals, microcomputer equipment, microcomputer inputs and outputs, computerized instrumentation, and computerized control systems. The specific automotive applications of microcomputers are explained in later chapters.

MICROCOMPUTER FUNDAMENTALS

Digital versus Analog Computers

A digital computer represents each variable in terms of binary numbers.

In digital computer-based systems, physical variables are represented by a numerical equivalent using a form of the binary (base 2) number system. In the previous chapter it was shown that transistor circuits can be constructed to have one of two stable states: saturation and cutoff. These two states can be used to represent a 0 (zero) or a 1 (one) in a binary number system. To be practically useful, there must be groups of such circuits that are arranged in the form of a place position, binary number system.

By contrast, an analog system has a single lead with a voltage (relative to ground) that is proportional to the relevant physical variable. A digital system will have a group of leads, each one of which can have only two voltage levels representing 0 or 1 (as discussed in Chapter 3). It is common practice for a digital computer to have the number of voltages representing the binary digits (bits) be a multiple of 8. For example, early automotive engine control computers used 8 bits to represent data, which means that 256 (2^8) possible levels can be represented. In any application, including automotive, a computer performs various operations on the data. To explain the operation of a digital computer, it is helpful to first explain the operation of its various components.

Parts of a Computer

The parts of a digital computer are shown in Figure 4.1. The *central processing unit* (CPU) is the processor that is the heart of the system. When made in an integrated circuit, it is called a microprocessor. This is where all of

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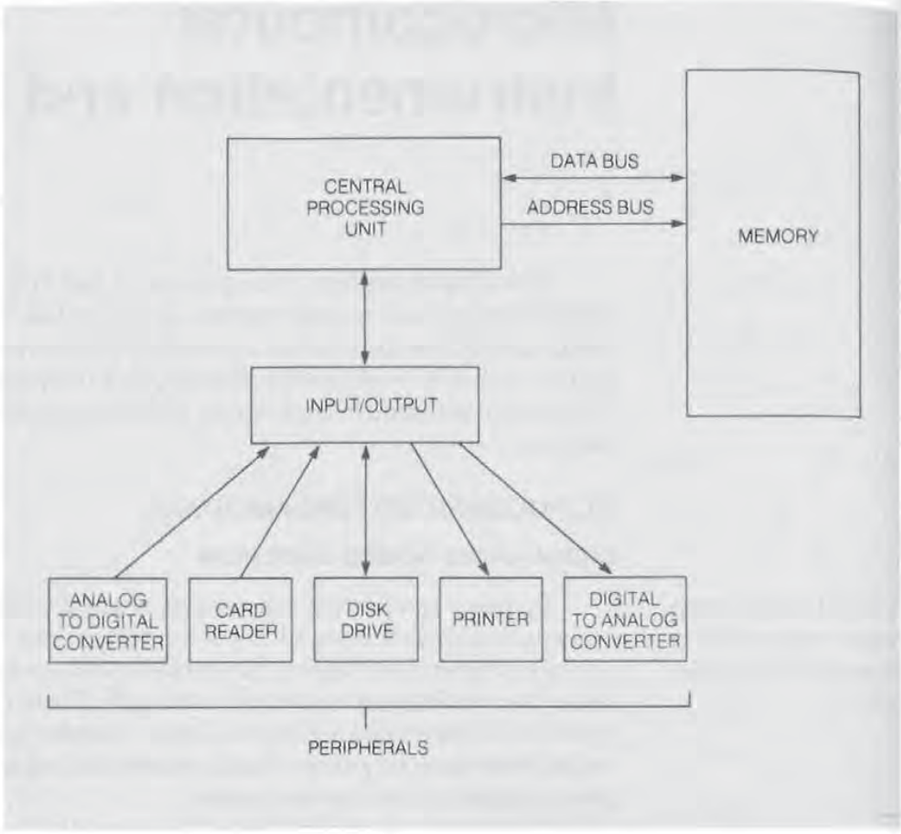


Figure 4.1
Basic Computer Block Diagram

A digital computer consists of a CPU to process information, a memory to store information, and input/output sections to communicate with the user.

the arithmetic and logic decisions are made and is the calculator part of the computer.

The *memory* holds the program and data. The computer can change the information in memory by writing new information into memory, or it can obtain information contained in memory by reading the information from memory. Each memory location has a unique address that the CPU uses to find the information it needs.

Information (or data) must be put into the computer in a form that the computer can read, and the computer must present an output in a form that can be read by humans. The input and output devices, called *peripherals*, perform these conversions. Peripherals are devices such as keyboards, monitors, magnetic tape units, magnetic disk units, modems, and printers. The arrows on the interconnection lines in Figure 4.1 indicate the flow of data.

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Microcomputers versus Mainframe Computers

Microcomputers cost less and occupy less space than the mainframe computers commonly used by governments and large businesses. However, microcomputers operate more slowly and are less accurate in mathematical operations.

With this general idea of what a computer is, it is instructive to compare a general-purpose mainframe computer and a microcomputer. A microcomputer is just a small computer, typically thousands of times smaller than the large, general-purpose mainframe computers used by banks and large corporations. Microcomputers cost much less than mainframes, and their computing power and speed is only a fraction of that of a mainframe. A typical mainframe computer costs from tens of thousands of dollars to millions of dollars and is capable of hundreds of thousands of arithmetic operations per second (additions, subtractions, multiplications, and divisions). A microcomputer costs from a little less than $1,000 to $15,000 and can perform several thousand operations per second. More important for mathematical calculations than the speed of the operation is the accuracy of the operation. Mainframe computers use up to 64 bits to obtain high accuracy when doing arithmetic. The decimal equivalent for the largest number that can be represented using 64 bits is roughly 10 to the 19th power (1 followed by 19 zeros). A typical engine control microcomputer does arithmetic using only 16–32 bits. The largest decimal number that can be represented in 8 bits is 127, if one of the bits is used as a sign bit to indicate whether the number is positive or negative.

Programs

A program is a set of steps (instructions) in a logical order. The computer follows these steps to perform a given task.

A *program* is a set of instructions organized into a particular sequence to do a particular task. The first computers were little more than fancy calculators. They did only simple arithmetic and made logic decisions. They were programmed (given instructions) by punching special codes into a paper tape that was then read by the machine and interpreted as instructions. A program containing thousands of instructions running on an early model machine might require yards of paper tape. The computer would process the program by reading an instruction from the tape, performing the instruction, reading another instruction from the tape, performing the instruction, and so on until the end of the program. Reading paper tape was a slow process compared with the speed with which a modern computer can perform requested functions. In addition, the tape had to be fed through the computer each time the program was run, which was cumbersome and allowed for the possibility of the tape wearing and breaking.

To minimize the use of paper tape, and to increase computational efficiency, a method was invented to store programs inside the computer. The program is read into a large electronic memory made out of thousands of data latches (flip-flops), one for each bit, that provide locations in which to store program instructions and data. Each instruction is converted to binary

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numbers with a definite number of bits and stored in a memory location. Each memory location has an address number associated with it like a post office box. In fact, one could think of the computer memory bank as a large bank of post office boxes. The computer reads the binary number (instruction or data) stored in each memory location by going to the address (box number) of the information it wants to read. When the address for a particular memory location is generated, a *copy* of its information is transferred to the computer. (Note that the original information stays in its location in memory while the memory is being read.)

All modern electronic computers have the ability to store a program in internal memory and use it over and over to accomplish tasks.

Storing a computer program inside the computer's memory is what separates a real computer from a fancy calculator. The computer can use some of its memory for storing programs (instructions) and other memory for storing data. The program or data can be easily changed simply by loading in a different program or different data. The stored program concept is fundamental to all modern electronic computers.

MICROCOMPUTER TASKS

A microcomputer-based engine control system has much greater flexibility than the early systems which were partly analog.

A suitably configured microcomputer can potentially perform any control or instrumentation task. For example, it will be shown in a later chapter that a microcomputer can be configured to control fuel metering and ignition for an engine. The microcomputer-based engine control system has much greater flexibility than the earliest electronic engine control systems, which, typically, used elementary logic circuits as well as analog circuits. For these early systems, changes in the performance of the control system required changes in the circuitry. With a microcomputer performing the logic functions, most changes can be made simply by reprogramming the computer. That is, the software (program) is changed rather than the hardware (logic circuits). This makes the microcomputer a very attractive building block in any digital system.

Microcomputers can also be used to replace analog circuitry. Special interface circuits can be used to enable a digital computer to input and output analog signals (this will be discussed later). The important point here is that microcomputers are excellent alternatives to hardwired (dedicated) logic and analog circuitry that is interconnected to satisfy a particular design.

In the subsequent portions of this chapter, both the computer hardware configuration and programs (software) are discussed. Because these two aspects of computers are so strongly interrelated, it is necessary for the following discussion to switch back and forth between the two.

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MICROCOMPUTER OPERATIONS

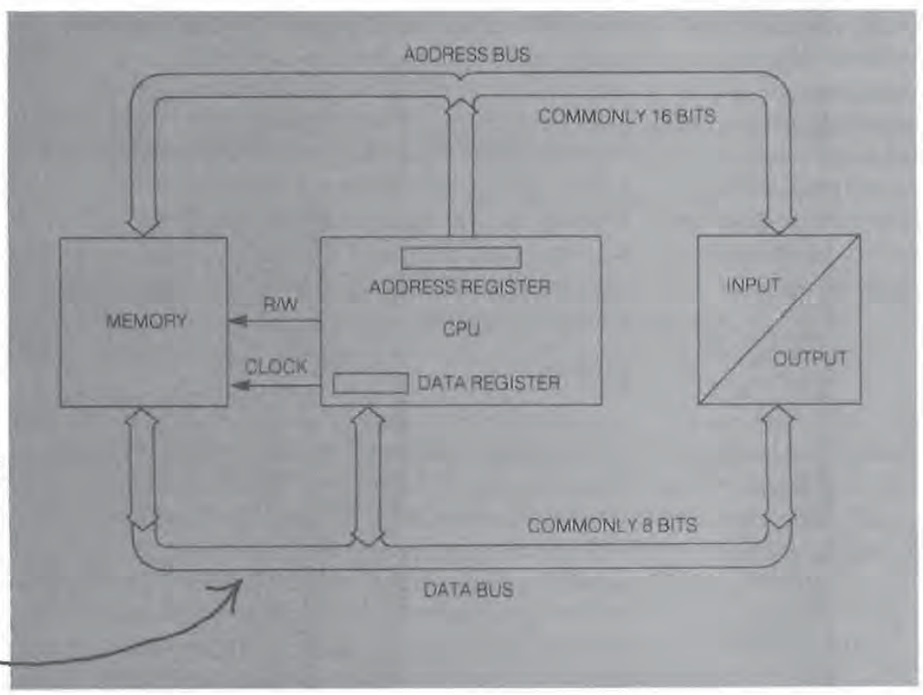
A microcomputer stores information on a temporary basis within the CPU registers. Information is transferred between the CPU registers and the memory or input/output sections by means of one or more sets of multiple wires; each set is called a *bus.*

Recall the basic computer block diagram of Figure 4.1. The central processing unit (CPU) requests information from memory (or from an input device) by generating the address for the data in memory. The address with all its bits is stored in the CPU is a binary number in a temporary data latch type memory called a *register.* The outputs of the register are sent at the same time over multiple wires to the computer memory and peripherals.

Buses

As shown in Figure 4.2, the group of wires that carries the address is called the address bus. (The word *bus* refers to one or more wires that is a common path to and from various components in the computer.) The address register used in most microcomputers holds 32 bits; these bits enable the CPU to access 2^{32} memory locations. In a microcomputer, each memory location usually contains multiples of 8 bits of data. A group of 8 bits is called a *byte* and a group of 16 bits is sometimes called a *word.*

Figure 4.2
Buses and Registers



Carries bits of a code in parallels.

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Information is sent to or received from memory locations and input/output devices via the bidirectional data bus.

Data is sent to the CPU over a data bus (Figure 4.2). The data bus is slightly different from the address bus in that the CPU uses it to *read* information from memory or peripherals, and to *write* information to memory or peripherals. Signals on the address bus originate only at the CPU and are sent to devices attached to the bus. Signals on the data bus can either be inputs to or outputs from the CPU that are sent or received at the CPU by the data register. In other words, the data bus is a two-way street while the address bus is a one-way street. Another difference is that the data bus in many microcomputers is only 16 bits wide whereas the address bus is typically 32 bits wide.

Memory Read/Write

The CPU always controls the direction of data flow on the data bus because, although it is bidirectional, data can move in only one direction at a time. The CPU provides a special read/write control signal (Figure 4.2) that tells the memory in which direction the data should flow. For example, when the read/write (R/W) line is high, the CPU reads information into a memory location.

During a memory read operation, the CPU changes the state of the read/write line and puts the appropriate address on the address bus. This causes the contents of the addressed memory location to be placed on the data bus, where it can be read by the CPU.

The timing diagram for a memory read operation is shown in Figure 4.3. Suppose the computer has been given the instruction to read data from memory location number 10. To perform the read operation, the CPU raises the R/W line to the high level to tell the memory to prepare for a read operation. Almost simultaneously, the address for location 10 is placed on the address bus ("address valid" in Figure 4.3). The number 10 in binary (0000 0000 0000 1010) is sent to the memory in the address bus. The binary electrical signals corresponding to 10 operate the specific circuits in the memory to cause the binary data at that location to be placed on the data bus. The CPU has an internal register that is activated during this read operation to receive and store the data. The data is then processed by the CPU during the next cycle of operation according to the relevant instruction.

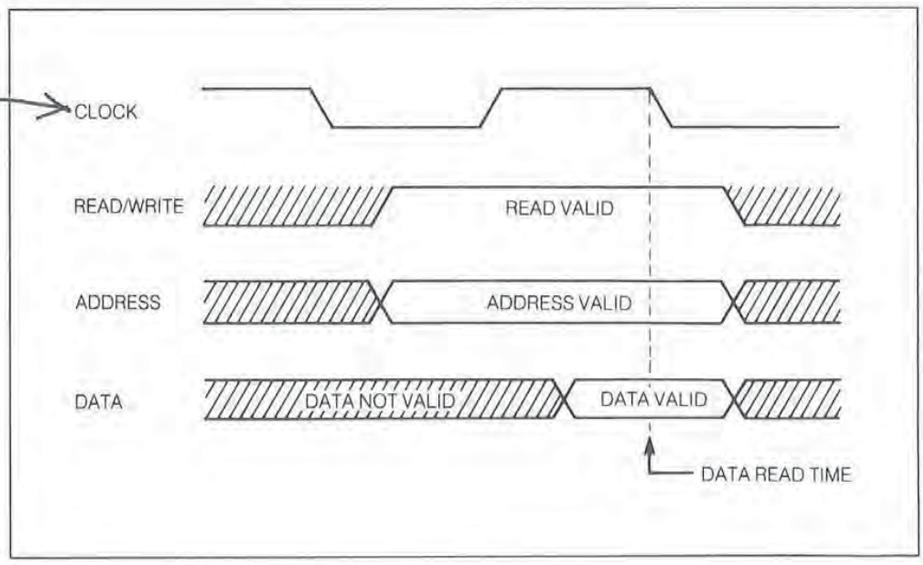
Timing

Microcomputers use a timing signal, called a *clock*, to determine when data should be written to or read from memory.

A certain amount of time is required for the memory's address decoder to decode which memory location is called for by the address, and also for the selected memory location to transfer its information to the data bus. To allow time for this decoding, the processor waits a while before receiving the information requested from the data bus. Then, at the proper time, the CPU opens the logic gating circuitry between the data bus and the CPU data register so that the information on the bus from memory location 10 is latched into the CPU. During the memory read operation, the memory has temporary control of the data bus. Control must be returned to the CPU, but not before the processor has read in the data. The CPU provides a timing control signal, called the *clock*, that tells the memory when it can take and release control of the data bus.

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Figure 4.3
Timing Diagram for Memory Read



Provides the synchronization for the system.

Refer again to Figure 4.3. Notice that the read cycle is terminated when the clock goes from high to low during the time that the read signal is valid. This is the signal the CPU uses to tell the memory that it has read the data and the data bus can be released. The timing for a memory write operation is very similar to the memory read operation except that the R/W line is low instead of high.

The bus timing signals are very important to the reliable operation of the computer. However, they are built into the design of the machine and, therefore, are under machine control. As long as the machine performs the read and write operations correctly, the programmer can completely ignore the details of the bus timing signals and concentrate on the logic of the program.

Addressing Peripherals

In memory-mapped input/output a peripheral device is treated like a memory location by the CPU.

The reason for distinguishing between memory locations and peripherals is that they perform different functions. Memory is a data storage device, while peripherals are input/output devices. However, many microcomputers address memory and peripherals in the same way because they use a design called memory-mapped I/O (input/output). With this design, peripherals, such as data terminals, are equivalent to memory to the CPU so that sending data to a peripheral is as simple as writing data to a memory location. In systems where this type of microcomputer has replaced some digital logic, the digital inputs enter the computer through a designated memory slot. If outputs are required, they exit the computer through another designated memory slot.

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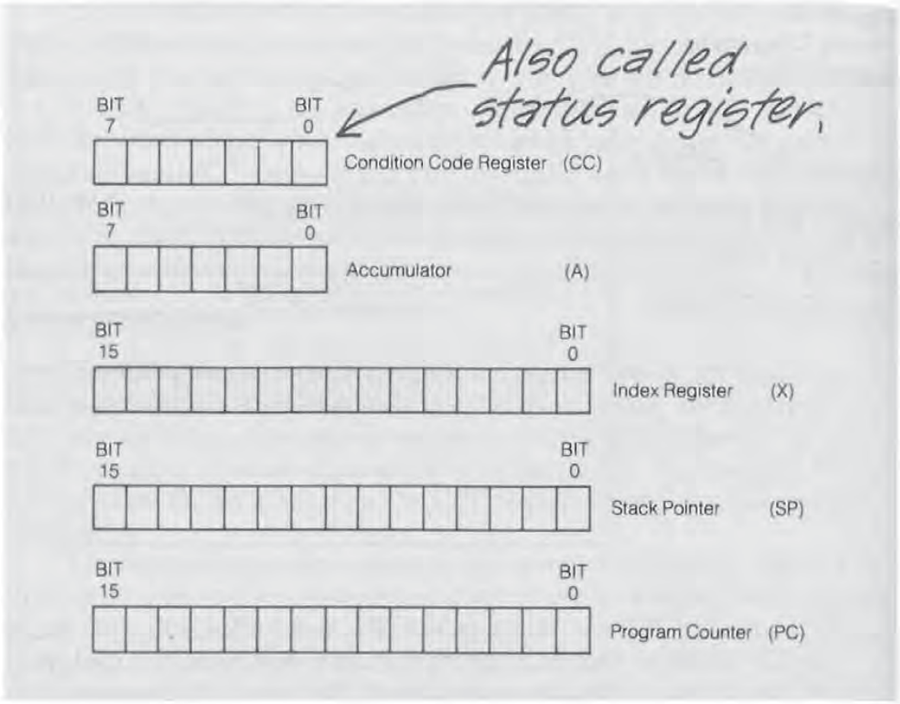


Figure 4.4 Registers Available in a Typical Microcomputer

CPU REGISTERS

The programmer (the person who writes the sequences of instructions for a particular task) uses a different model (a programming model) of the microprocessor used in a system than does the hardware designer. This model shows the programmer which registers in the CPU are available for program use, and what function the registers perform. By way of illustration Figure 4.4 shows a programming model microprocessor for a typical 8-bit (now obsolete) microcomputer. The computer has two 8-bit registers and three 16-bit registers. The 16-bit registers are discussed later; the 8-bit registers are discussed here.

Accumulator Register

The accumulator register, also called the A register, is used for arithmetic and logical operations.

One of the 8-bit registers is an *accumulator*, a general-purpose register that is used for arithmetic and logical operations. The accumulator can be loaded with data from a memory location, or its data can be stored in a memory location. The number held in the accumulator can be added to, subtracted from, or compared with another number from memory. The accumulator is the basic work register of a computer. It is commonly called the *A register.*

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Condition Code Register

The condition code register, also called the *status register*, indicates certain conditions that take place during various accumulator operations.

The other 8-bit register, the *condition code* (CC) *register* (also called *status register*), indicates or flags certain conditions that occur during accumulator operations. Rules are established in the design of the microprocessor so that a 1 or 0 in the bit position of the CC register represents specific conditions that have happened in the last operation of the accumulator. The bit positions and rules are shown in Figure 4.5a. One bit of the CC register indicates that the A register is all zeros. Another bit, the carry bit, indicates that the last operation performed on the accumulator caused a carry to occur. The carry bit acts like the ninth bit of the accumulator. Notice what happens when we add 1 to 255 in binary:

Decimal	Binary
255	11111111
+ 1	+ 1
256	100000000

The condition code register can indicate if the value contained in the accumulator is negative. This gives the CPU the ability to represent a much wider range of numbers.

The eight bits in the accumulator are all zeros, but the carry bit being set to a 1 (high) indicates that the result is actually not 0, but 256. Such a condition can be checked by examining the CC register carry bit for a 1.

The condition code register also provides a flag that, when set to a 1, indicates that the number in the accumulator is negative. Most microcomputers use a binary format called *two's complement notation* for doing arithmetic. In two's complement notation, the leftmost bit indicates the sign of the number. Since one of the 8 bits is used for the sign, 7 bits (or 15 if 16 bits are used) remain to represent the magnitude of the number. The largest positive number that can be represented in two's complement with 8 bits is +127 (or +32,767 for 16 bits); the largest negative number is –128 (–32,768). Since the example accumulator is only 8 bits wide, it can handle only 1 byte at a time. However, by combining bytes and operating on them one after another in time sequence (as is done for 16-bit arithmetic), the computer can handle very large numbers or can obtain increased accuracy in calculations. Handling bits or bytes one after another in time sequence is called *serial operation.*

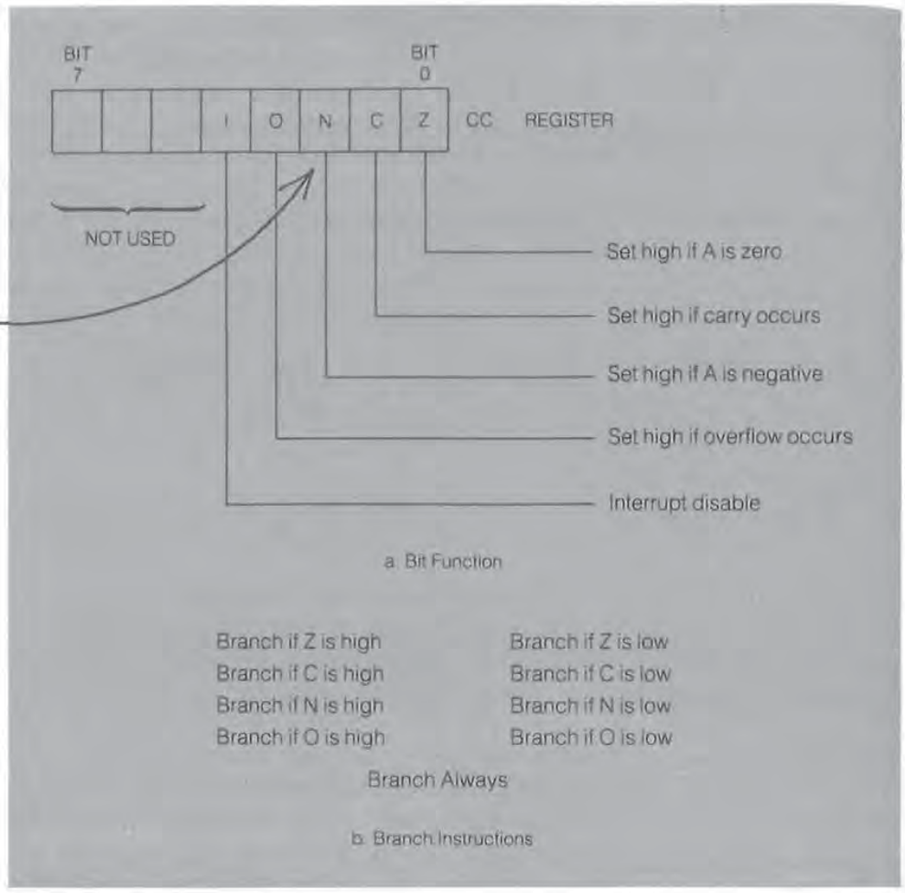
Branching

Instructions that direct the microcomputer to other parts of the program are called *branches.* Branches may be conditional or unconditional.

The CC register provides programmers with status indicators (the flags) that enable them to monitor what happens to the data as the program executes the instructions. The microcomputer has special instructions that allow it to go to a different part of the program. Bits of the CC register are labeled in Figure 4.5a. Typical branch-type instructions are shown in Figure 4.5b.

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Figure 4.5
Use of the CC Register



These bits are called flags.

Program branches are either conditional or unconditional. Eight of the nine branch instructions listed in Figure 4.5b are conditional branches. That is to say, the branch is taken only if certain conditions are met. These conditions are indicated by the CC register bit as shown. The branch-always instruction is the only unconditional branch. Such a branch is used to branch around the next instruction to a later instruction or to return to an earlier instruction. Another type of branch instruction that takes the computer out of its normal program sequence is indicated for the I bit of the CC register. It is associated with an interrupt. An interrupt is a request, usually from an input or output (I/O) peripheral, that the CPU stop what it is doing and accept or take care of (service) the special request. There will be more about interrupts later in this chapter.

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Microprocessor Architecture

Understanding how the microprocessor operates is aided by Figure 4.6, which is a block diagram of a typical commercial microprocessor. This block diagram is divided into two main portions—a register section and a control section. The actual operations performed by the microprocessor are

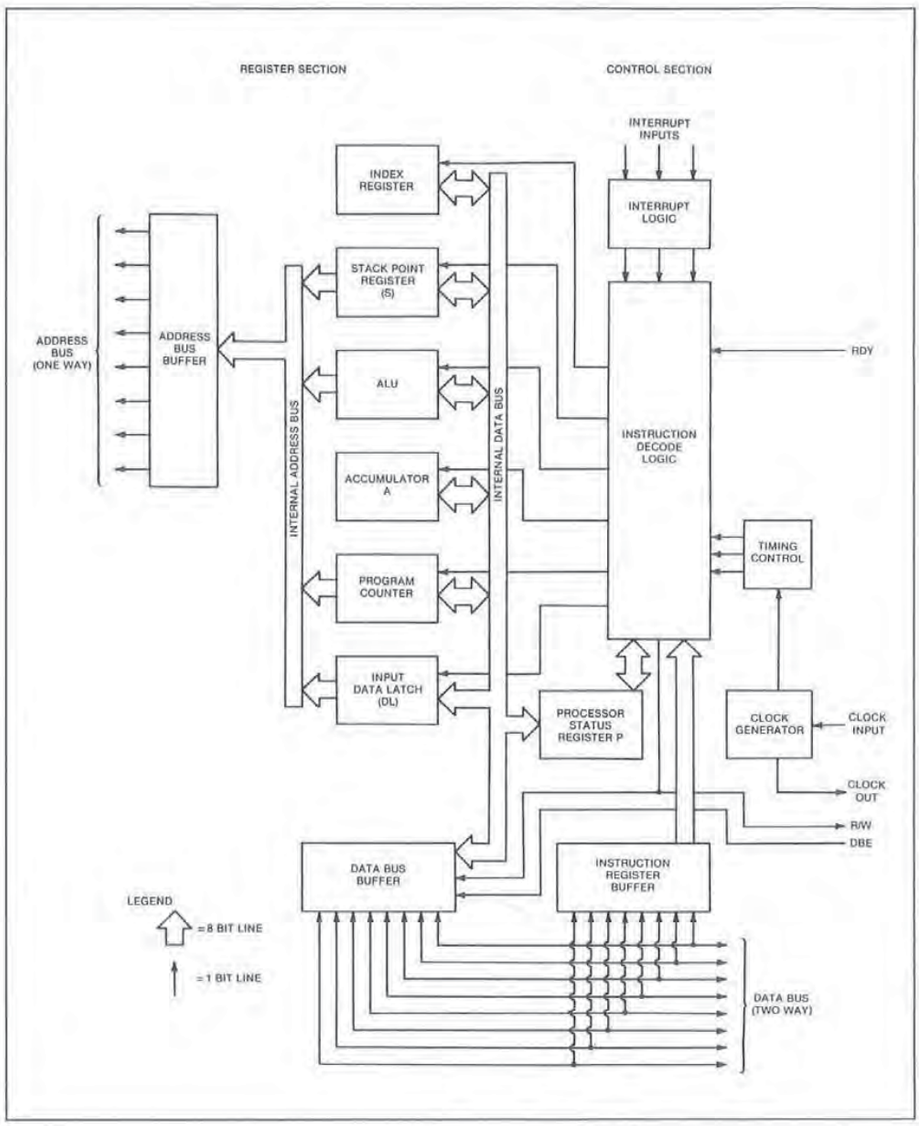


Figure 4.6 Typical Microprocessor Internal Architecture

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accomplished in the register section. The specific operations performed during the execution of a given step in the program are controlled by electrical signals from the instruction decoder.

During each program step, an instruction in the form of an 8-bit (or possibly 16-bit) number is transferred from memory to the instruction register. This instruction is decoded using logic circuits similar to those presented in Chapter 3. The result of this decoding process is a set of electrical control signals that are sent to the specific components of the register section that are involved in the instruction being executed.

The data upon which the operation is performed is similarly transferred from memory to the data bus buffer. From this buffer the data is then transferred to the desired component in the register section for execution of the operation.

Note that an arithmetic and logic unit (ALU) is included in the register section of the typical microprocessor is shown in Figure 4.6. This device is a complex circuit capable of performing the arithmetic and logical operations, as explained in Chapter 3. Also included in the register section is the accumulator, which is the register used most frequently to receive the results of arithmetic or logical operation. In addition, the example microprocessor register section has an index register, stack pointer register, and program counter register. The program counter register holds the contents of the program counter and is connected through the internal address bus to the address buffer register. The address bus for the example microprocessor has 16 lines, and thereby can directly address 65,536 (i.e., 64K) of memory.

READING INSTRUCTIONS

To understand how the computer performs a branch, one must first understand how the computer reads program instructions from memory. Recall that program instructions are stored sequentially (step by step) in memory as binary numbers, starting at a certain binary address and ending at some higher address. The computer uses a register called the program counter (Figure 4.4) to keep track of where it is in the program.

Initialization

The first step in starting up a computer is initialization.

To start the computer, a small startup (boot) program that is permanently stored in the computer is run. This program sets all of the CPU registers with the correct values and clears all information in the computer memory to zeros before the operations program is loaded. This is called *initializing* the system. Then, the operations program is loaded into memory, at which point the address of the first program instruction is loaded into the program counter. The first instruction is read from the memory location whose address is contained in

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the program counter register; that is, the 16 bits in the program counter are used as the address for a memory read operation. Each instruction is read from memory in sequence and set on the data bus into the instruction register, where it is decoded. The instruction register is another temporary storage register inside the CPU (or microprocessor). It is connected to the data bus when the information on the bus is an instruction.

Operation Codes

The actual instructions in the program are in the form of numeric codes called operation codes (op codes).

Numeric codes called *operation codes* (or *op codes* for short) contain the instructions that represent the actual operation to be performed by the CPU. The block diagram of Figure 4.7, which illustrates part of the CPU hardware organization, should help clarify the flow of instructions through the CPU. The instruction register has a part that contains the numeric op codes. A decoder determines from the op codes the operation to be executed, and a data register controls the flow of data inside the CPU as a result of the op code instructions.

Instructions often are contained in more than one byte. In such cases, the first byte contains the op code, and succeeding bytes contain the address.

One important function of the op-code decoder is to determine how many bytes must be read to execute each instruction. Many instructions require two or three bytes. Figure 4.8 shows the arrangement of the bytes in an instruction. The first byte contains the op code. The second byte contains address information, usually the low or least significant byte of the address.

Program Counter

Each successive read of a memory location causes the program counter to be incremented to the address of the next byte.

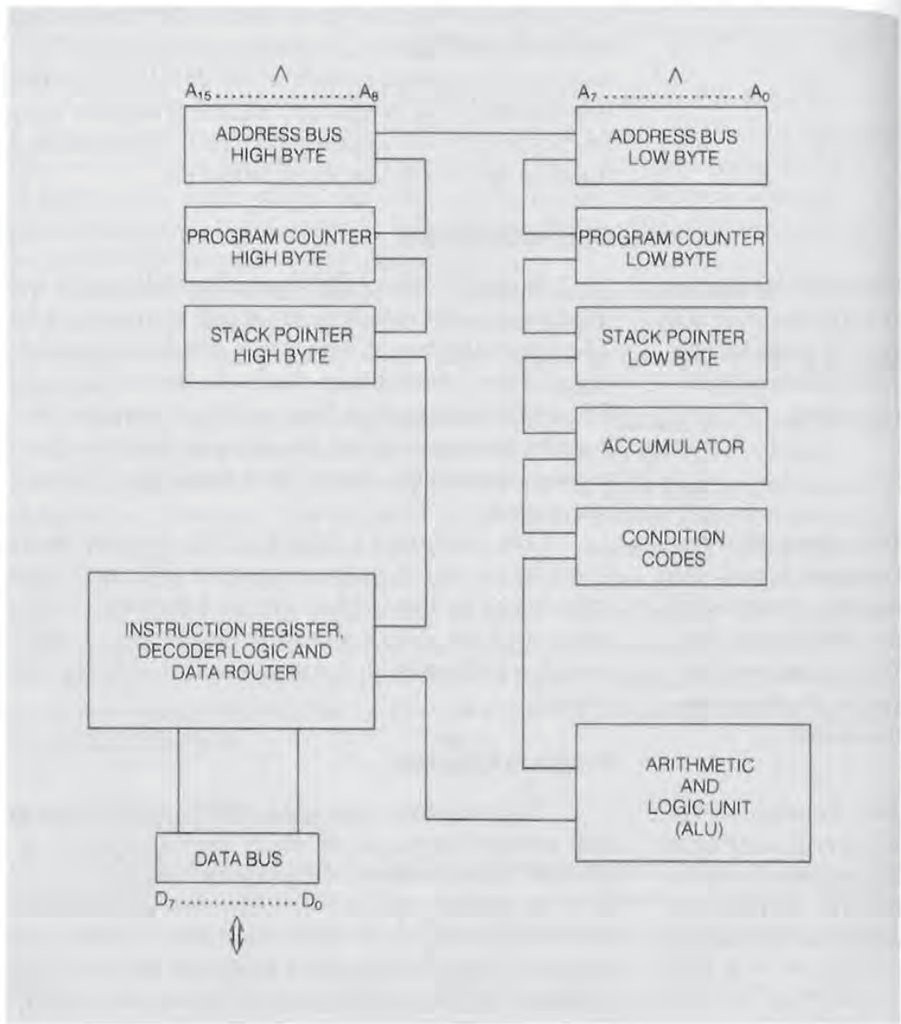
The program counter is used by the CPU to address memory locations that contain instructions. Every time an op code is read (this is often called *fetched*) from memory, the program counter is incremented (advanced by one) so that it points to (i.e., contains the address of) the next byte following the op code. If the operation code requires another byte, the program counter supplies the address, the second byte is fetched from memory, and the program counter is incremented. Each time the CPU performs a fetch operation, the program counter is incremented; thus, the program counter always points to the next byte in the program. Therefore, after all bytes required for one complete instruction have been read, the program counter contains the address for the beginning of the next instruction to be executed.

Branch Instruction

All of the branch instructions require two bytes. The first byte holds the operation code, and the second byte holds the location to which the processor is to branch.

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Figure 4.7
CPU Organization

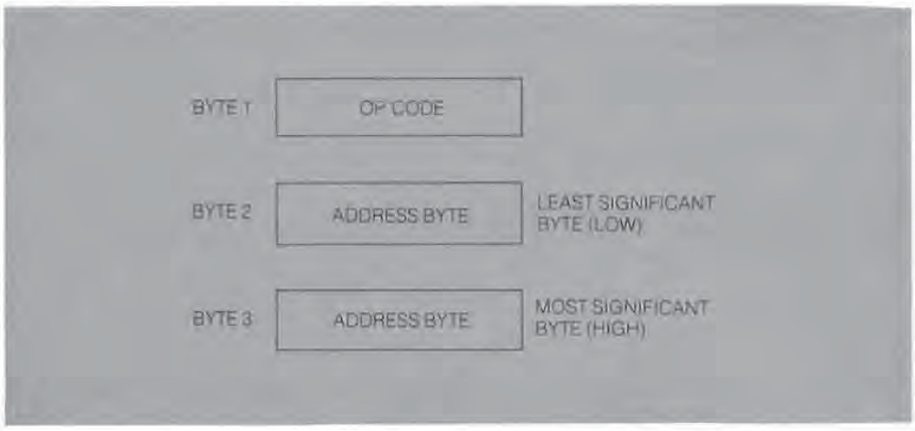


A positive branch offset address results in a branch to a higher memory location, while a negative branch offset address results in a branch to a lower memory location.

Now, if the address information associated with a branch instruction is only 8 bits long and totally contained in the second byte, it cannot be the actual branch address. In this case, the code contained in the second byte is actually a two's complement number that the CPU adds to the lower byte of the program counter to determine the actual new address. This number in the second byte of the branch instruction is called an *address offset* or just *offset*. Recall that in two's complement notation, the 8-bit number can be either positive or negative; therefore, the branch address offset can be positive or negative. A positive branch offset causes a branch forward to a higher memory location. A negative branch offset causes a branch to a lower memory location. Since 8 bits are used

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Figure 4.8
Instruction Byte Arrangement



in the present example, the largest forward branch is 127 memory locations and the largest backward branch is 128 memory locations.

Offset Example

Suppose the program counter is at address 5,122 and the instruction at this location is a branch instruction. The instruction to which the branch is to be made is located at memory address 5,218. Since the second byte of the branch instruction is only 8 bits wide, the actual address 5,218 cannot be contained therein. Therefore, the difference or offset (96) between the current program counter value (5,122) and the desired new address (5,218) is contained in the second byte of the branch instruction. The offset value (96) is added to the address in the program counter (5,122) to obtain the new address (5,218), which is then placed on the address bus. The binary computation of the final address from the program counter value and second byte of the branch instruction is shown in Figure 4.9

Jump Instruction

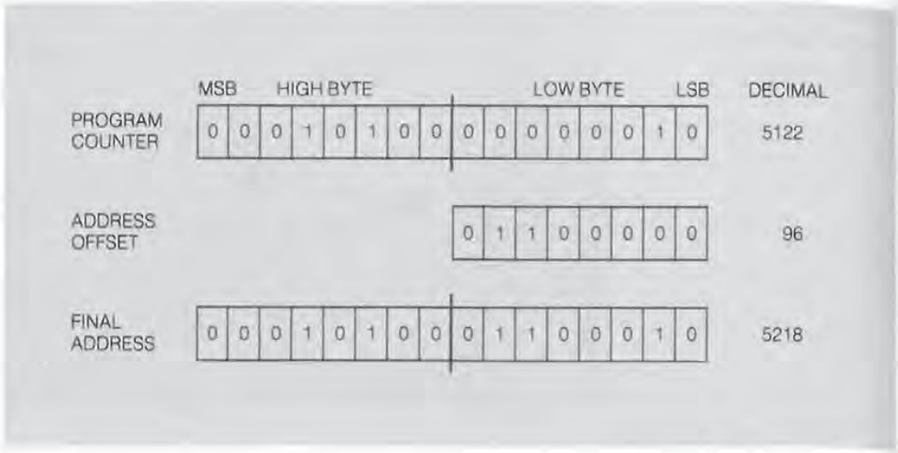
8-bit branch operations are limited to an offset range of +127 or –128 memory locations. Thus, program branches to locations farther away must use jump instructions. These 3-byte instructions contain the entire memory address.

Branch instructions have a range of +127 or –128 (in the present 8-bit example). If the branch needs to go beyond this range, a jump instruction must be used. The jump instruction is a 3-byte instruction. The first byte is the jump op code, and the next two bytes are the actual jump address. The CPU loads the jump address directly into the program counter, and the program counter effectively gets restarted at the new jump location. The CPU continues to fetch and execute instructions in exactly the same way it did before the jump was made.

The jump instruction causes the CPU to jump out of one section of the program into another. The CPU cannot automatically return to the first section because no record was kept of the previous location. However, another instruction, the jump-to-subroutine, does leave a record of the previous instruction address.

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Figure 4.9
Binary Computation of Branch Address



Jump-to-Subroutine Instruction

Subroutines are short programs used to perform specific tasks, particularly those tasks that must be performed several times within the same program.

A *subroutine* is a short program that is used by the main program to perform a specific function. It is located in sequential memory locations separated from the main program sequence. If the main program requires some function such as addition several times at widely separated places within the program, the programmer can write one subroutine to perform the addition, then have the main program jump to the memory locations containing the subroutine each time it is needed. This saves having to rewrite the addition program over and over again. To perform the addition, the programmer simply includes instructions in the main program that first load the numbers to be added into the data memory locations used by the subroutine and then jump to the subroutine.

The second and third bytes of a jump-to-subroutine instruction provide the address of the subroutine to be jumped to.

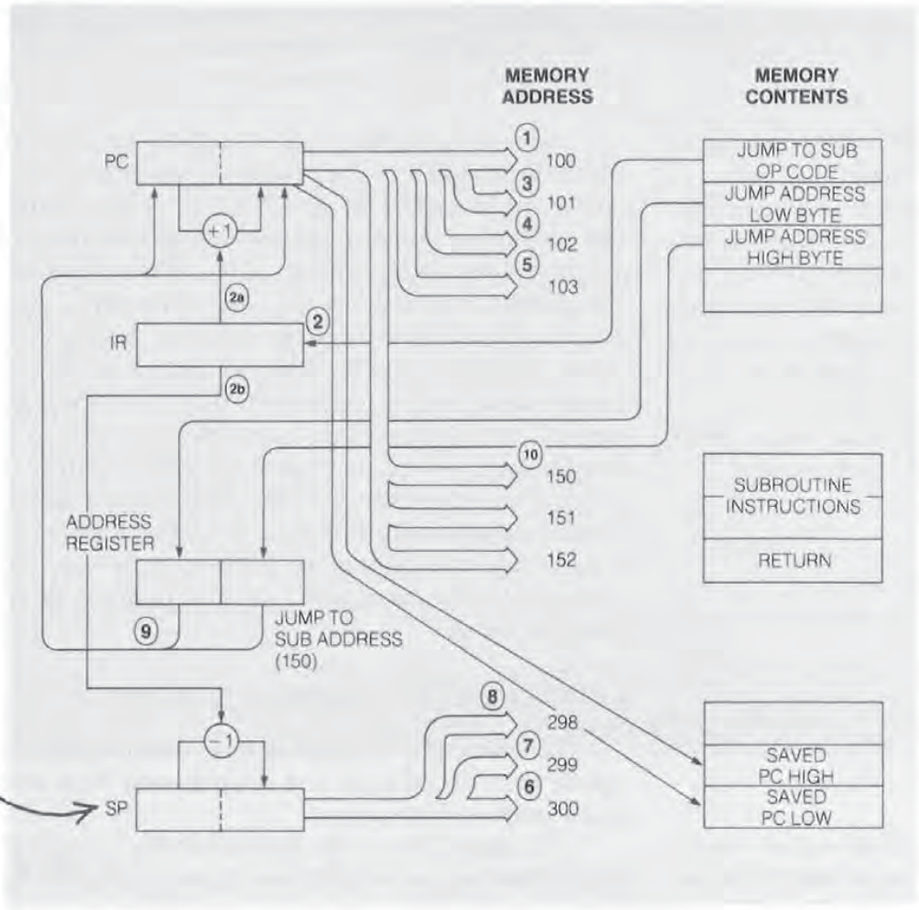
Refer to Figure 4.10 to follow the sequence. It begins with the program counter pointing to address location 100, where it gets the jump-to-subroutine instruction (step 1). Each jump-to-subroutine instruction (step 2) requires that the next two bytes must also be read to obtain the jump address (step 2a). Therefore, the program counter is incremented once for each byte (steps 3 and 4) and the jump address is loaded into the address register. The program counter is then incremented once more so that it points to the op-code byte of the next instruction (step 5).

Saving the Program Counter

The contents of the program counter are saved by storing them in a special memory location before the jump address is loaded into the program counter. This program counter address is saved so that it can be returned to in the main program when the subroutine is finished. This is the record that was mentioned before.

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Figure 4.10
Jump-to-Subroutine



For a jump-to-subroutine, the contents of the program counter (after being incremented) are stored in two memory locations pointed to by the stack pointer. After storing them, the stack pointer value is decreased by one to prepare it for the next store.

Now refer back to Figure 4.4. There is a register in Figure 4.4 called the stack pointer (SP). The address of the special memory location used to store the program counter content is kept in this 16-bit stack pointer register. When a jump-to-subroutine op code is encountered, the CPU uses the number code contained in the stack pointer as a memory address to store the program counter to memory (step 2b of Figure 4.10). The program counter is a 2-byte register, so it must be stored in two memory locations. The current stack pointer is used as an address to store the lower byte of the program counter to memory (step 6). Then the stack pointer is decremented (decreased by one) and the high byte of the program counter is stored in the next lower memory location (step 7). The stack pointer is then decremented again to point to the next unused byte in the stack to prepare for storing the program counter again when required (step 8).

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The special memory locations pointed to by the stack pointer are called stacks; if one considers memory locations as being slots stacked one atop the other, it makes sense to think of the stack pointer stacking data like plates on a shelf.

When the subroutine is completed, a return instruction retrieves the saved program counter value from the stack pointer and loads it into the program counter. Execution of the main program then resumes from the point at which the jump occurred.

After the program counter has been incremented and saved, the jump address is loaded into the program counter (step 9). The jump to the subroutine is made, and the CPU starts running the subroutine (step 10). The only thing that distinguishes the subroutine from another part of the program is the way in which it ends. When a subroutine has run to completion, it must allow the CPU to return to the point in the main program from which the jump occurred. In this way, the main program can continue without missing a step. The return-from-subroutine (RTS) instruction is used to accomplish this. It is decoded by the instruction register, and increments the stack pointer as shown in Figure 4.11, step 1. It uses the stack pointer to address the stack memory to retrieve the old program counter value from the stack (steps 2 and 4). The old program counter value is loaded into the program counter register (steps 3 and 5), and execution resumes in the main program (step 6). The return-from-subroutine instruction works like the jump-to-subroutine instruction, except in reverse.

EXAMPLE USE OF A MICROCOMPUTER

Let's look at an example of how a microcomputer might be used to replace some digital logic, and along the way learn about some more microcomputer instructions.

Microcomputers can be used in place of discrete logic circuits such as AND gates.

The digital logic to be replaced in this example is a simple AND gate circuit. Now, no one would use a microcomputer to replace only an AND gate, because an AND gate costs a fraction of what a microcomputer costs. However, if the system already has a microcomputer in it, the cost of the AND gate could be eliminated by performing the logical AND function in the computer rather than with the gate. This is a perfectly legitimate application for a microcomputer and is something that microcomputers do very well. Moreover, this example well illustrates the use of a microcomputer.

Suppose there are two signals that must be ANDed together to produce a third signal. One of the input signals comes from a pressure switch located under the driver's seat of an automobile; its purpose is to indicate whether someone is occupying the seat. This signal will be called A, and it is at logical high when someone is sitting in the seat. Signal B is developed within a circuit contained in the seat belt and is at logical high when the driver's seat belt is fastened. The output of the AND gate is signal C. It will be at logical high when someone is sitting in the driver's seat *and* has the seat belt fastened.

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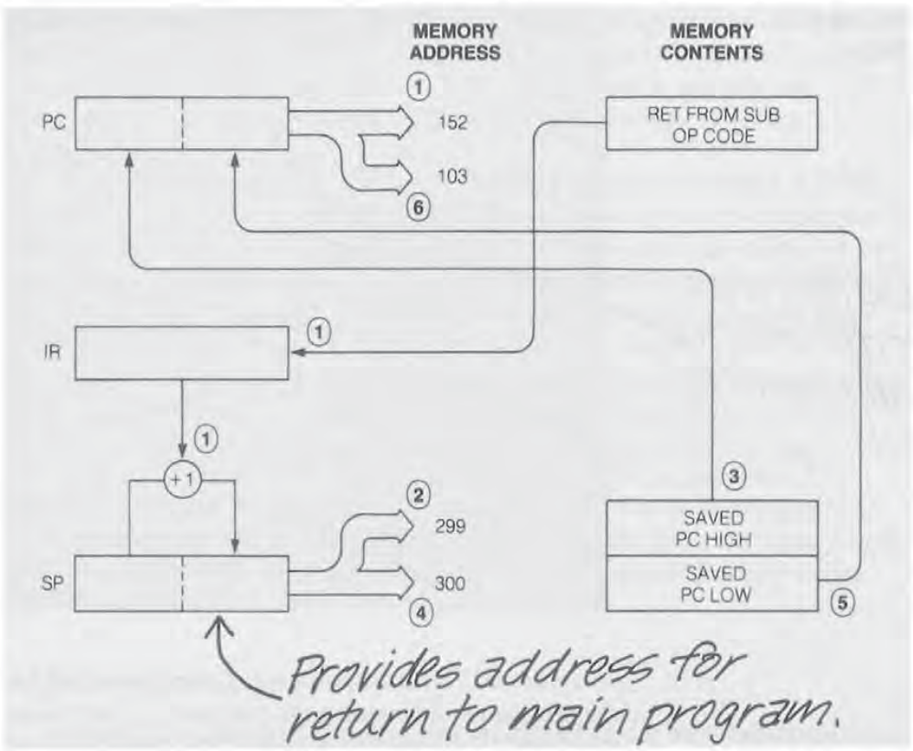


Figure 4.11 Return-from-Subroutine

Buffer

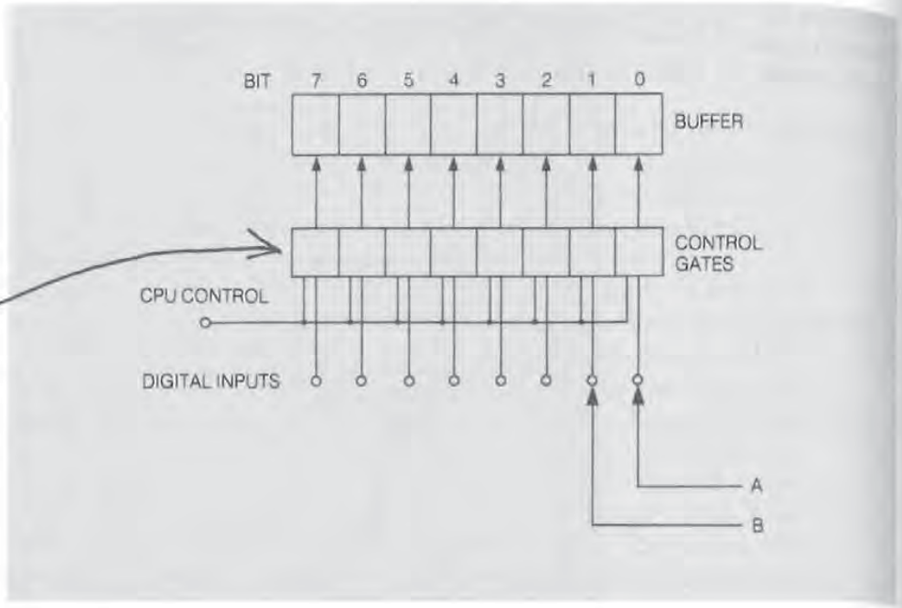
Buffers provide temporary storage for peripheral inputs and let the microcomputer treat peripherals, such as sensors, as if they were memory locations.

In order to use a microcomputer to replace the AND gate, the computer must be able to detect the status of each signal. Remember that the computer knows only what is stored in its memory. The microcomputer used here has memory-mapped I/O, in which peripherals are treated exactly like memory locations. The task is to provide a peripheral that allows the computer to look at the switch signals as if they were bits in a memory location. This can be done easily by using a device called a *buffer* (Figure 4.12). To the microcomputer, a buffer looks just like an 8-bit memory slot at a selected memory location. The 8 bits in the memory slot correspond to 8 digital signal inputs to the buffer. Each digital input controls the state of a single bit in the memory slot. The digital inputs are gated into the buffer under control of the CPU. The microcomputer can detect the state of the digital inputs by examining the bits in the buffer any time after the inputs are gated into the buffer.

In this application, signal A will be assigned to the rightmost bit (bit 0) and signal B to the next bit (bit 1). It doesn't matter that the other 6 bits are left

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Figure 4.12
Buffer



Gates input information into buffer.

unconnected. The computer will gate in and read the state of those lines, but the program will be written to purposely ignore them. With the logic signals interfaced to the microcomputer, a program can be written that will perform the required logic function.

However, before writing a program, one must know the code or language in which the program is to be written. Computer languages come in various levels, including high-level language such as BASIC, assembly language that is designed for a specific microprocessor, and machine language, which is the actual language in which a program is stored in memory. For the present example, we choose the intermediate-level language (assembly language) to illustrate specific CPU operations.

Assembly Language

Microcomputer instructions are written in assembly language, a type of shorthand that uses initials or shortened words to represent microcomputer instructions.

Assembly language is a special type of abbreviated language, each symbol of which pertains to a specific microprocessor operation. Some assembly language instructions, such as branch, jump, jump-to-subroutine, and return-from-subroutine, have already been discussed. Others will be discussed as they are needed to execute an example program. Assembly language instructions have the form of initials or shortened words that represent microcomputer functions. These

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abbreviations are only for the convenience of the programmer because the program that the microcomputer eventually runs must be in the form of binary numbers. When each instruction is converted to the binary code that the microcomputer recognizes, it is called a machine language program.

Once the program has been written in assembly language, a special kind of program, called an assembler, converts the assembly language program into the binary code recognized by the microcomputer.

The assembly language abbreviation for the jump instruction is JMP. Table 4.1 shows the assembly language equivalents for typical microcomputer instructions, along with a detailed description of the operation called for by the instruction. When writing a microcomputer program, it is easier and faster to use the abbreviated name rather than the complete function name. Assembly language simplifies programming tasks for the computer programmer because the abbreviations are easier to remember and write than the binary numbers the computer uses. However, the program eventually must be converted to the binary codes that the microcomputer recognizes as instructions, which is done by a special program called an *assembler*. The assembler program is run on the computer to convert assembly language to binary codes. This enables the programmer to write the program using words that have meaning to the programmer and also to produce machine codes that the computer can use.

Logic Functions

A microcomputer can AND the contents of its accumulator with a memory location to perform the logical AND function.

Microprocessors are capable of performing all of the basic logic functions such as AND, OR, NOT, and combinations of these. For instance, the NOT operation affects the accumulator by changing all ones to zeros and zeros to ones. Other logic functions are performed by using the contents of the accumulator and some memory location. All eight bits of the accumulator are affected, and all are changed at the same time. As shown in Figure 4.13, the AND operation requires two inputs. One input is the contents of the accumulator, and the other input is the contents of a memory location; thus, the eight accumulator bits are ANDed with the eight memory bits. The AND operation is performed on a bit-by-bit basis. For instance, bit 0 of the accumulator (the rightmost bit) is ANDed with bit 0 of the memory location, bit 1 with bit 1, bit 2 with bit 2, and so on. In other words, the AND operation is performed as if eight AND gates were connected with one input to a bit in the accumulator, and with the other input to a bit (in the same position) in the memory location. The resulting AND outputs are stored back into the accumulator in the corresponding bit positions. The OR logic function is performed in exactly the same way as the AND except that a 1 would be produced at the output if signal A or signal B were a 1, or if both were a 1 (i.e., using OR logic).

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Table 4.1 Assembly Language Mnemonics

Mnemonic	Operand	Comment
JMP	(Address)	Jump to new program location
JSR	(Address)	Jump to a subroutine
BRA	(Offset)	Branch using the offset
BEQ	(Offset)	Branch if accumulator is zero
BNE	(Offset)	Branch if accumulator is nonzero
BCC	(Offset)	Branch if carry bit is zero
BCS	(Offset)	Branch if carry bit is nonzero
BPL	(Offset)	Branch if minus bit is zero
BMI	(Offset)	Branch if minus bit is nonzero
RTS		Return from a subroutine

a. Program Transfer Instructions

Mnemonic	Operand	Comment
LDA	(Address)	Load accumulator from memory
STA	(Address)	Store accumulator to memory
LDA	# (Constant)	Load accumulator with constant
LDS	# (Constant)	Load stack pointer with constant
STS	(Address)	Store stack pointer to memory

b. Data Transfer Instructions

Mnemonic	Operand	Comment
COM		Complement accumulator (NOT)
AND	(Address)	AND accumulator with memory
OR	(Address)	OR accumulator with memory
ADD	(Address)	Add accumulator with memory
SUB	(Address)	Subtract accumulator with memory
AND	# (Constant)	AND accumulator with constant
OR	# (Constant)	OR accumulator with constant
SLL		Shift accumulator left logical
SRL		Shift accumulator right logical
ROL		Rotate accumulator left
ROR		Rotate accumulator right

c. Arithmetic and Logical Operations

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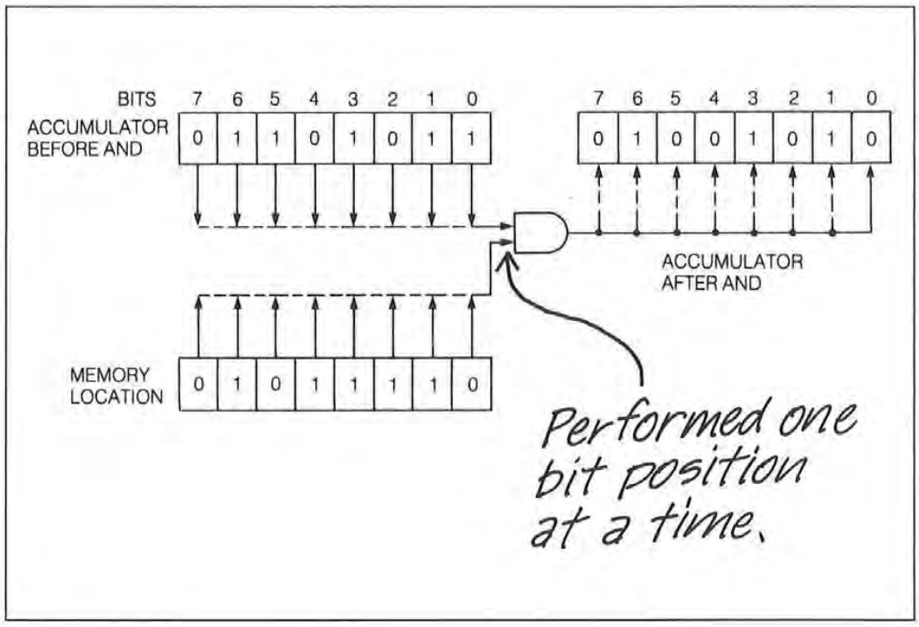


Figure 4.13 Microcomputer Logical AND Function

Shift

Using a logical operation known as a shift, a microcomputer can shift all the bits present in the accumulator to the left or right.

Instead of the AND gate inputs being switched to each bit position as shown in Figure 4.13, the microcomputer uses a special type of sequential logic operation, the shift, to move the bits to the AND gate inputs. A shift operation causes every bit in the accumulator to be shifted one bit position either to the right or to the left. It can be what is called a logical shift or it can be a circulating shift. Figure 4.14 shows the four types of shift (logical, circulating, right, left) and their effects on the accumulator. In a left shift, bit 7 (the leftmost bit) is shifted into the carry bit of the CC register, bit 6 is shifted into bit 7, and so on until each bit has been shifted once to the left. Bit 0 (the rightmost bit) can be replaced either by the carry bit or by a zero, depending on the type of shift performed. Depending on the microprocessor, it is possible to shift other registers as well as the accumulator.

Programming the AND Function

It is the task of the programmer to choose instructions and organize them in such a way that the computer performs the desired tasks. To program the AND function, one of the instructions will be the AND, which stands for "AND accumulator with contents of a specific memory location," as shown in

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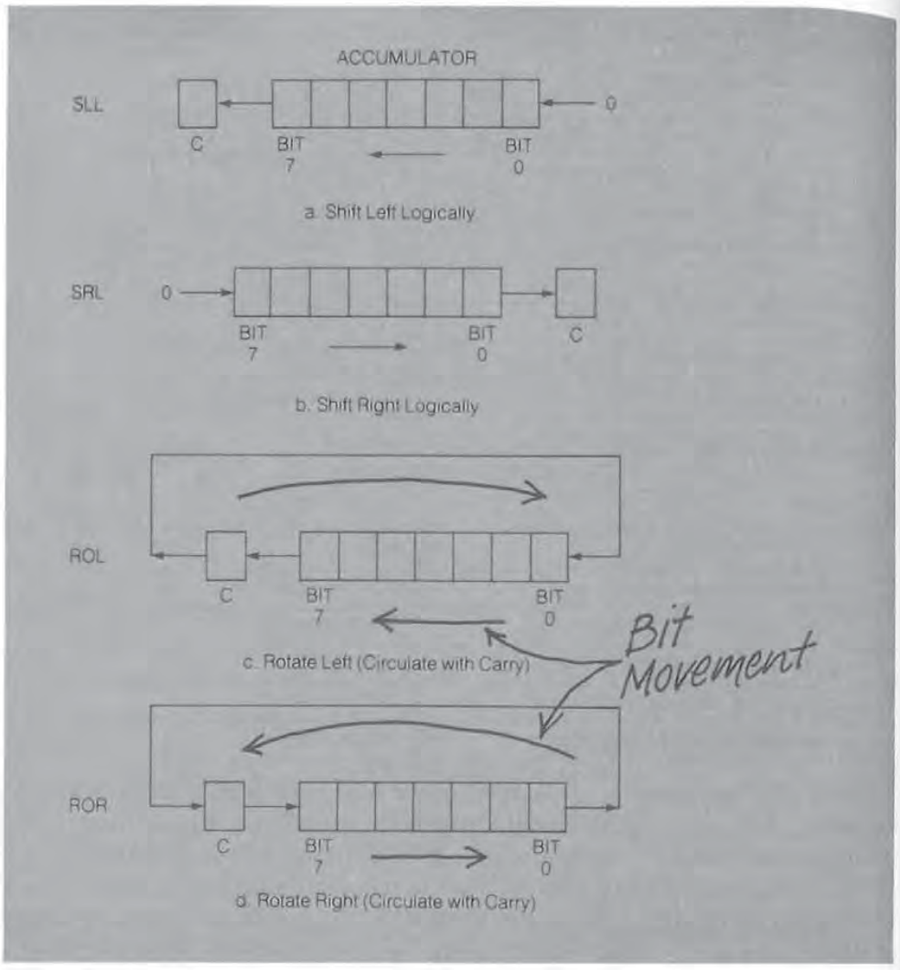


Figure 4.14 Types of Shift Operations

Table 4.1c. Since the AND affects the accumulator and memory, values must be put into the accumulator to be ANDed. This requires the load accumulator instruction, LDA.

The programmer often uses special names (labels) to refer to specific memory locations.

The assembly language program of Figure 4.15 performs the required AND function. The programmer must first know which memory location the digital buffer interface (Figure 4.12) occupies. This location is identified, and the programmer writes instructions in the assembler program so that the buffer memory location will be referred to by the label or name SEAT. SEAT is easier for the programmer to remember and write than the address of the buffer.

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Figure 4.15 Assembly Language Subroutines

Program Label	Mnemonic	Operand
1 CHECK	LDA	SEAT
2	AND	#00000001 B
3	SLL	
4	AND	SEAT
5	RTS	

a. Subroutine CHECK

Program Label	Mnemonic	Operand
1 WAIT	JRS	CHECK
2	BEQ	WAIT
3	RTS	

b. Subroutine WAIT

The use of a mask allows the microcomputer to separately examine two or more digital signals (bits) occupying the same 8-bit byte.

The operation of the program is as follows. The accumulator is loaded with the contents of the memory location SEAT. Note in Figure 4.12 that the two digital logic input signals, A and B, have been gated into bits 0 and 1, respectively, of the buffer that occupies the memory location labeled SEAT. Bit 0 is high when someone is sitting in the driver's seat. Bit 1 is high when the driver's seat belt is fastened. Only these two bits are to be ANDed together; the other six are to be ignored. But there is a problem because both bits are in the same 8-bit byte and there is no single instruction to AND bits in the same byte. However, the two bits can be effectively separated by using a mask.

Masking

During a mask operation, the accumulator contents are ANDed with the mask value, which has a zero in each bit location except for the bit(s) to be saved. The saved, or masked, bit(s) comes through unchanged, but all others are set to zero.

Masking is a technique used to allow only selected bits to be involved in a desired operation. Since the buffer contents have been loaded into the accumulator, only bits 0 and 1 have meaning, and these two bits are the only ones of importance that are to be kept in the accumulator. To do this, the accumulator is ANDed with a constant that has a zero in every bit location except the one that is to be saved. The binary constant in line 2 of Figure 4.15a (00000001) is chosen to select bit 0 and set all others to zero as the AND instruction is executed. The ANDing procedure is called *masking* because a mask has been placed over the accumulator that allows only bit 0 to come through unchanged. If bit 0 was a logical 1, it is still a logical 1 after masking. If bit 0 was a logical 0, it is still a logical 0. All other bits in the accumulator now contain the correct bit information about bit 0.

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Shift and AND

During the final part of the AND operation, the shift left logically instruction is used to align the bits of signal A with the correct bits in signal B so the logical AND can be accomplished.

In our example program, the accumulator is still not ready to perform the final AND operation. Remember that SEAT contains the contents of the buffer and the conditions of signal A and signal B. The contents of the accumulator must be ANDed with SEAT so that signals A and B are ANDed together. A copy of signal A is held in the accumulator in bit 0, but it is in the wrong bit position to be ANDed with signal B in SEAT in the bit 1 position. Therefore, signal A must be shifted into the bit 1 position. To do this the shift left logically instruction is used (Figure 4.14a). With signal A in bit 1 of the accumulator and signal B in bit 1 of SEAT, the AND operation can be performed on the two bits. If both A and B are high, the AND operation will leave bit 1 of the accumulator high (1). If either is low, bit 1 of the accumulator will be low (0).

Use of Subroutines

The previous example program has been written as a subroutine named CHECK so that it can be used at many different places in a larger program. For instance, if the computer is controlling the speed of the automobile, it might be desirable to be able to detect whether a driver is properly fastened in the seat before it sets the speed at 55 miles per hour.

Since the driver's seat information is very important, the main program must wait until the driver is ready before allowing anything else to happen. A program such as that shown in Figure 4.15b can be used to do this. The main program calls the subroutine WAIT, which in turn immediately calls the subroutine CHECK. CHECK returns to WAIT with the condition codes set as they were after the last AND instruction. The Z bit (see Figure 4.5a) is set if A and B are not both high (the accumulator is zero). The BEQ instruction (see Table 4.1) in line 2 of WAIT branches back because the accumulator is zero and causes the computer to reexecute the JSR instruction in line 1 of WAIT. This effectively holds the computer in a loop rechecking signals A and B until the accumulator has a nonzero value (A and B are high).

Timing Error

The time required for the microcomputer to sample sensor inputs and perform its instructions must be taken into account during program design; otherwise, timing errors may result.

A flaw in the subroutine CHECK could cause it to incorrectly perform the AND function. Notice that the logic states of A and B are sampled at different times. Signal A is first read in and masked off, then signal A and B are ANDed together. There is a possibility that during the interval between the time A is read and the time A and B are ANDed, the state of A could change. A computer is fast, but it still takes a certain amount of time for the microprocessor to execute the program instructions. For the driver's seat application, the signals have a long time between change so the time lag is not critical. However, in systems in which the timing of signals is very tight, the program would have to be rewritten to remove the lag. Even after correcting

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such a lag, there may be applications where variables change more rapidly than the sampling time. Special compromises must be made in such cases, or a new technique must be found to solve the problem.

MICROCOMPUTER HARDWARE

The microcomputer system electronic components are known as computer hardware. (The programs that the computer runs are called software.) The basic microcomputer parts are the CPU, memory, and I/O (input and output peripherals). We next expand upon this discussion of important components and their associated operations.

Central Processing Unit

The central processing unit is a microprocessor. It is an integrated circuit similar to the one shown in Figure 4.16a. It contains thousands of transistors and diodes on a chip of silicon small enough to fit on the tip of a finger. It includes some form of arithmetic logic unit (ALU), as well as registers for data and instruction storage and a control section. The chip is housed in a rectangular, flat package similar to the one shown in Figure 4.16b. It is less than three inches long and has two rows of small pins that make connections to external circuits. The CPU gets program instructions from a memory device.

Memory: ROM

Permanent memory, called *ROM,* maintains its contents even when power is turned off. ROM is used for CPU instructions requiring permanent storage.

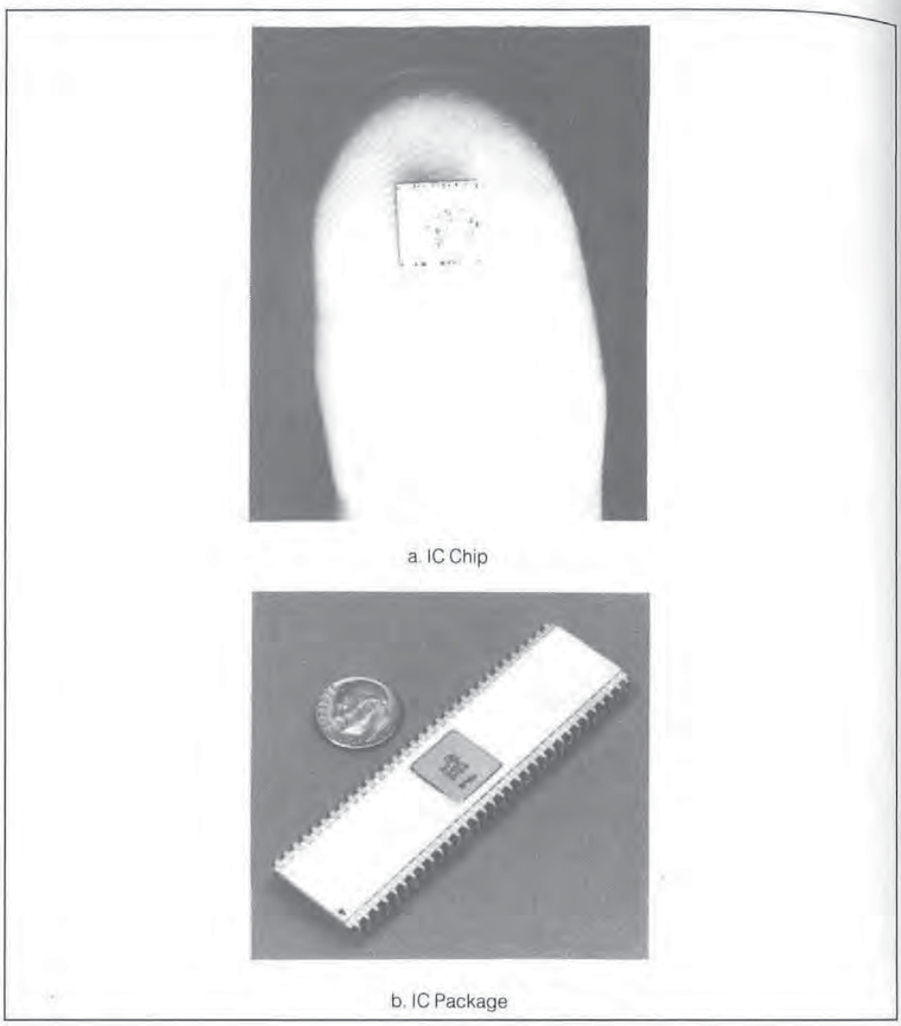
There are several types of memory devices available, and each has its own special features. Systems such as those found in the automobile that must permanently store their programs use a type of permanent memory called *read-only memory* (ROM). This type of memory can be programmed only one time and the program is stored permanently, even when the microcomputer power is turned off. The programs stored in ROM are sometimes called *firmware* rather than software since they are unchangeable. This type of memory enables the microcomputer to immediately begin running its program as soon as it is turned on.

Memory: RAM

A form of memory that can be written to and changed, as well as read from, is commonly referred to as *RAM.*

Another type of memory, one that can be written to as well as read from, is required for the program stack, data storage, and program variables. This type of memory is called *random access memory* (RAM). This is really not a good name to distinguish this type of memory from ROM because ROM is also a random access type of memory. Random access means the memory locations can be accessed in any order rather than in a particular sequence. A better name for the data storage memory would be read/write memory (RWM). However, the term RAM is commonly used to indicate a read/write memory, so that is what will be used here. A typical microcomputer contains both ROM and RAM type memory.

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a. IC Chip

b. IC Package

Figure 4.16
Integrated Circuit Chip Microprocessor

I/O Parallel Interface

Microcomputers require interface devices that enable them to communicate with other systems. The digital buffer interface used in the driver's seat application discussed earlier is one such device. The digital buffer interface is an example of a parallel interface because the eight buffer lines are all sampled at one time, that is, in parallel. The parallel buffer interface in the driver's seat application is an input, or readable, interface. Output, or writable, interfaces allow the microcomputer to affect external logic systems. An output buffer must be implemented using a data latch so that the binary output is

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retained after the microcomputer has finished writing data into it. This permits the CPU to go on to other tasks while the external system reads and uses the output data. This is different from the parallel input, in which the states could change between samples.

Digital-to-Analog Converter

A DAC converts binary signals from the microcomputer to analog voltages that are proportional to the number encoded in the input signals.

The parallel input and output interfaces are used to examine and control external digital signals. The microcomputer can also be used to examine and control analog signals through the use of special interfaces. The microcomputer can produce an analog voltage by using a digital-to-analog converter (DAC). A DAC accepts inputs of a certain number of binary bits and produces an output voltage level that is proportional to the input number. DACs come in many different versions with different numbers of input bits and output ranges. A common microcomputer DAC has 8-bit inputs and a 0 to 5 volt output range.

A simple 8-bit DAC is shown in Figure 4.17. This type of DAC uses a parallel input interface and two operational amplifiers. The 8 bits are written into the parallel interface and stored in data latches. The output of each latch is a digital signal that is 0 volts if the bit is low and 5 volts if the bit is high. The first op amp is a summing amplifier and has a gain of $-(R_f/R_i)$. The second op amp has a gain of -1; thus, it is only an inverter. The effect of the two amplifiers is to scale each bit of the parallel interface by a specially chosen factor and add the resultant voltages together. For instance, if only bit 0 is high and all the others are low,

$$V_{out} = 5\left[1\left(\frac{1}{256}\right) + 0\left(\frac{1}{128}\right) + 0\left(\frac{1}{64}\right) + \cdots + 0\left(\frac{1}{2}\right)\right]$$

$$= \left(\frac{5}{256}\right)$$

$$= 0.0195 \text{ V}$$

If only bits 0 and 7 are high:

$$V_{out} = 5\left[1\left(\frac{1}{256}\right) + 0\left(\frac{1}{128}\right) + 0\left(\frac{1}{64}\right) + \cdots + 1\left(\frac{1}{2}\right)\right]$$

$$= \left(\frac{645}{256}\right)$$

$$= 2.5195 \text{ V}$$

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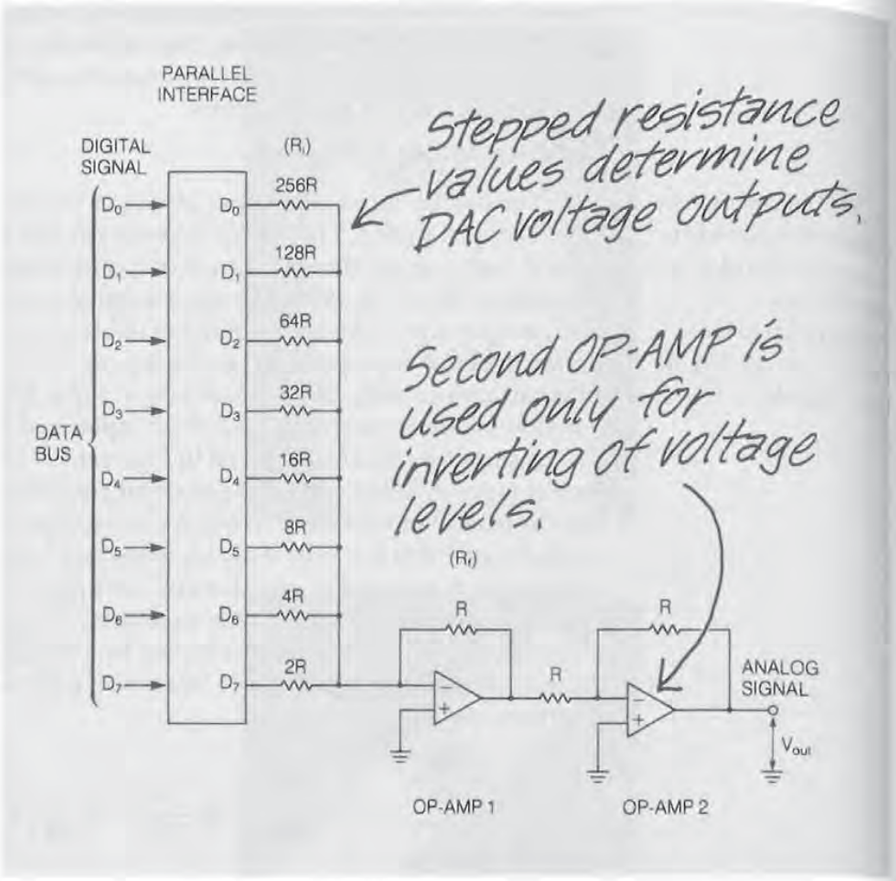


Figure 4.17 Digital-to-Analog Converter Circuit Block

The DAC output voltage can only change in discrete steps. This causes the analog output voltage to have a staircase appearance as the binary number at the input is increased one bit at a time from minimum value to maximum value, as shown in Figure 4.18. This DAC can have any one of 256 different voltage levels. For many applications, this is a close enough approximation to a continuous analog signal.

The accuracy of the DAC's representation of the digital input signal varies with circuit design, and with the rate at which the input signal is sampled.

The DAC output voltage can change only when the computer writes a new number into the DAC data latches. The computer must generate each new output often enough to ensure an accurate representation of the changes in the digital signal. The analog output of the DAC can take only a specific number of different values and can change only at specific times determined by the sampling rate. The output of the converter will always have small discrete step changes (resolution). The designer must decide how small the steps must be to

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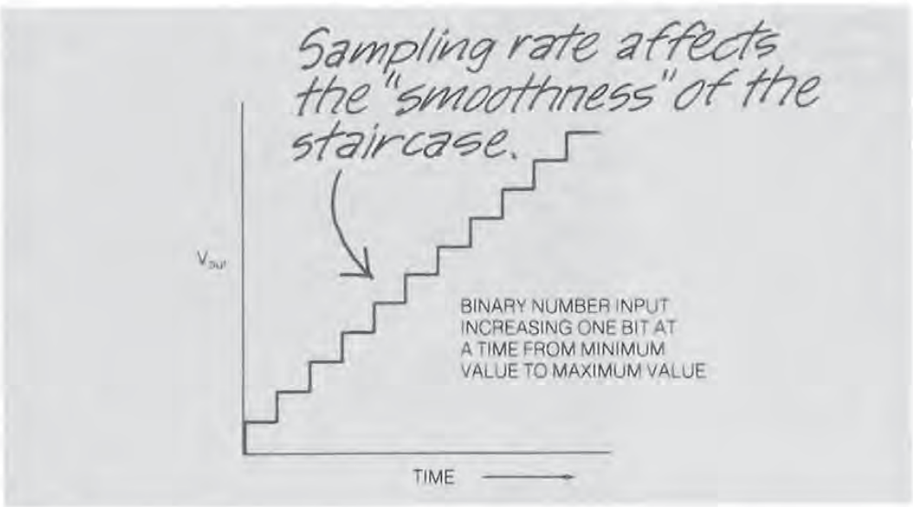


Figure 4.18 Staircase Output Voltage of the DAC in Figure 4.17

produce the desired shape and smoothness in the analog signal so that it is a reasonable duplication of the variations in the digital levels.

Analog-to-Digital Converter

In addition, microcomputers can measure analog voltages by using a special interface component called an analog-to-digital converter (ADC). Analog-to-digital converters convert an analog voltage input into a digital number output that the microcomputer can read.

The ADC performs a function opposite of the DAC: It converts an analog signal into digital form for processing by the microcomputer.

Figure 4.19 shows a conceptually simple, but not very practical, way of making an ADC by using a DAC and a voltage comparator. The input to the DAC is a binary number generated by the microcomputer that starts at the minimum value and increases toward the maximum value, as seen in Figure 4.18. This binary number is generated at the parallel output of the microcomputer. The output of the DAC, V_{out}, is one input to the comparator. The other input is the input voltage, V_{in}, that the ADC is measuring. When the V_{out} voltage of the DAC is less then V_{in}, the output of the comparator, V_{comp}, is a low logic level. When V_{out} is greater than V_{in}, the output of the comparator is a high level.

As soon as the binary number generated by the microcomputer causes V_{out} from the DAC to be greater than V_{in}, the comparator output goes high and stops the microcomputer from changing the binary number input further. The binary number is used by the microcomputer as the equivalent of the analog input voltage V_{in}. The microcomputer then resets and starts the binary number generation again to make another match to the V_{in} voltage. In this manner, a binary number, equivalent to a V_{in} and analog voltage, is produced at a selected

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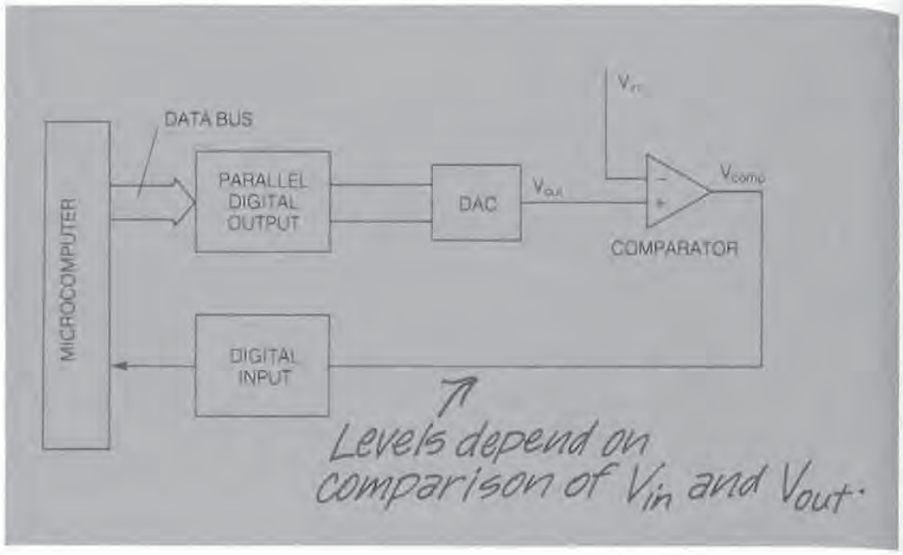


Figure 4.19 Analog-to-Digital Converter

sampling rate. The output of the comparator is fed back to the microcomputer through a digital input.

Sampling

The accuracy of the DAC increases as the rate of sampling of the input signal increases.

The designer determines how quickly the microcomputer must change the DAC voltage to accurately follow the analog signal. Figure 4.20 shows a sine wave analog signal and some digital approximations with various sampling rates. Notice that Figure 4.20a with 13 samples per sine wave cycle follows the sinusoid much closer then Figure 4.20b, which only samples twice in a cycle. When the sampling rate is less than 2, as in Figure 4.20c, the staircase output doesn't follow well at all. This is because the computer didn't change the DAC input often enough to produce an output signal that closely approximates the desired signal.

The input sampling theorem states that an input signal must be sampled at least twice per cycle to be minimally accurate.

An engineer named H. Nyquist studied the sampling rate problem and determined that in order to reproduce a sinusoidal signal properly, the signal must be sampled at least twice per cycle (the Nyquist sampling theorem). Of course, more samples per cycle is better, but two samples per cycle is the minimum required.

Polling

Analog-to-digital converters that perform everything by themselves are available. The microcomputer simply tells them when to make a conversion and then waits until the conversion is done. ADCs require anywhere from a few millionths of a second to a second to complete the conversion.

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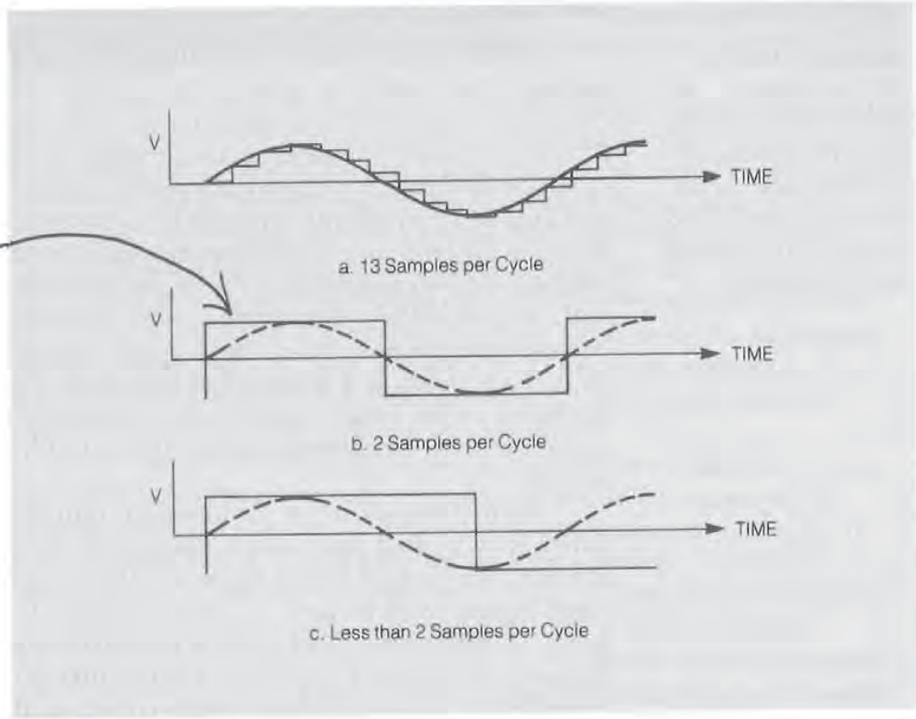


Figure 4.20 Analog Output Voltage versus Sampling Rate

Minimum to produce signal accurately.

Conversion time can be a serious limitation when slow converters are used. The microcomputer cannot afford to waste time waiting while the converter works. This is especially true when the microcomputer is used to control and monitor many systems at the same time. Instead of waiting for the ADC to finish, the computer could be off running another part of the program and come back only when the conversion is done. But how will the computer know when the conversion is finished?

Polling is used in some microcomputers to periodically check the ADC interface rather than waiting in an idle state for the ADC to do the conversion.

One way of doing this is for the microcomputer to periodically check the interface while it is running another part of the program. This method is called *polling*. A subroutine is included in the main program and is called up whenever an ADC interface is being used. This usually consists of a few lines of assembly language code that checks to see if the interface is done and collects the result when it is finished. When the polling subroutine determines that the ADC is finished, the main program continues without using the polling subroutine until the ADC interface is called up again. The problem with such a scheme is that the polling routine may be called many times before the interface is finished. This can waste the computer's time and slow it down. Therefore, an evaluation must be made in certain systems to determine if polling is worthwhile.

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Interrupts

Interrupts cause the CPU to jump to a specific location in the program. By signaling the microprocessor for service only when needed, interrupts are more efficient than polling.

An efficient alternative to polling uses control circuitry called an *interrupt.* An interrupt is an electrical signal that is generated outside of the CPU and is connected to an input on the CPU. The interrupt causes the CPU to temporarily discontinue the program execution and to perform some operation on data coming from an external device. A slow ADC, for instance, could use an interrupt line to tell the processor when it is finished converting. When an interrupt occurs, the processor automatically jumps to a designated program location and executes the interrupt service subroutine. For the ADC, this would be a subroutine to read in the conversion result. When the interrupt subroutine is done, the computer returns to the place where it left off in the program as if nothing had happened. (Recall the previous discussion on the jump-to-subroutine instruction.) Interrupts reduce the amount of time the computer spends dealing with the various peripheral devices.

Another important use for interrupts is in timekeeping. Suppose that a system is being used that requires things to be done at particular times; for instance, sampling an analog signal is a timed process. A special component called a timer could be used. A timer is a device that works like a digital watch. A square-wave clock signal is counted in counter registers like the one discussed in Chapter 3. The timer can be programmed to turn on the interrupt line when it reaches a certain count and then reset itself (start over). It may be inside the CPU itself or it may be contained in peripheral devices in the microcomputer system. Timers have many automotive applications (as shown later).

Such a technique is sometimes used to trigger the output of a new number to a DAC at regular intervals. The microcomputer simply programs the timer for the desired amount of time by presetting the counter to some starting value other than zero. Each time the timer counts out the programmed number of pulses, it interrupts the computer. The interrupt service subroutine then gets the new binary number that has been put into memory by the microcomputer and transfers this number to the DAC data latches at the input to the DAC.

Vectored Interrupts

All of the interrupt activity is completely invisible to the program that gets interrupted. In other words, the interrupted program doesn't know it was interrupted because its execution continues without program modification with minimum delay. Interrupts allow the computer to handle two or more things almost simultaneously. In some systems, one interrupt line may be used by more than one device. For instance, two or more ADCs may use the same interrupt line to indicate when either is ready. In this case, the computer doesn't know which device caused the interrupt. The computer could poll all

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the devices each time an interrupt occurs to see which one needs service, but as discussed, polling may waste time. A better way is to use vectored interrupts.

Vectored interrupts tell the CPU which specific device needs service, and also may implement a priority of service scheme. Vectored interrupts allow a microcomputer to handle a number of different tasks quickly.

In computer parlance, a *vector* is a memory location that contains another address that locates data or an instruction. It may be a specific memory location that contains the address of the first instruction of a subroutine to service an interrupt; it may be a register that contains the same type address. In this specific case, an interrupt vector is a register that peripherals use to tell the processor which device interrupted it. When a peripheral causes an interrupt, it writes a code into the interrupt vector register so that the processor can tell which device interrupted it by reading the code. The decoder for an interrupt vector usually includes circuitry that allows each device to be assigned a different interrupt priority. If two devices interrupt at the same time, the processor will service the most important one first.

The vectored interrupt enables the microcomputer to efficiently handle the peripheral devices connected to it and to service the interrupts rapidly. Interrupts allow the processor to respond to things happening in peripheral devices without having to constantly monitor the interfaces. They enable the microcomputer to handle many different tasks and to keep track of all of them. A microcomputer system designed to use interrupts is called a *real-time computing system* because it rapidly responds to peripherals as soon as requests occur. Such real-time systems are used in digital instrumentation and control systems.

MICROCOMPUTER APPLICATIONS IN AUTOMOTIVE SYSTEMS

There is a great variety of applications of microprocessors in automobiles. As will be explained in later chapters of this book, microprocessors find applications in engine and driveline control, instrumentation, ride control, antilock braking and other safety devices, entertainment, heating/air conditioning control, automatic seat position control, and many other systems. In each of these applications, the microprocessor serves as the functional core of what can properly be called a special-purpose microcomputer.

Although these applications are widely varied in operation, the essential configuration (or *architecture*) has much in common for all applications. Figure 4.21 is a simplified block diagram depicting the various components of each of the automotive systems having the applications listed previously. In this block diagram, the microprocessor is denoted MPU. It is connected to the other components by means of three buses: address bus (AB), data bus (DB), and control bus (CB). Each bus consists of a set of wires over which binary electrical signals are transmitted. By way of illustration, in early automotive application, the DB consists of 8 wires, the AB is typically 8 to 16 wires, and the control bus is a set of 3 or 4 wires.

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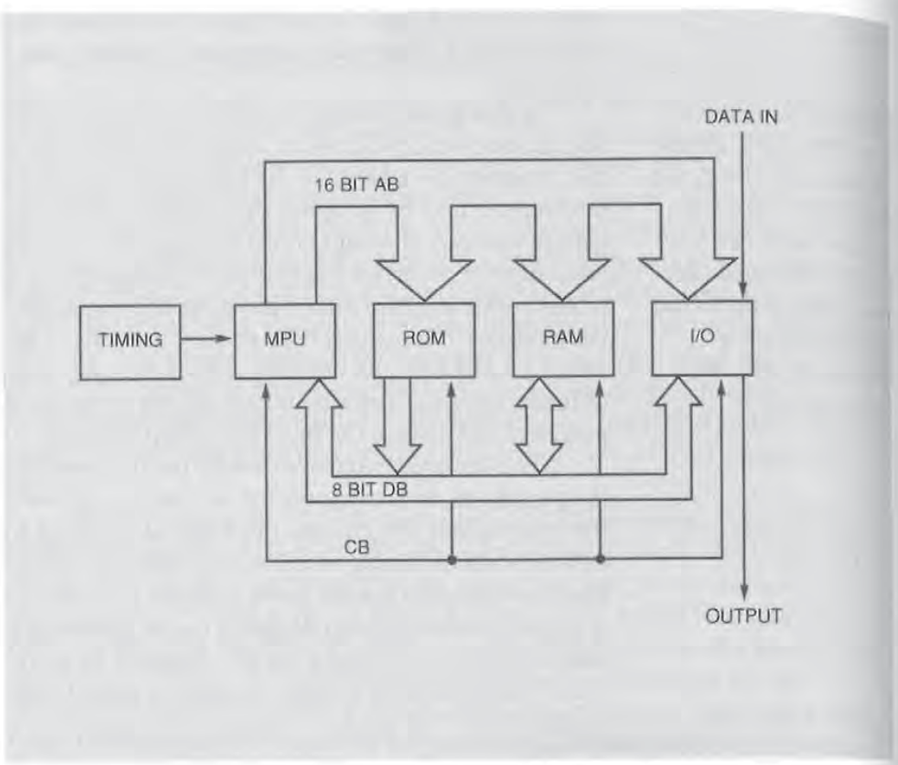


Figure 4.21 Architecture for Typical Automotive Computer

The hardware in the microcomputer remains fixed, while the programs stored in ROM can be changed as desired to perform different applications.

The operation of each special-purpose microcomputer system is controlled by a program stored in ROM. As explained earlier in this chapter, the MPU generates addresses for the ROM in sequence to obtain each instruction in corresponding sequence. The operation of each microprocessor-based automotive subsystem has a specific program that is permanently stored (electronically) in the ROM. Changes in the system operation can be achieved by replacing the ROM chip(s) with new chip(s) that contain the appropriate program for the desired operation. This feature is advantageous during the engineering development phase for any microprocessor-based system. While the hardware remains fixed, the system modifications and improvements are achieved by substituting ROM chips.

A typical automotive microprocessor-based system also incorporates some amount of RAM. This memory is used for a variety of purposes, including storing temporary results, storing the stack, and storing all of the variables, not to mention all of the other activities discussed earlier in this chapter.

The input/output (I/O) device for any given automotive microcomputer system serves as the interface connection of the microcomputer with the

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particular automotive system. Standard commercial I/O devices are available from the manufacturers of each microprocessor that are specifically configured to work with that processor. These I/O devices are implemented as an IC chip and are very versatile in application. A typical such I/O device has two 8-bit data ports for connecting to peripheral devices, and an 8-bit port that is connected to the data bus of the computer.

Figure 4.22 is a block diagram of a typical commercial I/O device. In this device there are two ports labeled A and B, respectively. These ports can be configured to act as either input or output, depending on the data in the data direction register. Normally the correct code for determining direction is transferred to the I/O device from the microprocessor via the system data bus.

Whenever the microprocessor is either to transfer data to the I/O device or receive data from it, a specific address is generated by the processor. This address is decoded, using standard logic, to form an electrical signal that activates the chip select inputs to the I/O. In addition, the read/write (R/W) output of the microprocessor is activated, causing data to be received (read) from a peripheral device, or transmitted (write) to a peripheral device.

This use of address lines to activate the I/O is known as *memory-mapped I/O.* In memory-mapped I/O, input or output of data is selected by reading from the I/O input address or writing to the I/O output address.

INSTRUMENTATION APPLICATIONS OF MICROCOMPUTERS

Microcomputers can convert the nonlinear output voltage of some sensors into a linear voltage representation. The sensor output voltage is used to look up the corresponding linear value stored in a table.

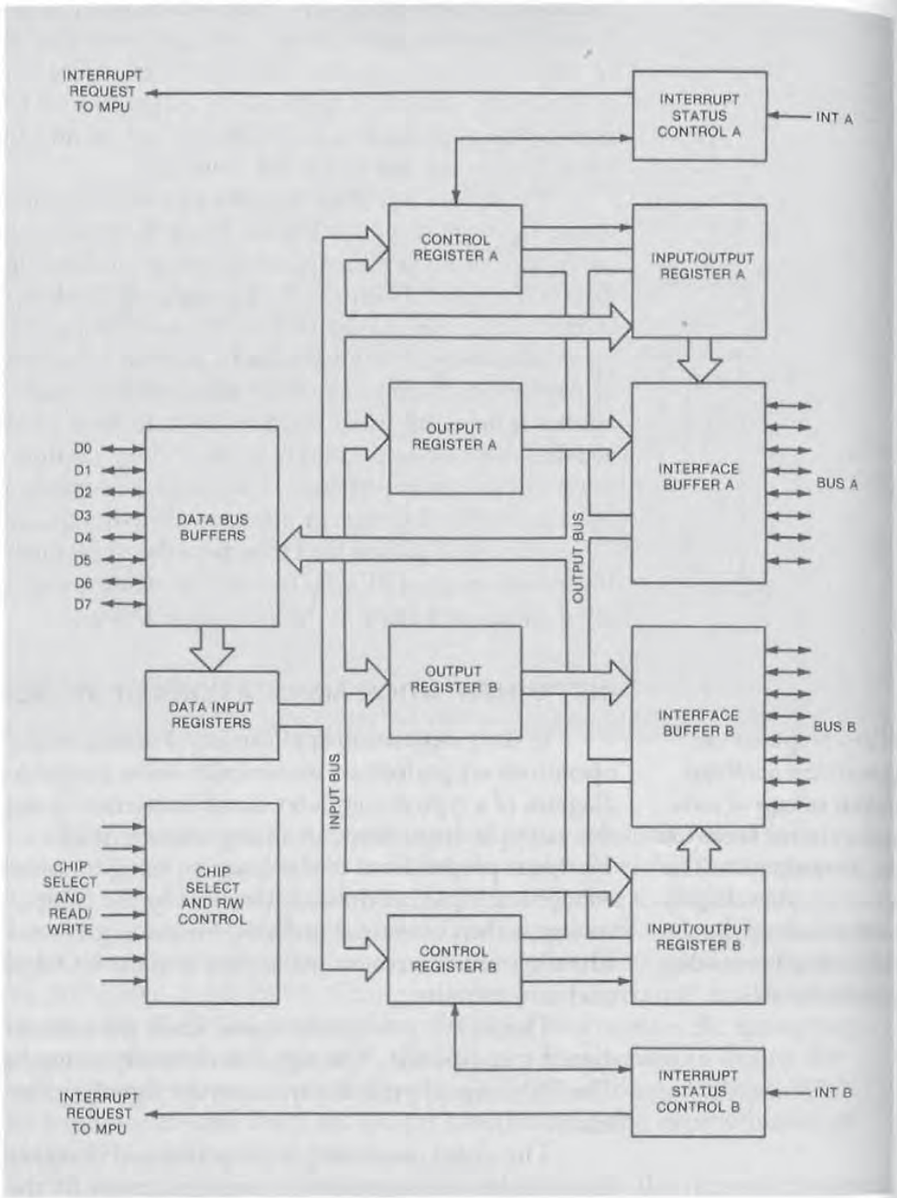
In instrumentation applications of microcomputers, the signal processing operations are performed numerically under program control. The block diagram of a typical computer-based instrument is depicted in Figure 4.23. In this example instrument, an analog sensor provides a continuous-time voltage, V_o, that is proportional to the quantity being measured. The continuous-time voltage is sampled at times determined by the computer. The sampled analog voltage is then converted to digital format (e.g., 8 to 16 bits) using an ADC. The digital data is connected to port A of the I/O device of the computer to be read into memory.

The ADC generates a signal when the conversion from analog to digital is completed. This signal is normally termed *end of conversion* (EOC). The EOC signal provides an interrupt signaling the computer that data is ready.

The signal processing to be performed is expressed as a set of operations that is to be performed by the microprocessor on the data. These operations are termed the *algorithm* for the signal processing operation. The algorithm is converted to a set of specific computer operations that becomes the program for the signal processing. After the signal processing is completed, the result is ready to be sent to the display device. The digital data is sent through I/O to port B to the DAC. There it is converted back to sampled analog. The

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Figure 4.22
Block Diagram of a Typical Interface Adapter



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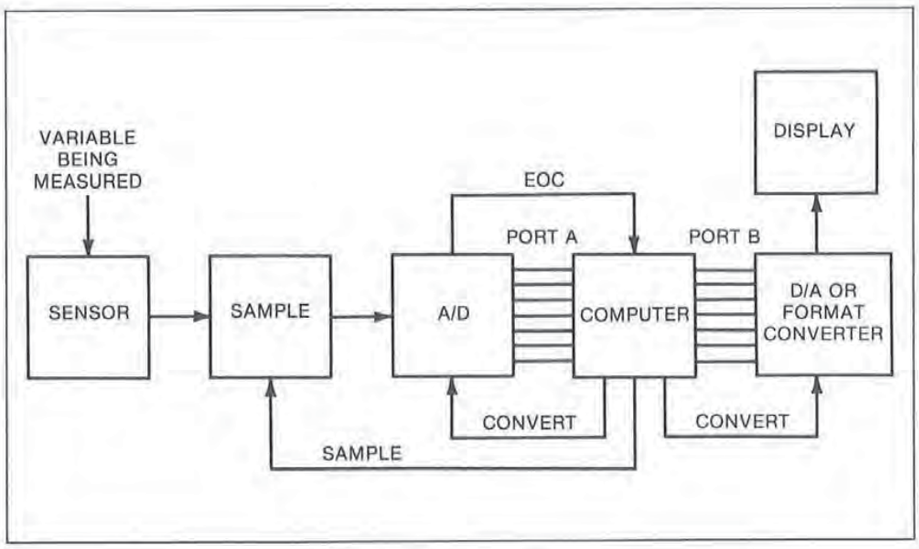


Figure 4.23 Typical Automotive Instrumentation Architecture

sampled data is "smoothed" to a suitable continuous-time voltage by means of a special filter known as a reconstruction filter. The continuous-time output of this filter drives the continuous-time display.

In a great many applications, the display is digital (e.g., automotive speed measurement). In this case, the conversion from digital to analog is not required, and the computer output data can directly activate the digital display.

Digital Filters

Digital filters can be programmed on a microcomputer to reject specific types of signals while passing other signals.

As an example of computer-based instrumentation signal processing applications, consider the relatively straightforward task of filtering the output of a sensor. Low-pass filters pass low-frequency signals but reject high-frequency signals. High-pass filters do just the reverse: They pass high-frequency signals and reject low-frequency signals. Bandpass filters pass midrange frequencies but reject both low and high frequencies. Analog filters use resistive, capacitive, and inductive components, and sometimes operational amplifiers. Digital low-pass and bandpass filters can be programmed on a microcomputer to perform basically the same functions as their analog counterparts.

A digital low-pass filter could be used, for instance, to smooth the output of an automotive fuel level sensor. The fuel level sensor produces an electrical signal that is proportional to the height of the fuel in the center of the tank.

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The level at that point will change as fuel is consumed, but it also will change as the car slows, accelerates, turns corners, and hits bumps. The sensor's output voltage varies widely because of fuel slosh even though the amount of fuel in the tank changes slowly. If that voltage is sent directly to the fuel gauge, the resulting variable indication will fluctuate too rapidly to be read.

The measurement can be made more readable and more meaningful by using a low-pass filter to smooth out the signal fluctuations to reduce the effects of sloshing. The low-pass filter can be implemented in a microcomputer by programming the computer to average the sensor signal over several seconds before sending it to the display. For instance, if the fuel level sensor signal is sampled once every second and it is desirable to average the signal over a period of 60 seconds, the computer saves only the latest 60 samples, averages them, and displays the average. When a new sample is taken, the oldest sample is discarded so that only the 60 latest samples are kept. A new average can be computed and displayed each time a new sample is taken.

Digital filters are implemented completely through the use of software, thus their characteristics can be easily changed. Because digital filters require no extra hardware, they are low in cost.

Digital filtering (averaging) can be performed by a computer under the control of the software. Sometimes the section of code that performs the filtering task is simply called "the filter." Digital signal processing is very attractive because the same computer can be used to process several different signals. Also, since digital filters require no extra hardware, the filters can be made much more complex with relatively little increase in cost. In addition, the characteristics of the digital filter can be changed by changing the software. Changing the characteristics of an analog filter usually requires changing the hardware components. Another feature of digital filters (true for digital signal processing in general) is that they don't change with age or temperature, unlike analog filters.

There are limitations to the use of digital filters, however. The frequency range of digital filters is determined by the speed of the processor. The microcomputer must be able to sample each signal at or above the rate required by the Nyquist sampling theorem. It must also be fast enough to perform all of the averaging and linearization for each signal before the next sample is taken. This is an important limitation, and the system designer must be certain that the computer is not overloaded by trying to make it do too many things too quickly.

MICROCOMPUTERS IN CONTROL SYSTEMS

Computers can also be used in control applications.

Microcomputers are able to handle inputs and outputs that are either digital or converted analog signals. With the proper software, they are capable of making decisions about those signals and can react to them quickly and precisely. These features make microcomputers ideal for controlling other digital or analog systems, as discussed in the following sections.

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Closed-Loop Control System

Recall the basic closed-loop control system block diagram of Chapter 2. The error amplifier compares the command input with the plant output and sends the error signal to the control logic. The control logic uses the error signal to generate a plant control signal that causes the plant to react with a new output so that the error signal will be reduced toward zero. The control logic is designed so that the plant's output follows or tracks the command input. A microcomputer can replace the error amplifier and the control logic. The computer can compare command input and plant output and perform the computation required to generate a control signal.

Limit-Cycle Controller

The limit-cycle controller, discussed in Chapter 2, can be readily implemented with a microcomputer. Recall that the limit-cycle controller controls the plant output so that it falls somewhere between an upper and lower limit, preferably so that its average value is equal to the command input. The controller must read in the command input and the plant output and decide what control signal to send to the plant based on those signals alone.

Using a microcomputer, the upper and lower limit can be determined from the command input by using a lookup table similar to that discussed later in this chapter. The plant output is compared against these two limits. If the plant output is above the higher limit or below the lower limit, the microcomputer outputs the appropriate on/off signal to the plant to bring the output back between the two limits.

With proper software, a microcomputer can replace the error amplifier and control logic used in the closed-loop control system.

Recall that in Chapter 2 the concept of a feedback control system was introduced. There it was shown that a control system compares the value of some controlled variable with a desired value (or set point) for that variable. In such a control system, the difference between the desired and actual value is first obtained, then an electrical signal is generated. The resulting error signal is processed electronically, thereby generating a control signal that operates an actuator. The actuator changes the controlled system in such a way as to reduce the error. In Chapter 2, it was presumed that analog electronics were used for the control.

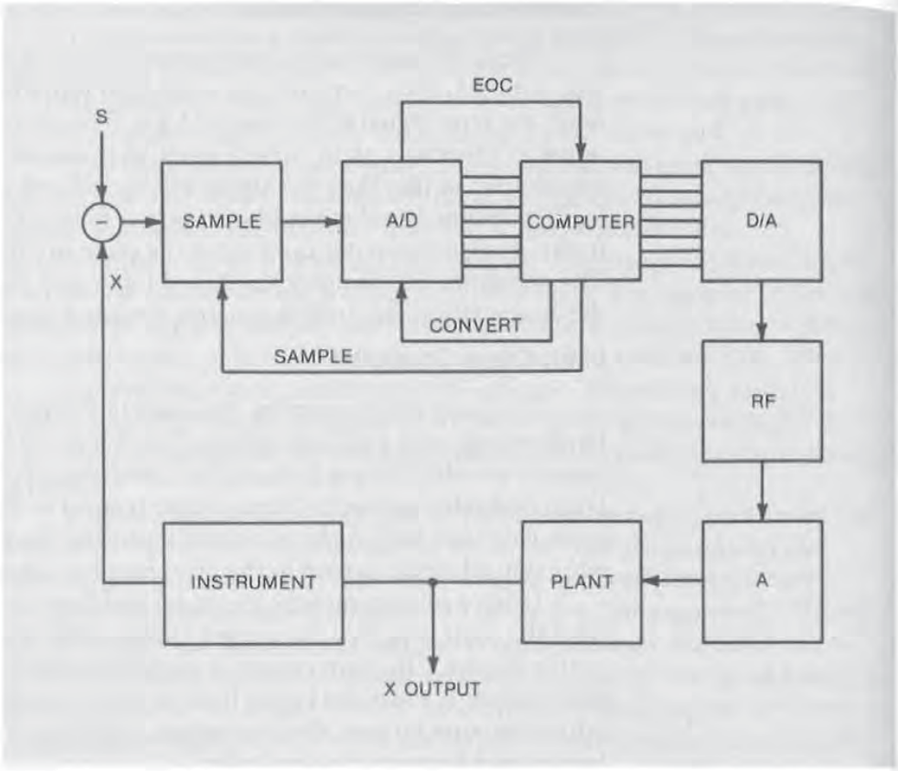
A feedback control system can also be implemented using digital electronics. Figure 4.24 is a block diagram of a control system employing a computer. In this diagram, there is a physical system, or plant, that is to be controlled. The specific variable being controlled is denoted X. For example, in an automobile, the plant might be the engine and the controlled variable might be brake torque.

The desired value for X is the set point S. An error signal e is obtained:

$$e = S - X$$

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Figure 4.24
Typical Digital Control System



The error signal is sampled, yielding samples e_n (where n represents sample number; i.e., $n = 1,2, \ldots$). In a typical digital control system, the computer generates an output y_n for each input sample:

$$y_n = y_o + Pe_n + I(e_n + e_{n-1} + e_{n-2})\Delta T + D\frac{(e_n - e_{n-1})}{\Delta T}$$

where

P is the proportional gain
I is the integral gain
D is the differential gain
ΔT is the time between successive samples

The previous equation represents an example of an algorithm for the particular control strategy. The example algorithm is a form of a PID (proportional integral differential) control strategy.

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After computing y_n for each input sample, a digital version of y_n is transmitted through the I/O to the DAC. There it is converted to analog format, providing a control signal to the actuator (A), which is presumed here to be analog. The actuator controls the plant in such a way as to cause the error to be reduced toward zero. Many examples of the application of computer-based electronic control systems in automobiles are presented in a later chapters of this book.

Multivariable Systems

With the appropriate control program, microcomputers have the ability to sample and control multiple inputs and outputs independently. This type of control is much more difficult to design when using analog circuitry.

A very important feature of microcomputer control logic is the ability to control multiple systems independently and to control systems with multiple inputs and outputs. The automotive applications for microcomputer control involve both of these types of *multivariable* systems. For instance, the automobile engine has several inputs (such as air/fuel ratio, throttle angle, and spark timing). All of the outputs must be controlled simultaneously because some inputs affect more than one output. These types of controllers can be very complicated and are difficult to implement in analog fashion. The increased complexity (and cost) of a multivariable microcomputer system is not much higher than for a single-variable microcomputer system, presuming the microcomputer has the capacity to do the task. It only affects the task of programming the appropriate control scheme into the microcomputer. This type of control is discussed in a later chapter.

Table Lookup

One of the important functions of a microcomputer in automotive applications is table lookup. These applications include:

1. Linearization of sensor data
2. Multiplication
3. Calibration conversion

These applications are explained in detail in later chapters where appropriate. In this chapter, we explain the basic principle using a specific example.

The concept of table lookup is illustrated in Figure 4.25, in which a pair of variables, V_o and X, are related by the graph depicted therein. Also shown in Figure 4.25 is a table listing certain specific values for the relationship. The functional relationship between V_o and X might, for example, be the output voltage of a nonlinear sensor V_o for measuring a quantity X. If the value for V_o is known, then the corresponding value for X can theoretically be found using the graph or the tabulated values. In the latter case, the nearest two tabulated values for V_o are located, and the corresponding values for X are read from the table. Denoting V_1 and V_2 as the nearest values and X_1, X_2 as the corresponding

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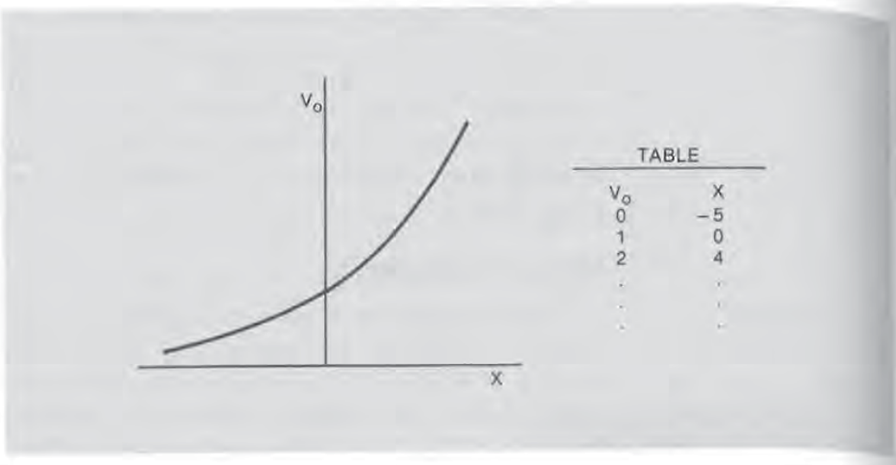


Figure 4.25 Illustration of Table Lookup and Interpolation

tabulated values, the value for X corresponding to V_o is found by linear interpolation:

$$X = X_1 + (X_2 - X_1)(V_o - V_2)/(V_1 - V_2)$$

A microcomputer can perform the same operation using tabulated values for the relationship between V_o and X (i.e., $V_o(X)$ in correct mathematical notation). This method is illustrated using a specific example of the measurement of a variable X using a sensor output voltage, and variable X is assumed to be that which is illustrated in Figure 4.24. A microcomputer is to obtain the value for X using a table lookup operation.

The portion of the microcomputer that is involved in the table lookup process is illustrated in Figure 4.26. The relationship $V_o(X)$ is stored in ROM for representative points along the curve. This data is stored using V_o values as addresses, and corresponding values of X as data. For example, consider a point (V_1, X_1). The data X_1 is stored at memory location V_1 in binary format.

The operation of the table lookup is as follows. The sensor S has output voltage V_o. The computer reads the values of V_o (using an ADC to convert to digital format) through the I/O device. Then the MPU under program control (program ROM) calculates the addresses for the two nearest values to V_o, which are V_1 and V_2 ($V_1 < V_o < V_2$). The computer, under program control, reads values X_1 and X_2 and then calculates X using the preceding formula.

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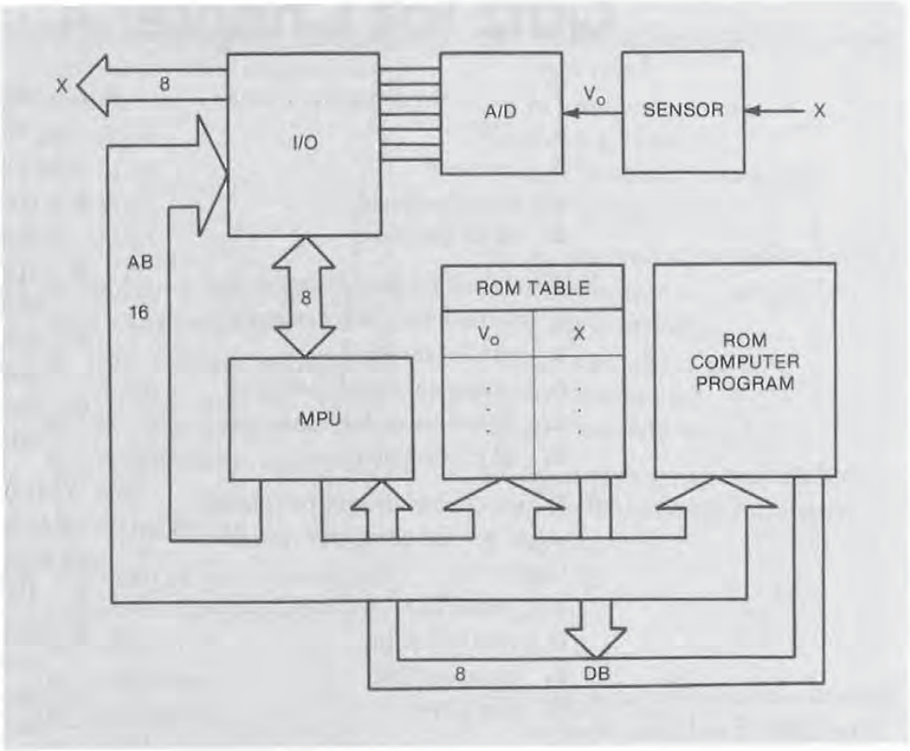


Figure 4.26
Architecture Involved in Table Lookup

Repeated reference will be made to the table lookup function in later chapters. In particular, Chapter 7 will discuss how a typical digital engine control system frequently obtains data using table lookup.

After a chapter on basics of automotive engine control and a chapter on sensors and actuators, this book will deal more specifically with particular microcomputer automotive instrumentation and control systems to show how these systems are used in the automobile to control the engine and drivetrain and many auxiliary functions.

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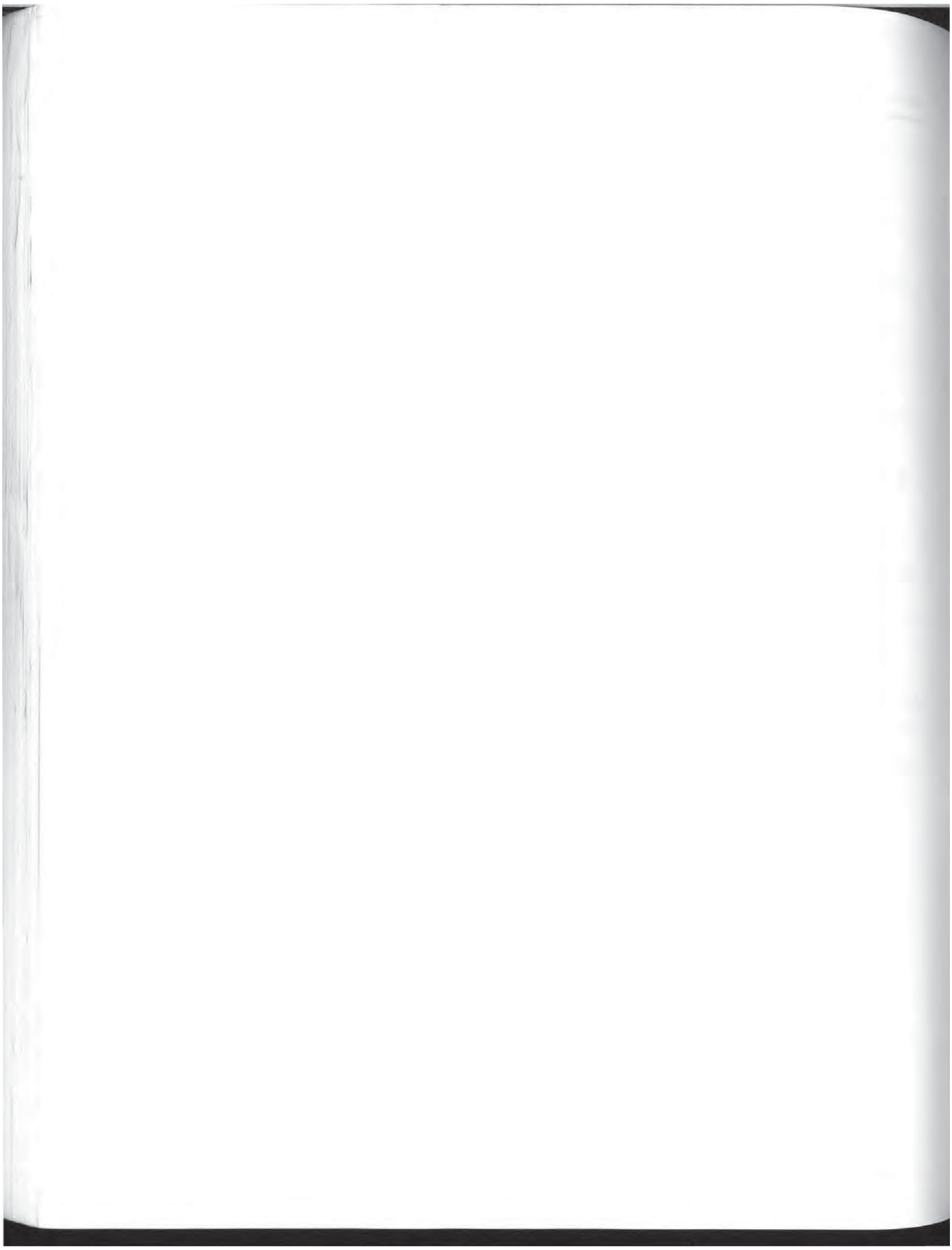
Quiz for Chapter 4

1. The parts of a computer include
   - **a.** CPU
   - **b.** memory
   - **c.** input/output
   - **d.** all of the above
2. What does a microcomputer use to interface with other systems?
   - **a.** parallel interface
   - **b.** analog-to-digital converter
   - **c.** digital-to-analog converter
   - **d.** all of the above
3. Which control line do peripherals use to get the computer's attention?
   - **a.** power line
   - **b.** read/write line
   - **c.** interrupt line
   - **d.** clock line
4. What is a data bus?
   - **a.** a set of wires that carries bits to or from the processor and memory or peripherals
   - **b.** a large yellow vehicle for carrying data
   - **c.** a bus carrying addresses
   - **d.** a set of wires for control signals
5. What are computers used for in instrumentation systems?
   - **a.** signal processing
   - **b.** sensor, actuator, and display linearization
   - **c.** display formatting
   - **d.** filtering
   - **e.** all of the above
6. According to the Nyquist sampling theorem, a signal must be sampled at
   - **a.** the highest frequency in the signal
   - **b.** at least twice the highest frequency in the signal
   - **c.** less than half the lowest frequency in the signal
   - **d.** more than half the lowest frequency in the signal
7. What advantages does digital signal processing have over analog signal processing?
   - **a.** digital is more precise
   - **b.** digital doesn't drift with time and temperature
   - **c.** the same digital hardware can be used in many filters
   - **d.** all of the above
8. What advantage does analog signal processing have over digital signal processing?
   - **a.** analog is always less expensive
   - **b.** the same analog hardware can be used for many filters
   - **c.** analog is sometimes less expensive
   - **d.** high-frequency signals can only be filtered with analog filters
9. What type of memory is used to permanently store programs?
   - **a.** RAM
   - **b.** ROM
   - **c.** MAP
   - **d.** RPM

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10. What type of memory is used to temporarily store data and variables?
    a. RAM
    b. ROM
    c. MAP
    d. RPM
11. What distinguishes a computer from a fancy calculator?
    a. add, subtract, multiply, and divide
    b. stored program
    c. the calculators can read paper tape
    d. digital circuits
12. What part of the computer performs the arithmetic and logic functions?
    a. peripherals
    b. memory
    c. CPU
    d. address bus
13. Which computer register is the main work register?
    a. program counter
    b. stack pointer
    c. condition code register
    d. accumulator
14. A short initialization program is called what kind of program?
    a. subroutine
    b. boot program
    c. main program
    d. branch
15. Which register keeps track of program steps?
    a. program counter
    b. stack pointer
    c. condition code register
    d. accumulator
16. A programmer uses what type of statements in an assembly language program?
    a. op codes
    b. mnemonics
    c. machine code
17. Most microcomputers use how many bits to address memory?
    a. 16
    b. 32
    c. 4
    d. 6
18. Most automotive microcomputers use how many bits in arithmetic?
    a. 1
    b. 6
    c. 4
    d. 8
19. Which of the following is a short program that ends with an RTS instruction?
    a. main program
    b. interrupt
    c. boot
    d. subroutine

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The Basics of Electronic Engine Control

Engine control in the vast majority of engines means regulating fuel and air intake as well as spark timing to achieve desired performance in the form of torque or power output. Until the late 1960s, control of the engine output torque and RPM was accomplished through some combination of mechanical, pneumatic, or hydraulic systems. Then, in the 1970s, electronic control systems were introduced.

This chapter is intended to explain, in general terms, the theory of electronic control of the automotive engine. Chapter 7 explains practical control methods and systems. The examples used to explain the major developments and principles of electronic control have been culled from the techniques used by various manufacturers and are not necessarily representative of any single automobile manufacturer at the highest level of detail.

MOTIVATION FOR ELECTRONIC ENGINE CONTROL

The motivation for electronic engine control came in part from two government requirements. The first came about as a result of legislation to regulate automobile exhaust emissions under the authority of the Environmental Protection Agency (EPA). The second was a thrust to improve the national average fuel economy by government regulation.

Exhaust Emissions

The combustion of gasoline in an engine results in exhaust gases including CO_2, H_2O, CO, oxides of nitrogen, and various hydrocarbons.

The engine exhaust consists of the products of combustion of the air and gasoline mixture. Gasoline is a mixture of chemical compounds that are called *hydrocarbons*. This name is derived from the chemical formation of the various gasoline compounds, each of which is a chemical union of hydrogen (H) and carbon (C) in various proportions. Gasoline also contains natural impurities as well as chemicals added by the refiner. All of these can produce undesirable exhaust elements.

During the combustion process, the carbon and hydrogen combine with oxygen from the air, releasing heat energy and forming various chemical compounds. If the combustion were perfect, the exhaust gases would consist only of carbon dioxide (CO_2) and water (H_2O), neither of which are considered harmful in the atmosphere. In fact, both are present in a human's breath.

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Unfortunately, the combustion of the SI engine is not perfect. In addition to the CO_2 and H_2O, the exhaust contains amounts of carbon monoxide (CO), oxides of nitrogen (chemical unions of nitrogen and oxygen that are denoted NO_x), unburned hydrocarbons (HC), oxides of sulfur, and other compounds. Some of the exhaust constituents are considered harmful and have come under the control of the federal government. The exhaust emissions controlled by government standards are CO, HC, and NO_x.

Automotive exhaust emission control requirements started in the United States in 1966 when the California state regulations became effective. Since then, the federal government has imposed emission control limits for all states, and the standards became progressively more difficult to meet through the decade 1970–1980. Auto manufacturers found that the traditional engine controls could not control the engine sufficiently to meet these emission limits and maintain adequate engine performance at the same time, so they turned to electronic controls.

Fuel Economy

Everyone has some idea of what fuel economy means. It is related to the number of miles that can be driven for each gallon of gasoline consumed. It is referred to as miles per gallon (MPG) or simply *mileage*. Just like it improves emission control, another important feature of electronic engine control is its ability to improve fuel economy.

Electronic engine control is used to reduce exhaust emissions and improve fuel economy, both of which have limits set by the government.

It is well recognized by layman and expert alike that the mileage of a vehicle is not unique. It depends on size, shape, weight, and how the car is driven. The best mileage is achieved under steady cruise conditions. City driving, with many starts and stops, yields worse mileage than steady highway driving.

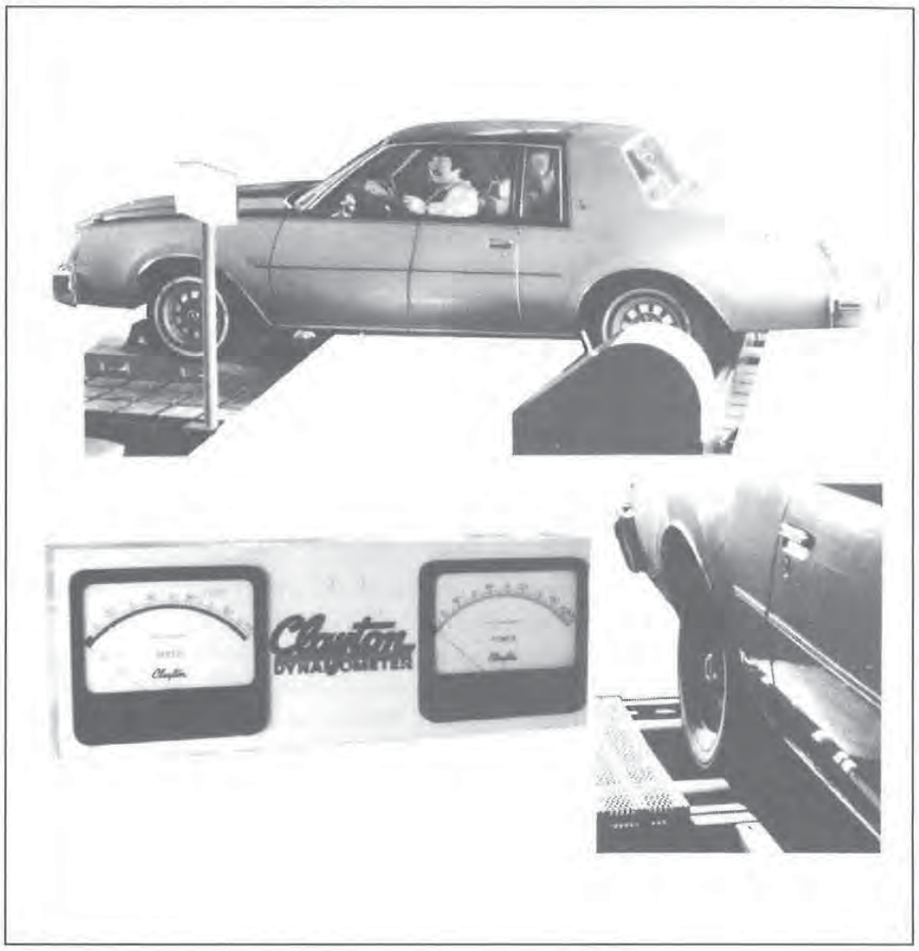
The government fuel economy standards are not based on just one car, but are stated in terms of the average rated miles per gallon fuel mileage for the production of all models by a manufacturer for any year. This latter requirement is known in the automotive industry by the acronym CAFE (corporate average fuel economy). It is a somewhat complex requirement and is based on measurements of the fuel used during a prescribed simulated standard driving cycle.

FEDERAL GOVERNMENT TEST PROCEDURES

For an understanding of both emission and CAFE requirements, it is helpful to review the standard cycle and how the emission and fuel economy measurements are made. The U.S. federal government has published test procedures that include several steps. The first step is to place the automobile on a chassis dynamometer, like the one shown in Figure 5.1.

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Figure 5.1
Chassis Dynamometer



Government test procedures use a chassis dynamometer to simulate actual driving conditions in a controlled environment.

A *chassis dynamometer* is a test stand that holds a vehicle such as a car or truck. It is equipped with instruments capable of measuring the power that is delivered at the drive wheels of the vehicle under various conditions. The vehicle is held on the dynamometer so that it cannot move when power is applied to the drive wheels. The drive wheels are in contact with two large rollers. One roller is mechanically coupled to an electric generator that can vary the load on its electrical output. The other roller has instruments to measure and record the vehicle speed. The generator absorbs all mechanical power that is delivered at the drive wheels, and the horsepower is calculated from the electrical output. (746 watts of electrical output equals 1 horsepower.) The controls of the dynamometer can be set to simulate the

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correct load and inertia of the vehicle moving along a road under various conditions. The conditions are the same as if the vehicle actually were being driven.

Emission samples are collected and measured during a simulated urban trip containing a high percentage of stop-and-go driving.

The vehicle is operated according to a prescribed schedule of speed and load to simulate the specified trip. One is an urban trip and one is a highway trip. The schedules are shown in Figure 5.2. The 18 cycles of the urban simulated trip take 1,372 seconds and include acceleration, deceleration, stops, starts, and steady cruise such as would be encountered in a "typical" city automobile trip of 7.45 miles (12 km). The highway schedule takes 765 seconds and simulates 10.24 miles (16.5 km) of highway driving.

During the operation of the vehicle in the urban test, the exhaust is continuously collected and sampled. At the end of the test, the absolute mass of each of the regulated exhaust gases is determined. The regulations are stated in terms of the total mass of each exhaust gas divided by the total distance of the simulated trip.

Fuel consumption also is measured during the tests. Emission and MPG requirements have grown increasingly stringent since 1968.

In addition to emission measurement, each manufacturer must determine the fuel consumption in MPG for each type of vehicle and must compute the corporate average mileage for all vehicles of all types produced in a year. Fuel consumption is measured during both an urban and a highway test, and the composite fuel economy is calculated.

Table 5.1 is a summary of the exhaust emission requirements and CAFE for representative years. It shows the emission requirements and increased fuel economy required. Because of these requirements, each manufacturer has a strong incentive to minimize exhaust emissions and maximize fuel economy for each vehicle produced.

Table 5.1
Emission and MPG Requirements

Year	Federal HC/CO/NO_x	California HC/CO/NO_x	CAFE MPG
1968	3.22/33.0/–	—	—
1971	2.20/23.0/–	—	—
1978	1.50/15.0/2.0	0.41/9.0/1.5	18.0
1979	1.50/15.0/2.0	0.41/9.0/1.5	19.0
1980	0.41/7.0/2.0	0.41/9.0/1.5	20.0
⋮	⋮	⋮	⋮
1989	0.31/4.1/1.0	0.31/4.1/1.0	27.5

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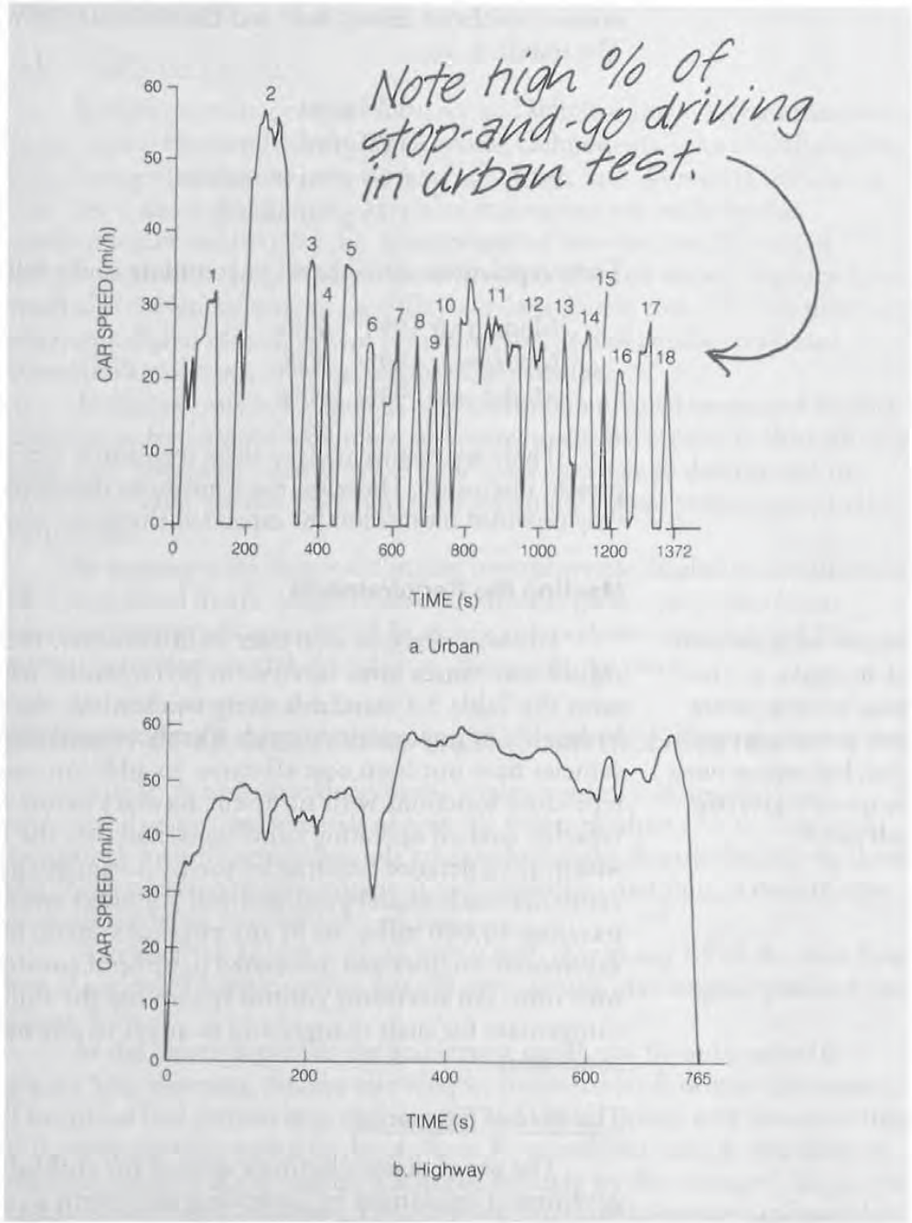


Figure 5.2 Federal Driving Schedules (*Title 40 United States Code of Federal Regulations*)

New regulations for emissions have recently come into effect. These regulations affect not only passenger cars but also light utility vehicles and both heavy- and light-duty trucks. Furthermore, regulations apply to a variety of fuels, including gasoline, diesel, natural gas, and alcohol-based fuels involving mixtures of gasoline with methanol or ethanol.

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Standards have been written for the vehicle half-life (5 years or 50,000 miles—whichever comes first) and full life cycle (10 years or 100,000 miles). The standards are:

HC	0.31 g/mi
CO	4.20 g/mi
NO_x	0.60 g/mi (nondiesel)
	1.25 g/mi (diesel)

These regulations were phased in according to the following schedules:

Model year 1994: 40%
Model year 1995: 80%
Model year 1996: 100%

There are many details to these regulations that are not relevant to the present discussion. However, the regulations themselves are important in that they provided motivation for expanded electronic controls.

Meeting the Requirements

Engines using mechanical, hydraulic, or pneumatic controls cannot meet government regulations, but engines using electronic engine controls can.

Unfortunately, as seen later in this chapter, meeting the government regulations causes some sacrifice in performance. Moreover, attempts to meet the Table 5.1 standards using mechanical, electromechanical, hydraulic, or pneumatic controls like those used in pre–emission control vehicles have not been cost effective. In addition, such controls cannot reproduce functions with sufficient accuracy across a range of production vehicles, over all operating conditions, and over the life of the vehicle to stay within the tolerance required by the EPA regulations. Each automaker must verify that each model produced will still meet emission requirements after traveling 50,000 miles. As in any physical system, the parameters of automotive engines and associated peripheral control devices can change with time. An electronic control system has the ability to automatically compensate for such changes and to adapt to any new set of operating conditions.

The Role of Electronics

The use of digital electronic control has enabled automakers to meet the government regulations by controlling the system accurately with excellent tolerance. In addition, the system has long-term calibration stability. As an added advantage, this type of system is very flexible. Because it uses microcomputers, it can be modified through programming changes to meet a variety of different vehicle/engine combinations. Critical quantities that

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describe an engine can be changed easily by changing data stored in the system's computer memory.

Additional Cost Incentive

Dropping costs of microprocessors and other very large scale integrated circuits have made electronic engine control an increasingly attractive system for automobile manufacturers.

Besides providing control accuracy and stability, there is a cost incentive to use digital electronic control. The system components—the multifunction digital integrated circuits—are decreasing in cost, thus decreasing the system cost. From about 1970 on, considerable investment was made by the semiconductor industry for the development of low-cost, multifunction integrated circuits. In particular, the microprocessor and microcomputer have reached an advanced state of capability at relatively low cost. This has made the electronic digital control system for the engine, as well as other on-board automobile electronic systems, commercially feasible.

As pointed out in Chapter 3, as multifunction digital integrated circuits continue to be designed with more and more functional capability through very large scale integrated circuits (VLSI), the costs continue to decrease. At the same time, these circuits offer improved electronic system performance in the automobile.

In summary, the electronic engine control system duplicates the function of conventional fluidic control systems, but with greater precision. It can optimize engine performance while meeting the exhaust emission and fuel economy regulations and can adapt to changes in the plant.

CONCEPT OF AN ELECTRONIC ENGINE CONTROL SYSTEM

In order to understand electronic engine control it is necessary to understand some fundamentals of how the power produced by the engine is controlled. Any driver understands intuitively that the throttle directly regulates the power produced by the engine at any operating condition. It does this by controlling the air flow into the engine.

In essence the engine is an air pump such that at any RPM the mass flow rate of air into the engine varies directly with throttle plate angular position (see Figure 5.3).

As the driver depresses the accelerator pedal, the throttle angle (θ in Figure 5.3) increases, thereby allowing an increased air flow into the engine. The role of fuel control is to regulate the fuel that is mixed with the air so that it increases in proportion to the air flow. As we will see later in this chapter, the performance of the engine is affected strongly by the mixture (i.e., by the ratio of air to fuel). However, for any given mixture the power produced by the engine is directly proportional to the mass flow rate of air into the engine. In the U.S. system of units, an air flow rate of about 6 lb/hr produces 1 horsepower of usable mechanical power as the output of the engine. Metric

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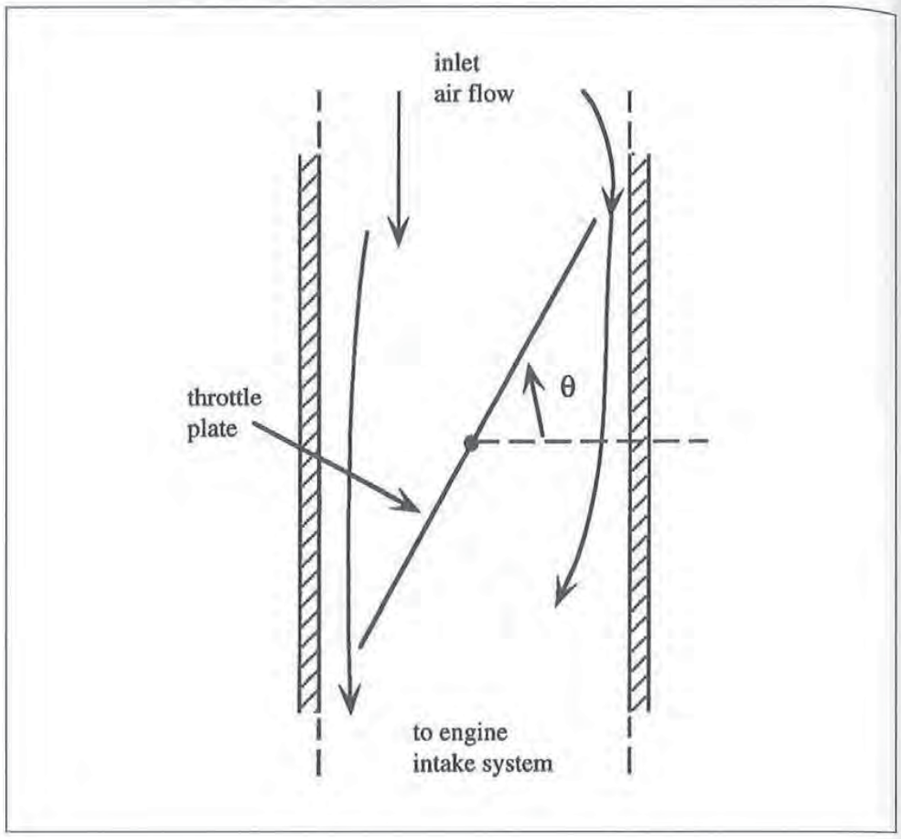


Figure 5.3
Intake System with Throttle Plate

units are sometimes used, in which engine power is given in kilowatts (kw) and air mass is given in kilograms (kg). In mathematical terms we can write:

$$P_b = KM_A$$

where

P_b = power from the engine (hp or kw)
M_A = mass air flow rate (kg/hr)
K = constant relating power to air flow (hp/kg/hr)

Of course, it is assumed that all parts of the engine, including ignition timing, are functioning correctly for this relationship to be valid.

We consider next an electronic engine control system that regulates fuel flow to the engine. An electronic engine control system is an assembly of electronic and electromechanical components that continuously varies the fuel and spark settings in order to satisfy government exhaust emission and fuel economy regulations. Figure 5.4 is a block diagram of a generalized electronic engine control system.

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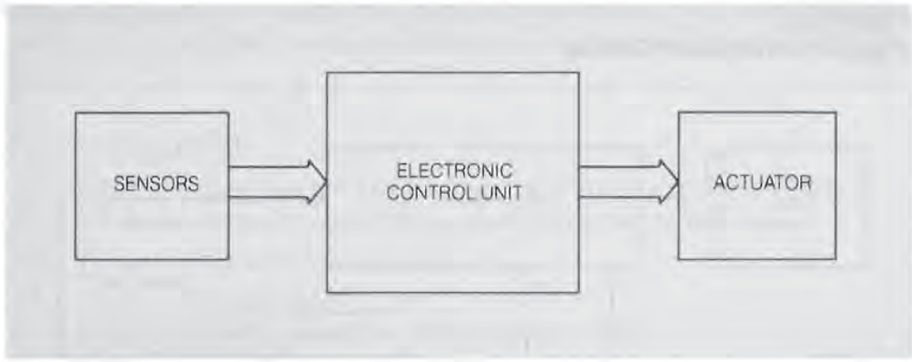


Figure 5.4 Generic Electronic Engine Control System

As explained in Chapter 2, a closed-loop control system requires measurements of certain variables that tell the controller the state of the system being controlled. The electronic engine control system receives input electrical signals from the various sensors that measure the state of the engine. From these signals, the controller generates output electrical signals to the actuators that determine the engine calibration (i.e., correct fuel delivery and spark timing).

Examples of automotive engine control system sensors will be discussed in Chapter 6. As mentioned, the configuration and control for an automotive engine control system are determined in part by the set of sensors that is available to measure the variables. In many cases, the sensors available for automotive use involve compromises between performance and cost. In other cases, only indirect measurements of certain variables are feasible. From measurement of these variables, the desired variable is found by computation.

Overall engine functions that are subject to electronic engine controls are air/fuel ratio, spark control, and exhaust gas recirculation.

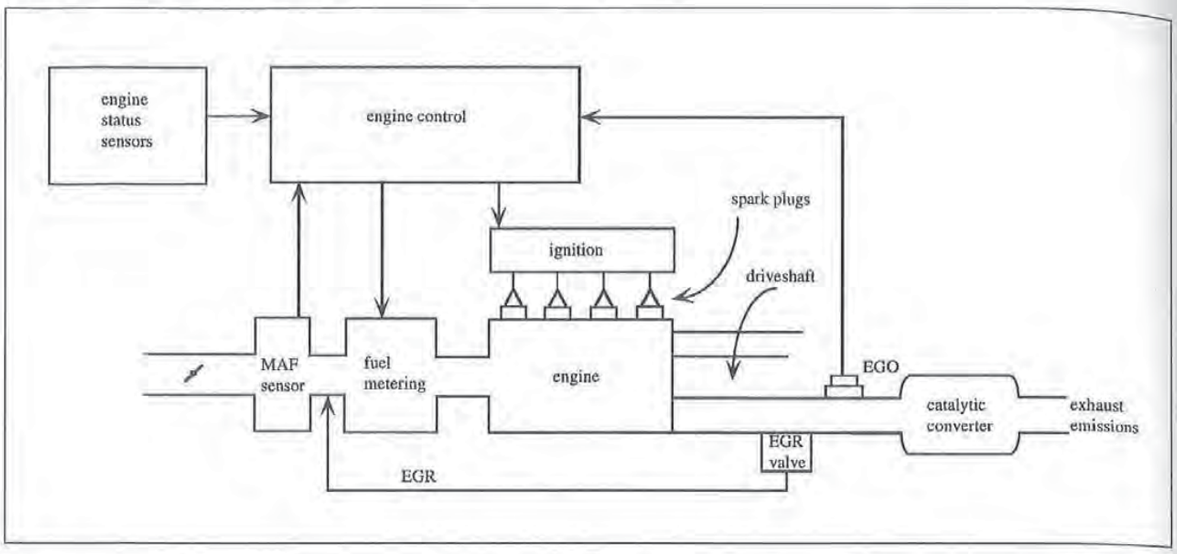
Figure 5.5 identifies the automotive functions that surround the engine. There is a fuel metering system to set the air–fuel mixture flowing into the engine through the intake manifold. Spark control determines when the air–fuel mixture is ignited after it is compressed in the cylinders of the engine. The power is delivered at the driveshaft, and the gases that result from combustion flow out of the exhaust system. In the exhaust system, there is a valve to control the amount of exhaust gas being recirculated back to the input, and a catalytic converter to further control emissions. This addition to the engine, as well as various sensors and actuators depicted in Figure 5.5, is explained later.

At one stage of development, the electronic engine control consisted of separate subsystems for fuel control, spark control, and exhaust gas recirculation. The ignition system in Figure 5.5 is shown as a separate control system, although engine control is evolving toward an integrated digital system (see Chapter 7).

This chapter discusses the various electronic engine control functions separately and explains how each function is implemented by a separate control system. Chapter 7 shows how these separate control systems are being integrated into one system.

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Figure 5.5
Engine Functions and Control



DEFINITION OF GENERAL TERMS

Before proceeding with the details of engine control systems, certain definitions of terms must be clarified—first some general terms and then some specific engine performance terms.

Parameters

Design parameters such as engine size, compression ratio, and so forth, are fixed; therefore, they are not subject to any engine operating control.

A *parameter* is a numerical value of some engine dimension that is fixed by design. Examples of engine design parameters include the piston diameter (*bore*), the distance the piston travels on one stroke (*stroke*), and the length of the crankshaft lever arm (*throw*). The bore and stroke determine the cylinder volume and the displacement. *Displacement* is the total volume of air that is displaced as the engine rotates through two complete revolutions. *Compression ratio* is the ratio of cylinder volume at BDC to the volume at TDC. Other parameters that engine designers must specify include combustion chamber shape, camshaft cam profile, intake and exhaust valve size, and valve timing. All of these design parameters are fixed and are not subject to control while the engine is operating.

Variables

A *variable* is a quantity that changes or may be changed as the engine operates, typically under the control of the electronic control system. Some of

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the important engine variables are mass air flow, fuel flow rate, spark timing, power, intake manifold pressure, and many others that will be encountered in this chapter.

A variable is a quantity that can be changed as the engine operates.

Inputs to Controllers

Figure 5.6 identifies the major physical quantities that are sensed and provided to the electronic controller as inputs. They are as follows:

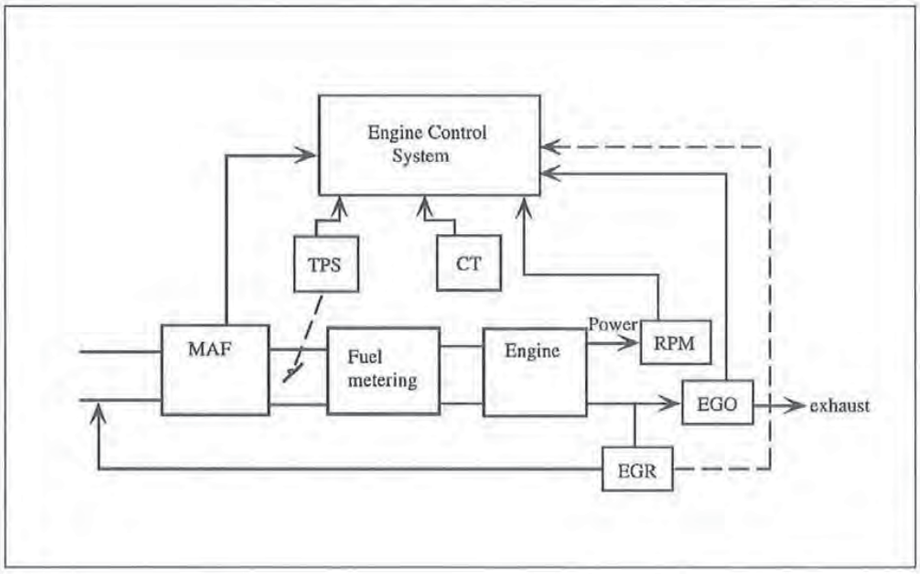
1. Throttle position sensor (TPS)
2. Mass air flow rate (MAF)
3. Engine temperature (coolant temperature) (CT)
4. Engine speed (RPM) and position
5. Exhaust gas recirculation (EGR) valve position
6. Exhaust gas oxygen (EGO)

Outputs from Controllers

Figure 5.7 identifies the major physical quantities that are outputs from the controller. These outputs are

1. Fuel metering control
2. Ignition control
3. Ignition timing
4. Exhaust gas recirculation control

Figure 5.6 Major Controller Inputs from Engine



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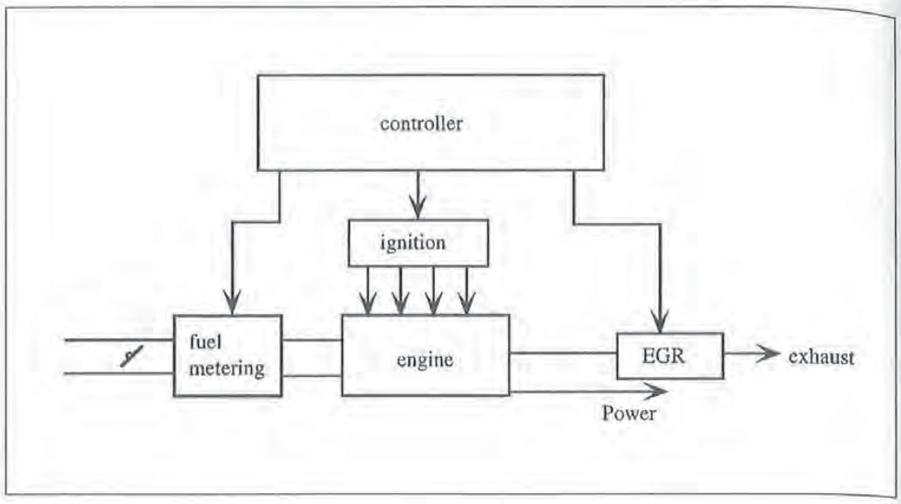


Figure 5.7
Major Controller Outputs to Engine

DEFINITION OF ENGINE PERFORMANCE TERMS

Several common terms are used to describe an engine's performance. Here are a few.

Power

Power is a measurement of an engine's ability to perform useful work. Brake power, which is measured with an engine dynamometer, is the actual power developed by the engine minus losses due to internal friction.

The most common performance rating that has been applied to automobiles is a power rating of the engine. It normally is given in kilowatts or, formerly, in horsepower (note: $^3/_4$ kilowatt = 1 horsepower). *Power* is the rate at which the engine is doing useful work. It varies with engine speed and throttle angle. Power may be measured at the drive wheels or at the engine output shaft. It is more convenient and useful to the designer of an electronic engine control system to know the output power of only the engine. This permits realistic comparisons of engine data as engine controls are varied. To make such measurements, an engine dynamometer is used. This dynamometer is similar to the one in Figure 5.1 except that the engine output shaft drives the dynamometer directly instead of coupling the output through wheels and rollers.

The power delivered by the engine to the dynamometer is called the *brake power* and is designated P_b. The brake power of an engine is always less than the total amount of power that is actually developed in the engine. This developed power is called the *indicated power* of the engine and is denoted P_i. The indicated power differs from the brake power by the loss of power in the engine due to friction between cylinders and pistons, and other friction losses. That is,

$$P_b = P_i - \text{friction and other losses}$$

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BSFC

BSFC is a measurement of an engine's fuel economy. It is the ratio of fuel flow to the brake power output of the engine.

Fuel economy can be measured while the engine delivers power to the dynamometer. The engine is typically operated at a fixed RPM and a fixed brake power (fixed dynamometer load), and the fuel flow rate (in kg/hr) is measured. The fuel consumption is then given as the ratio of the fuel flow rate (r_f) to the brake power output (P_b). This fuel consumption is known as the *brake-specific fuel consumption*, or BSFC.

$$\text{BSFC} = \frac{r_f}{P_b}$$

By improving the BSFC of the engine, the fuel economy of the vehicle in which it is installed is also improved. Electronic controls help to improve BSFC.

Torque

Torque is the twisting force of an engine's crankshaft.

Engine *torque* is the twisting action produced on the crankshaft by the cylinder pressure pushing on the piston during the power stroke. Torque is produced whenever a force is applied to a lever. The length of the lever (the lever arm) in the engine is determined by the throw of the crankshaft (the offset from the crankshaft centerline of the point where the force is applied). The torque is expressed as the product of this force and the length of the lever. The units of torque are N·m (newton meters) in the metric system or ft lb (foot-pounds) in the U.S. system. (One ft lb is the torque produced by one pound acting on a lever arm one foot long.) The torque of a typical engine varies with RPM.

Volumetric Efficiency

Other measurements of engine performance include volumetric, or "breathing," efficiency and thermal efficiency.

The variation in torque with RPM is strongly influenced by the *volumetric efficiency*, or "breathing efficiency." Volumetric efficiency actually describes how well the engine functions as an air pump, drawing air and fuel into the various cylinders. It depends on various engine design parameters such as piston size, piston stroke, and number of cylinders.

Thermal Efficiency

Thermal efficiency expresses the mechanical energy that is delivered to the vehicle relative to the energy content of the fuel. In the typical SI engine, 35% of the energy that is available in the fuel is lost as heat to the coolant and lubricating oil, 40% is lost as heat and unburned fuel in exhaust gases, and another 5% is lost in engine and drivetrain friction. This means that only about 20% is available to drive the vehicle and accessories. These percentages vary somewhat with operating conditions but are valid on the average.

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Calibration

The definition of engine *calibration* is the setting of the air/fuel ratio and ignition timing for the engine. With the new electronic control systems, calibration is determined by the electronic engine control system.

ENGINE MAPPING

Engine mapping is a process by which measurements are made of important engine variables while the engine is operated throughout its speed and load ranges.

The development of any control system comes from knowledge of the plant, or system to be controlled. In the case of the automobile engine, this knowledge of the plant (the engine) comes primarily from a process called *engine mapping*.

For engine mapping, the engine is connected to a dynamometer and operated throughout its entire speed and load range. Measurements are made of the important engine variables while quantities, such as the air/fuel ratio and the spark control, are varied in a known and systematic manner. Such engine mapping is done in engine test cells that have engine dynamometers and complex instrumentation that collects data under computer control.

From this mapping, a mathematical model is developed that explains the influence of every measurable variable and parameter on engine performance. The control system designer must select a control configuration, control variables, and control strategy that will satisfy all performance requirements (including stability) as computed from this model and that are within the other design limits such as cost, quality, and reliability. To understand a typical engine control system, let's look at the influence of control variables on engine performance.

Effect of Air/Fuel Ratio on Performance

Figure 5.8 illustrates the variation in the performance variables of torque (T) and brake power (BSFC) as well as engine emissions with variations in the air/fuel ratio with fixed spark timing and a constant engine speed.

In this figure the exhaust gases are represented in brake-specific form. This is a standard way to characterize exhaust gases whose absolute emission levels are proportional to power. The definitions for the brake-specific emission rates are

$$\text{BSHC} = \text{brake-specific HC concentration} = \frac{r_{\text{HC}}}{P_{\text{b}}}$$

$$\text{BSCO} = \text{brake-specific CO concentration} = \frac{r_{\text{CO}}}{P_{\text{b}}}$$

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$$\text{BSNO}_x = \text{brake-specific NO}_x \text{ concentration} = \frac{r_{NO_x}}{P_b}$$

where

r_{HC} = HC rate of flow
r_{CO} = CO rate of flow
r_{NO_x} = NO_x rate of flow

One specific air/fuel ratio is highly significant in electronic fuel control systems, namely, the *stoichiometric mixture.* The stoichiometric (i.e., chemically correct) mixture corresponds to an air and fuel combination such that if combustion were perfect all of the hydrogen and carbon in the fuel would be converted by the burning process to H_2O and CO_2. For gasoline the stoichiometric mixture ratio is 14.7:1.

Stoichiometry is sufficiently important that the fuel and air mixture is often represented by a ratio called the *equivalence ratio,* which is given the specific designation λ. The equivalence ratio is defined as follows:

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

A relatively low air/fuel ratio, below 14.7 (corresponding to $\lambda < 1$), is called a *rich* mixture; an air/fuel ratio above 14.7 (corresponding to $\lambda > 1$) is called a *lean* mixture. Emission control is strongly affected by air/fuel ratio, or by λ.

Note from Figure 5.8 that torque (T) reaches a maximum in the air/fuel ratio range of 12 to 14. The exact air/fuel ratio for which torque is maximum depends on the engine configuration, engine speed, and ignition timing.

The air/fuel ratio has a significant effect on engine torque and emissions.

Also note that the CO and unburned hydrocarbons tend to decrease sharply with increasing air/fuel ratios, as one might expect because there is relatively more oxygen available for combustion with lean mixtures than with rich mixtures.

Unfortunately for the purposes of controlling exhaust emissions, the NO_x exhaust concentration increases with increasing air/fuel ratios. That is, there is no air/fuel ratio that simultaneously minimizes all regulated exhaust gases.

Effect of Spark Timing on Performance

Spark timing also has a major effect on emissions and engine performance. Maximum engine torque occurs at MBT.

Spark advance is the time before top dead center (TDC) when the spark is initiated. It is usually expressed in number of degrees of crankshaft rotation relative to TDC. Figure 5.9 reveals the influence of spark timing on brake-specific exhaust emissions with constant speed and constant air/fuel ratio. Note that both NO_x and HC generally increase with increased advance of spark timing. BSFC and torque are also strongly influenced by timing. Figure 5.9 shows that maximum torque occurs at a particular advanced timing referred to as *minimum advance for best timing* (MBT).

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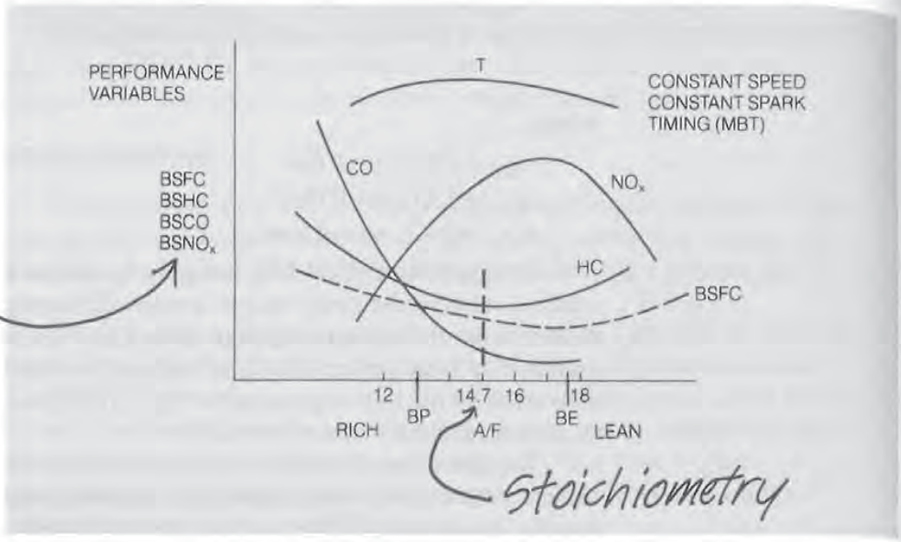


Figure 5.8
Typical Variation of Performance with a Variation in Air/Fuel Ratio

Operation at or near MBT is desirable since this spark timing tends to optimize performance. As will be explained, engine control strategy involves regulating fuel delivery at a stoichiometric mixture and varying ignition timing for optimized performance. However, there is yet another variable to be controlled, which assists the engine control system in meeting exhaust gas emission regulations.

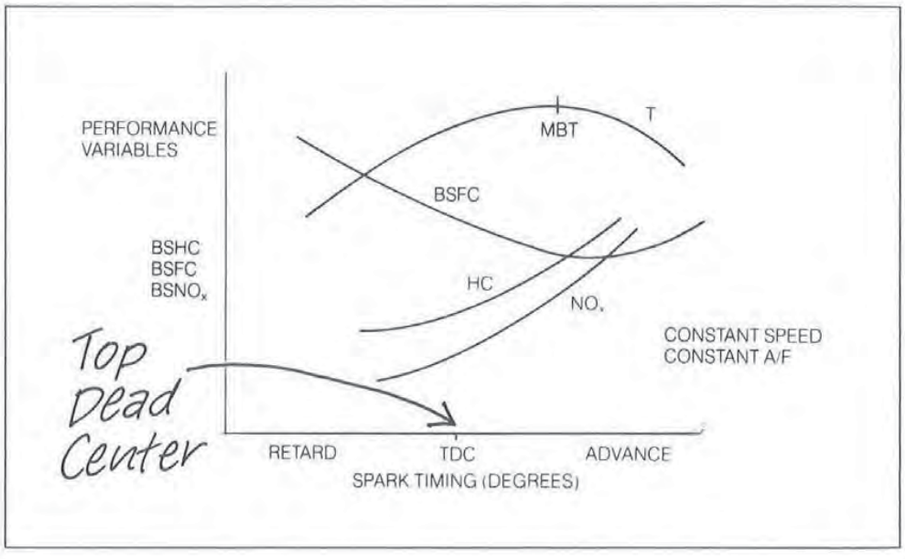


Figure 5.9
Typical Variation of Performance with Spark Timing

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Effect of Exhaust Gas Recirculation on Performance

Exhaust gas recirculation greatly reduces nitrous oxide emissions.

Up to this point in the discussion, only the traditional calibration parameters of the engine (air/fuel ratio and spark timing) have been considered. However, by adding another calibration parameter, the undesirable exhaust gas emission of NO_x can be significantly reduced while maintaining a relatively high level of torque. This new parameter, *exhaust gas recirculation* (EGR), consists of recirculating a precisely controlled amount of exhaust gas into the intake. Figure 5.5 shows that exhaust gas recirculation is a major subsystem of the overall control system. Its influence on emissions is shown in Figures 5.10 and 5.11 as a function of the percentage of exhaust gas in the intake. Figure 5.10 shows the dramatic reduction in NO_x emission when plotted against air/fuel ratio, and Figure 5.11 shows the effect on performance variables as the percentage of EGR is increased. Note that the emission rate of NO_x is most strongly influenced by EGR and decreases as the percentage of EGR increases. The HC emission rate increases with increasing EGR; however, for relatively low EGR percentages, the HC rate changes only slightly.

The mechanism by which EGR affects NO_x production is related to the peak combustion temperature. Roughly speaking, the NO_x generation rate increases with increasing peak combustion temperature if all other variables remain fixed. Increasing EGR tends to lower this temperature; therefore, it tends to lower NO_x generation.

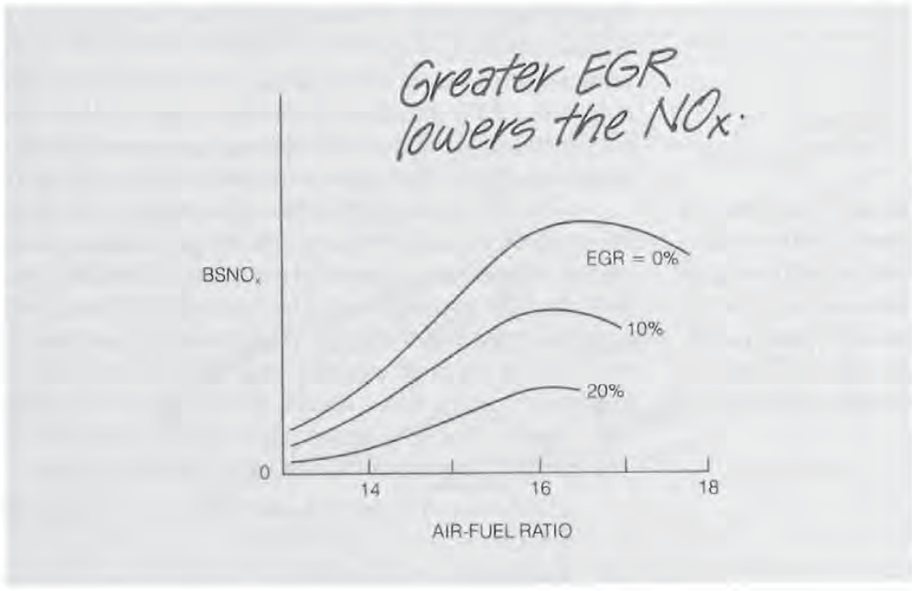


Figure 5.10 NO_x Emission as a Function of EGR at Various Air/Fuel Ratios

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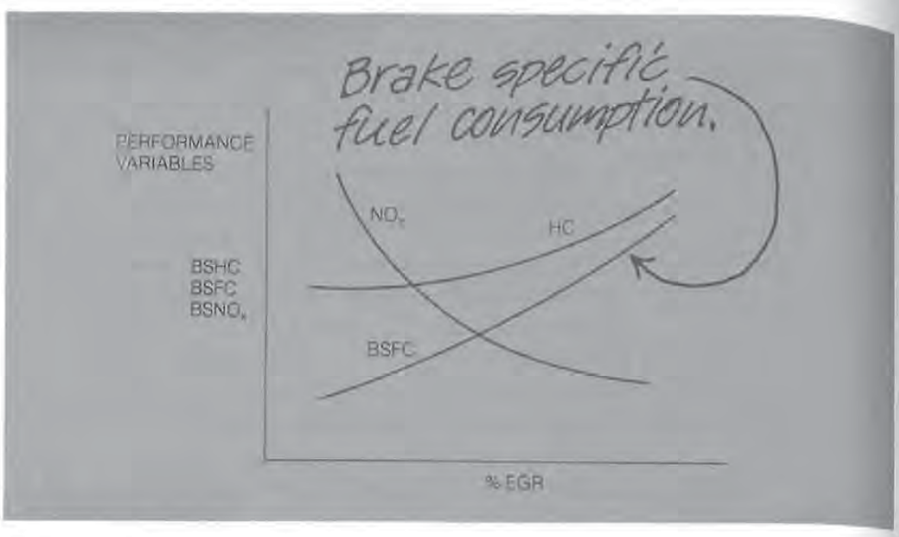


Figure 5.11 Typical Variation of Engine Performance with EGR

CONTROL STRATEGY

It is the task of the electronic control system to set the calibration for each engine operating condition. There are many possible control strategies for setting the variables for any given engine, and each tends to have its own advantages and disadvantages. Moreover, each automobile manufacturer has a specific configuration that differs from competitive systems. However, this discussion is about a typical electronic control system that is highly representative of the systems for engines used by U.S. manufacturers. This typical system is one that has a catalytic converter in the exhaust system. Exhaust gases passed through this device are chemically altered in a way that helps meet EPA standards. Essentially, the catalytic converter reduces the concentration of undesirable exhaust gases coming out of the tailpipe relative to engine-out gases (the gases coming out of the exhaust manifold).

The use of catalytic converters to reduce emissions leaving the tailpipe allows engines to be calibrated for better performance and still meet emission regulations.

The EPA regulates only the exhaust gases that leave the tailpipe; therefore, if the catalytic converter reduces exhaust gas emission concentrations by 90%, the engine exhaust gas emissions at the exhaust manifold can be about 10 times higher than the EPA requirements. This has the significant benefit of allowing engine calibration to be set for better performance than would be permitted if exhaust emissions in the engine exhaust manifold had to satisfy EPA regulations. This is the type of system that is chosen for the typical electronic engine control system.

Several types of catalytic converters are available for use on an automobile. The desired functions of a catalytic converter include

1. Oxidation of hydrocarbon emissions to carbon dioxide (CO_2) and water (H_2O)
2. Oxidation of CO to CO_2
3. Reduction of NO_x to nitrogen (N_2) and oxygen (O_2)

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The oxidizing catalytic converter increases the rate of oxidation of HC and CO to further reduce HC and CO emissions.

Oxidizing Catalytic Converter

The oxidizing catalytic converter (Figure 5.12) has been one of the more significant devices for controlling exhaust emissions since the era of emission control began. The purpose of the oxidizing catalyst (OC) is to increase the rate of chemical reaction, which initially takes place in the cylinder as the compressed air–fuel mixture burns, toward an exhaust gas that has a complete oxidation of HC and CO to H_2O and CO_2.

The extra oxygen required for this oxidation is often supplied by adding air to the exhaust stream from an engine-driven air pump. This air, called *secondary air*, is normally introduced into the exhaust manifold.

The most significant measure of the performance of the OC is its conversion efficiency, n_c.

$$n_c = \frac{M_o}{M_i}$$

where

M_o is the mass flow rate of gas that has been oxidized leaving the converter

M_i is the mass air flow rate of gas into the converter

The conversion efficiency of the OC depends on its temperature. Figure 5.13 shows the conversion efficiency of a typical OC for both HC and CO as functions of temperature. Above about 300°C, the efficiency approaches 98% to 99% for CO and more than 95% for HC.

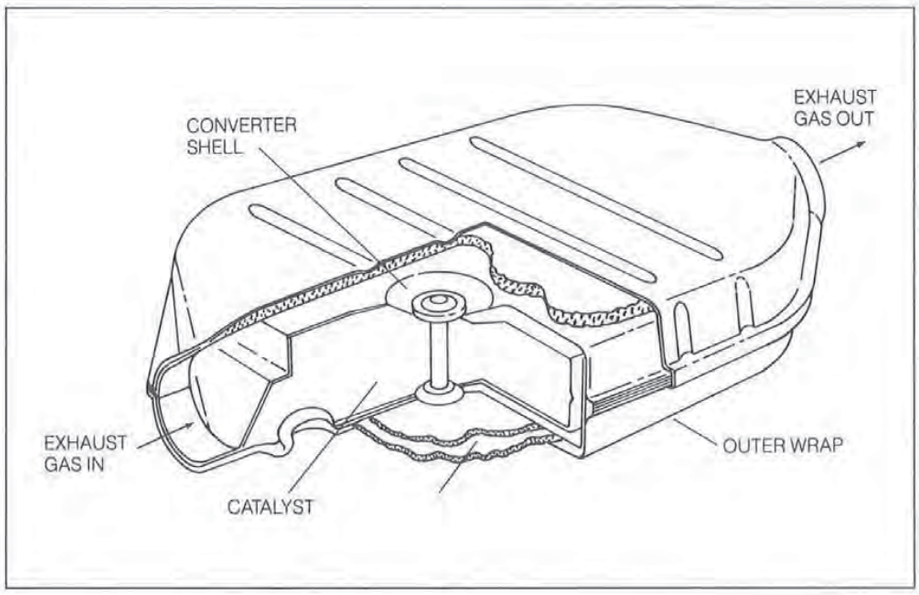


Figure 5.12 Oxidizing Catalytic Converter

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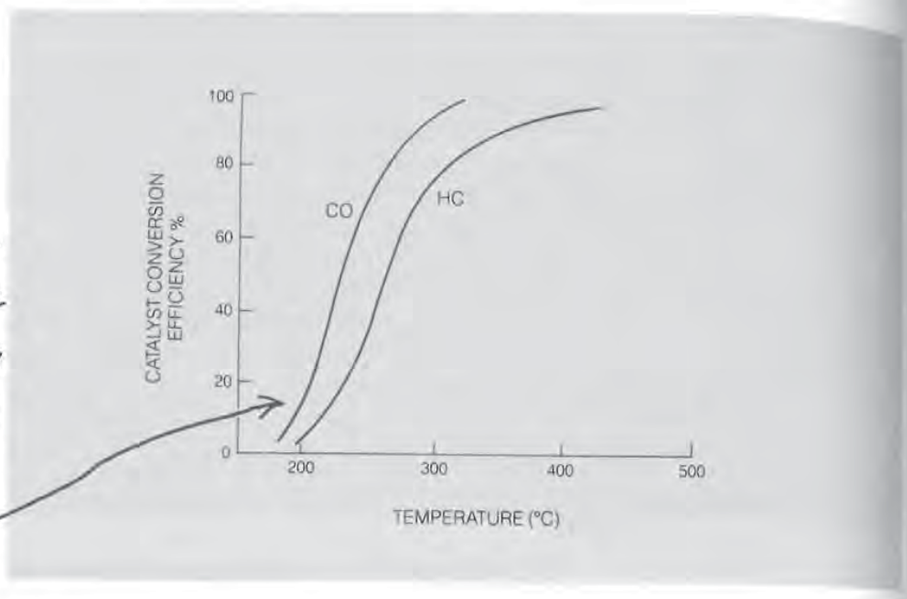


Figure 5.13 Oxidizing Catalyst Conversion Efficiency versus Temperature

Note loss of efficiency at low operating temperatures.

The three-way catalyst uses a specific chemical design to reduce all three major emissions (HC, CO, and NO_x) by approximately 90%.

The Three-Way Catalyst

Another catalytic converter configuration that is extremely important for modern emission control systems is called the three-way catalyst (TWC). It uses a specific catalyst formulation containing platinum, palladium, and rhodium to reduce NO_x and oxidize HC and CO all at the same time. It is called three-way because it simultaneously reduces the concentration of all three major undesirable exhaust gases by about 90% if used optimally.

The conversion efficiency of the TWC for the three exhaust gases depends mostly on the air/fuel ratio. Unfortunately, the air/fuel ratio for which NO_x conversion efficiency is highest corresponds to a very low conversion efficiency for HC and CO and vice versa. However, as shown in Figure 5.14, there is a very narrow range of air/fuel ratio (called the window) in which an acceptable compromise exists between NO_x and HC/CO conversion efficiencies. The conversion efficiencies within this window are sufficiently high to meet the very stringent EPA requirements established so far.

Note that this window is only about 0.1 air/fuel ratio wide (±0.05 air/fuel ratio) and is centered at stoichiometry. (Recall that stoichiometry is the air/fuel ratio that would result in complete oxidation of all carbon and hydrogen in the fuel if burning in the cylinder were perfect; for gasoline, stoichiometry corresponds to an air/fuel ratio of 14.7.) This ratio and the concept of stoichiometry is extremely important in an electronic fuel controller. In fact, the primary function of most modern electronic fuel control systems is to maintain average air/fuel ratio at stoichiometry. The operation of the three-way catalytic converter is adversely affected by lead. Thus, in automobiles using any catalyst, it is necessary to use lead-free fuel.

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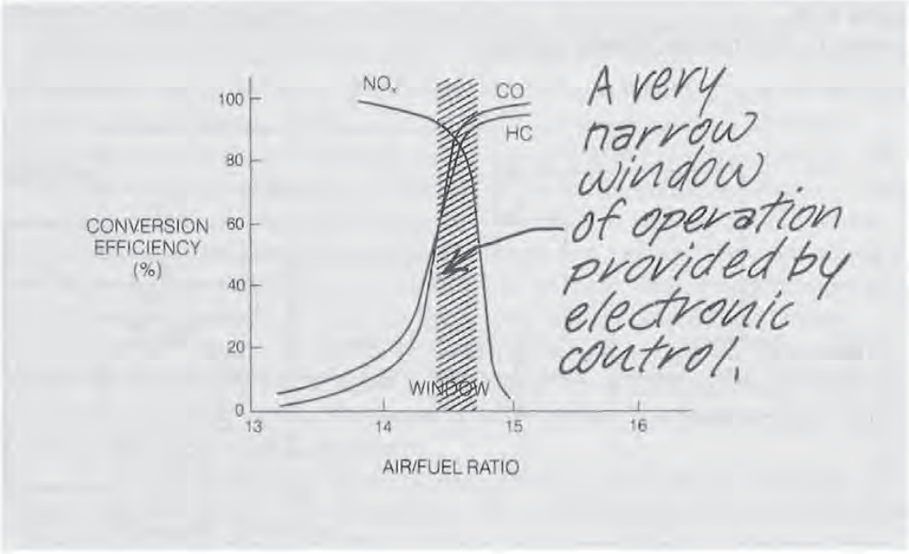


Figure 5.14 Conversion Efficiency of a TWC

The TWC operates at peak efficiency when the air/fuel ratio is at or very near stoichiometry. An electronic fuel control system is required to maintain the required air/fuel ratio.

Controlling the average air/fuel ratio to the tolerances of the TWC window (for 50,000 miles) requires accurate measurement of mass air flow rate and precise fuel delivery and is the primary function of the electronic engine control system. A modern electronic fuel control system can meet these precise fuel requirements. In addition, it can maintain the necessary tolerances for government regulations for over 50,000 miles.

ELECTRONIC FUEL CONTROL SYSTEM

For an understanding of the configuration of an electronic fuel control system, refer to the block diagram of Figure 5.15. The primary function of this fuel control system is to accurately determine the mass air flow rate into the engine. Then the control system precisely regulates fuel delivery such that the ratio of the mass of air to the mass of fuel in each cylinder is as close as possible to stoichiometry (i.e., 14.7).

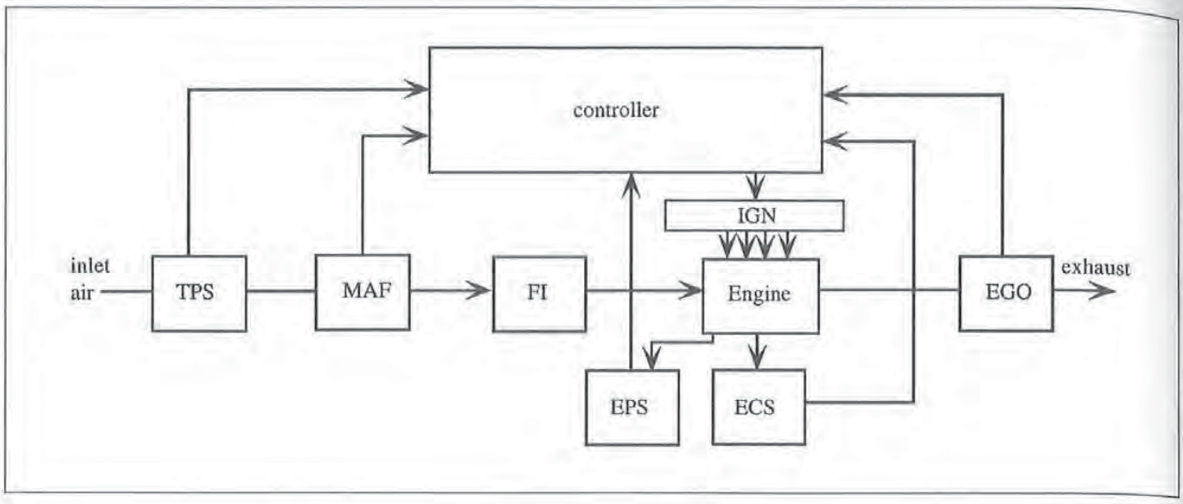
The components of this block diagram are as follows:

1. Throttle position sensor (TPS)
2. Mass air flow sensor (MAF)
3. Fuel injectors (FI)
4. Ignition systems (IGN)
5. Exhaust gas oxygen sensor (EGO)
6. Engine coolant sensor (ECS)
7. Engine position sensor (EPS)

The EPS has the capability of measuring crankshaft angular speed (RPM) as well as crankshaft angular position when it is used in conjunction with a stable and precise electronic clock (in the controller).

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Figure 5.15
Electronic Fuel Control Configuration



The signals from the various sensors enable the controller to determine the correct fuel flow in relation to the air flow to obtain the stoichiometric mixture. From this calculation the correct fuel delivery is regulated via fuel injectors. In addition, optimum ignition timing is determined and appropriate timing pulses are sent to the ignition control module (IGN).

There is an important property of the catalytic converter that allows for momentary (very short term) fluctuations of the air/fuel ratio outside the narrow window. As the exhaust gases flow through the catalytic converter they are actually in it for a short (but nonzero) amount of time, during which the conversions described above take place. Because of this time interval the conversion efficiency is unaffected by rapid fluctuations above and below stoichiometry (and outside the window) as long as the average air/fuel ratio over time remains at stoichiometry and provided the fluctuations are rapid enough. A practical fuel control system maintains the mixture at stoichiometry but has minor (relatively rapid) fluctuations about the average, as explained below.

The electronic fuel control system operates in two modes: open loop and closed loop. Recall the concepts for open-loop and closed-loop control as explained in Chapter 2. In the open-loop mode (also called feedforward), the mass air flow rate into the engine is measured. Then the fuel control system determines the quantity of fuel to be delivered to meet the required air/fuel ratio.

In the closed-loop control mode (also called feedback), a measurement of the controlled variable is provided to the controller (i.e., it is fed back) such that an error signal between the actual and desired values of the controlled variable is obtained. Then the controller generates an actuating signal that tends to reduce the error to zero.

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In the case of fuel control, the desired variables to be measured are HC, CO, and NO_x concentrations. Unfortunately there is no cost-effective, practical sensor for such measurements that can be built into the car's exhaust system. On the other hand, there is a relatively inexpensive sensor that gives an indirect measurement of HC, CO, and NO_x concentrations. This sensor generates an output that depends on the concentration of residual oxygen in the exhaust after combustion. As will be explained in detail in Chapter 6, this sensor is called an *exhaust gas oxygen* (EGO) *sensor.* It will be shown that the EGO sensor output switches abruptly between two voltage levels depending on whether the input air/fuel ratio is richer than or leaner than stoichiometry. Such a sensor is appropriate for use in a limit-cycle type of closed-loop control (described in Chapter 2). Although the EGO sensor is a switching-type sensor, it provides sufficient information to the controller to maintain the average air/fuel ratio over time at stoichiometry, thereby meeting the mixture requirements at the three-way catalytic converter.

In a typical modern electronic fuel control system, the fuel delivery is partly open loop and partly closed loop. The open-loop portion of the fuel flow is determined by measurement of air flow. This portion sets the air/fuel ratio at approximately stoichiometry. A closed-loop portion is added to the fuel delivery to ensure that time-average air/fuel ratio is at stoichiometry (within the tolerances of the window).

There are exceptions to the stoichiometric mixture setting during certain engine operating conditions, including engine start, heavy acceleration, and deceleration. These conditions represent a very small fraction of the overall engine operating times and are discussed in Chapter 7, which explains the operation of a modern, practical digital electronic engine control system.

Engine Control Sequence

Referring to Figure 5.15, the step-by-step process of events in fuel control begins with engine start. During engine cranking the mixture is set rich by an amount depending on the engine temperature (measured via the engine coolant sensor), as explained in detail in Chapter 7. Once the engine starts and until a specific set of conditions is satisfied, the engine control operates in the open-loop mode. In this mode the mass air flow is measured (via MAF sensor). The correct fuel amount is computed in the electronic controller as a function of engine temperature. The correct actuating signal is then computed and sent to the fuel metering actuator. In essentially all modern engines, fuel metering is accomplished by a set of fuel injectors (described in detail in Chapter 6).

After combustion the exhaust gases flow past the EGO sensor, through the TWC, and out the tailpipe. Once the EGO sensor has reached its operating temperature (typically a few seconds to about 2 min), the EGO sensor signal is read by the controller and the system begins closed-loop operation.

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Closed-Loop Control

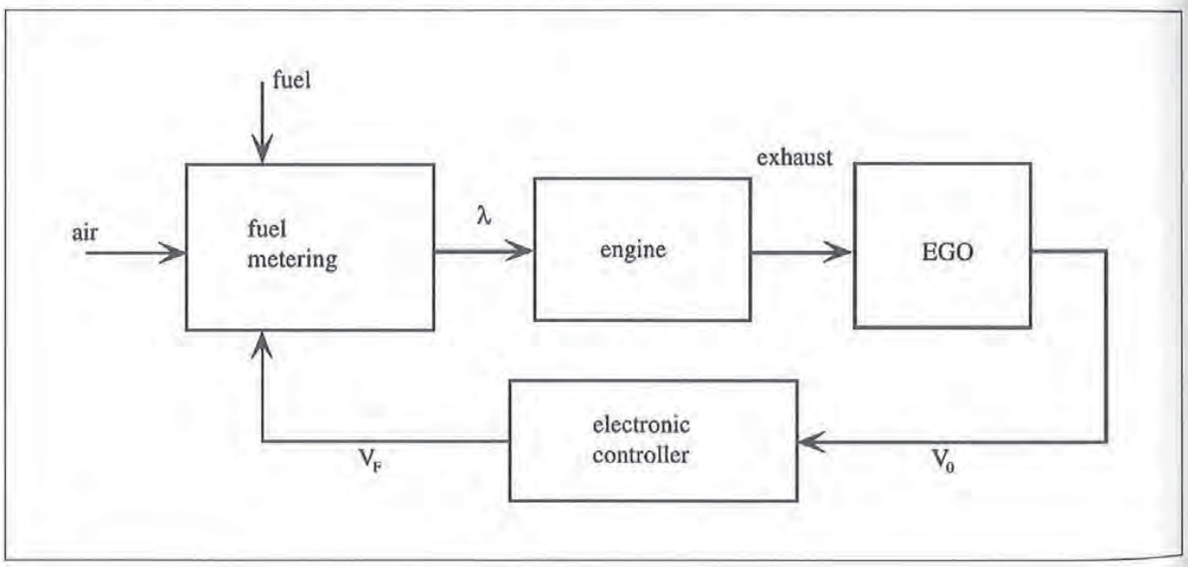
Figure 5.16 is a simplified block diagram of the closed-loop portion of the controller. The intake air passes through the individual pipes of the intake manifold to the various cylinders. The set of fuel injectors (one for each cylinder) is normally located near the intake valve (see Chapter 1). Each fuel injector is an electrically operated valve that is either fully open or fully closed. When the valve is closed there is, of course, no fuel delivery. When the valve is open, fuel is delivered at a fixed rate. The amount of fuel delivered to each cylinder is determined by the length of time that the fuel injector valve is open. This time is, in turn, computed in the engine controller to achieve the desired air/fuel ratio. Typically, the fuel injector open timing is set to coincide with the time that air is flowing into the cylinder during the intake stroke (see Chapter 1).

In the closed-loop mode of operation, the signals from the EGO sensor are used by the electronic controller to adjust the air/fuel ratio through the fuel metering actuator.

Referring to Figure 5.16, the control system operates as follows. For any given set of operating conditions, the fuel metering actuator provides fuel flow to produce an air/fuel ratio set by the controller output. This mixture is burned in the cylinder and the combustion products leave the engine through the exhaust pipe. The EGO sensor generates a feedback signal for the controller input that depends on the air/fuel ratio. This signal tells the controller to adjust the fuel flow rate for the required air/fuel ratio, thus completing the loop.

One control scheme that has been used in practice results in the air/fuel ratio cycling around the desired set point of stoichiometry. Recall from Chapter

Figure 5.16
Simplified Typical Closed-Loop Fuel Control System



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2 that this type of control is provided by a limit-cycle controller (e.g., a typical furnace controller). The important parameters for this type of control include the amplitude and frequency of excursion away from the desired stoichiometric set point. Fortunately, the three-way catalytic converter's characteristics are such that only the time-average air/fuel ratio determines its performance. The variation in air/fuel ratio during the limit-cycle operation is so rapid that it has no effect on engine performance or emissions, provided that the average air/fuel ratio remains at stoichiometry.

Exhaust Gas Oxygen Concentration

The EGO sensor is used to determine the air/fuel ratio.

The EGO sensor, which provides feedback, will be explained in Chapter 6. In essence, the EGO generates an output signal that depends on the amount of oxygen in the exhaust. This oxygen level, in turn, depends on the air/fuel ratio entering the engine. The amount of oxygen is relatively low for rich mixtures and relatively high for lean mixtures. In terms of equivalence ratio (λ), recall that $\lambda = 1$ corresponds to stoichiometry, $\lambda > 1$ corresponds to a lean mixture with an air/fuel ratio greater than stoichiometry, and $\lambda < 1$ corresponds to a rich mixture with an air/fuel ratio less than stoichiometry. (The EGO sensor is sometimes called a lambda sensor.)

Lambda is used in the block diagram of Figure 5.16 to represent the equivalence ratio at the intake manifold. The exhaust gas oxygen concentration determines the EGO output voltage (V_o). The EGO output voltage abruptly switches between the lean and the rich levels as the air/fuel ratio crosses stoichiometry. The EGO sensor output voltage is at its higher of two levels for a rich mixture and at its lower level for a lean mixture.

In a closed-loop system, the time delay between sensing a deviation and performing an action to correct for the deviation must be compensated for in system design.

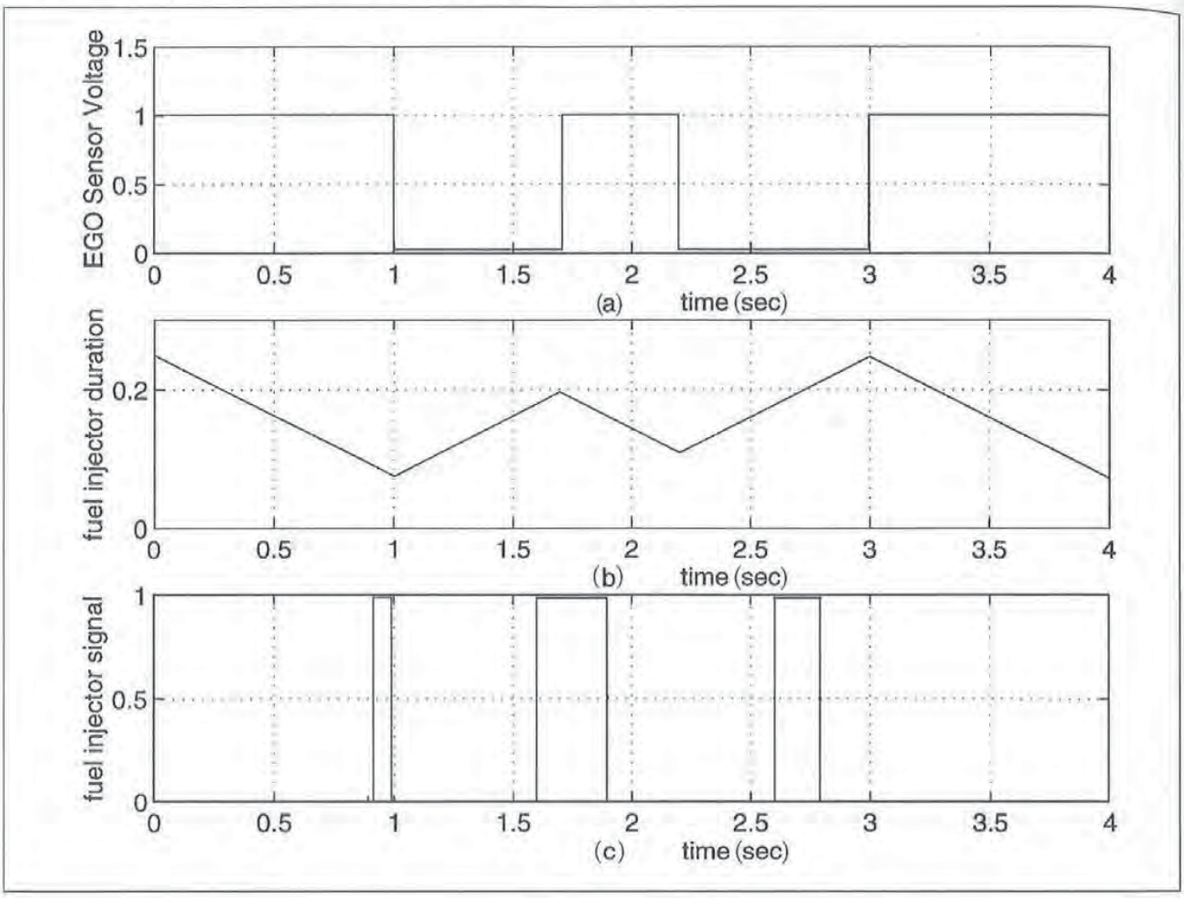
The operation of the control system of Figure 5.16 using EGO output voltage is complicated somewhat because of the delay from the time that λ changes at the input until V_o changes at the exhaust. This time delay, t_D, is in the range of 0.1 to 0.2 second, depending on engine speed. It is the time that it takes the output of the system to respond to a change at the input. The electrical signal from the EGO sensor voltage going into the controller produces a controller output of V_F, which energizes the fuel metering actuator.

Closed-Loop Operation

Reduced to its essential features, the engine control system operates as a limit-cycle controller in which the air/fuel ratio cycles up and down about the set point of stoichiometry, as shown in Figure 5.17. The air/fuel ratio is either increasing or decreasing; it is never constant. The increase or decrease is determined by the EGO sensor output voltage. Whenever the EGO output voltage level indicates a lean mixture, the controller causes the air/fuel ratio to decrease, that is, to change in the direction of a rich mixture. On the other hand, whenever the EGO sensor output voltage indicates a rich mixture, the controller changes the air/fuel ratio in the direction of a lean mixture.

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Figure 5.17
Simplified Waveforms in a Closed-Loop Fuel Control System



The air/fuel ratio in a closed-loop system is always increasing or decreasing in the vicinity of stoichiometry. This is in response to the EGO sensor's output, which indicates a rich or lean fuel mixture.

The electronic fuel controller changes the mixture by changing the duration of the actuating signal to each fuel injector. Increasing this duration causes more fuel to be delivered, thereby causing the mixture to become more rich. Correspondingly, decreasing this duration causes the mixture to become more lean. Figure 5.17b shows the fuel injector signal duration.

In Figure 5.17a the EGO sensor output voltage is at the higher of two levels over several time intervals, including 0 to 1 and 1.7 to 2.2. This high voltage indicates that the mixture is rich. The controller causes the pulse duration (Figure 5.17b) to decrease during this interval. At time 1 sec the EGO sensor voltage switches low, indicating a lean mixture. At this point the controller begins increasing the actuating time interval to tend toward a rich mixture. This increasing actuator interval continues until the EGO sensor switches high, causing

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the controller to decrease the fuel injector actuating interval. The process continues this way, cycling back and forth between rich and lean around stoichiometry.

During any one of the intervals shown in Figure 5.17, the fuel injectors may be activated several times. The engine controller continuously computes the desired fuel injector actuating interval (as explained later) and maintains the current value in memory. At the appropriate time in the intake cycle (see Chapter 1), the controller reads the value of the fuel injector duration and generates a pulse of the correct duration to activate the proper fuel injector.

Figure 5.17c illustrates the actuating signals for a single fuel injector. The pulses correspond to the times at which this fuel injector is activated. The duration of each pulse determines the quantity of fuel delivered during that activation interval. This fuel injector is switched on repeatedly at the desired time. The on duration is determined from the height of the desired actuator duration of Figure 5.17b. Note that the first pulse corresponds to a relatively low value. The second corresponds to a relatively high value, and the duration of the on time shown in Figure 5.17c is correspondingly longer. The last pulse shown happens to occur at an intermediate duration value and is depicted as being of duration between the other two. The pulses depicted in Figure 5.17c are somewhat exaggerated relative to an actual fuel control to illustrate the principle of this type of control system.

One point that needs to be stressed at this juncture is that the air/fuel ratio deviates from stoichiometry. However, the catalytic converter will function as desired as long as the time-average air/fuel ratio is at stoichiometry. The controller continuously computes the average of the EGO sensor voltage. Ideally the air/fuel ratio should spend as much time rich of stoichiometry as it does lean of stoichiometry. In the simplest case, the average EGO sensor voltage should be halfway between the rich and the lean values:

$$\text{avg. } V_{EGO} = \frac{V_{Rich} + V_{Lean}}{2}$$

Whenever this condition is not met, the controller adapts its computation of pulse duration (from EGO sensor voltage) to achieve the desired average stoichiometric mixture. Chapter 7 explains this adaptive control in more detail.

Frequency and Deviation of the Fuel Controller

Recall from Chapter 2 that a limit cycle controls a system between two limits and that it has an oscillatory behavior; that is, the control variable oscillates about the set point or the desired value for the variable. The simplified fuel controller operates in a limit-cycle mode and, as shown in Figure 5.17, the air/fuel ratio oscillates about stoichiometry (i.e., average air/fuel ratio is 14.7). The two end limits are determined by the rich and lean voltage levels of the EGO sensor, by the controller, and by the characteristics of the fuel metering actuator. The time necessary for the EGO sensor to sense a change in fuel metering is known as the transport delay. As engine speed increases, the transport delay decreases.

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The frequency of oscillation f_L of this limit-cycle control system is defined as the reciprocal of its period. The period of one complete cycle is denoted T_p, which is proportional to transport delay. Thus, the frequency of oscillation is

$$f_L = \frac{1}{T_p}$$

where f_L is the frequency of oscillation in hertz (cycles per second). This means that the shorter the transport delay, the higher the frequency of the limit cycle. The transport delay decreases as engine speed increases; therefore, the limit-cycle frequency increases as engine speed increases. This is depicted in Figure 5.18 for a typical engine.

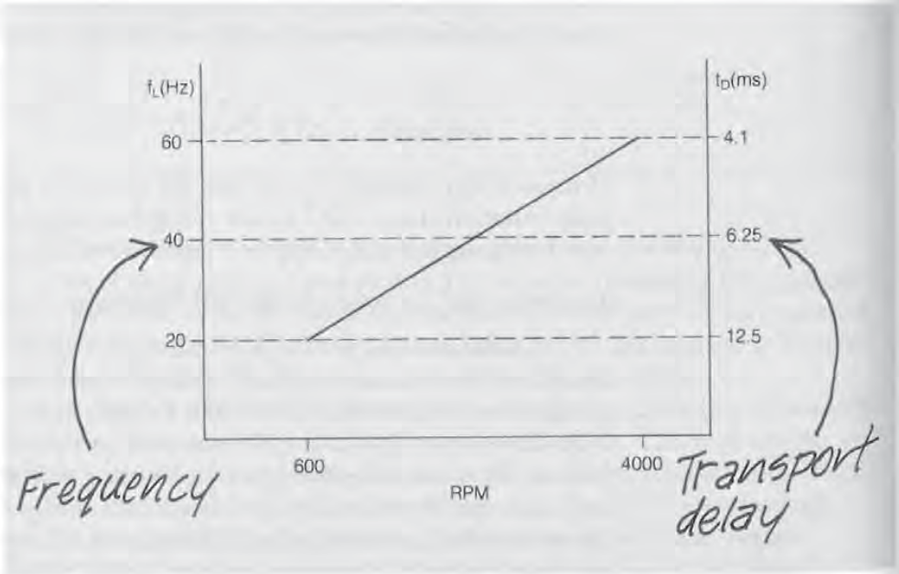
Although the air/fuel ratio is constantly swinging up and down, the average value of deviation is held within ±0.05 of the 14.7:1 ratio.

Another important aspect of limit-cycle operation is the maximum deviation of air/fuel ratio from stoichiometry. It is important to keep this deviation small because the net TWC conversion efficiency is optimum for stoichiometry. The maximum deviation typically corresponds to an air/fuel ratio deviation of about ±1.0.

It is important to realize that the air/fuel ratio oscillates between a maximum value and a minimum value. There is, however, an average value for the air/fuel ratio that is intermediate between these extremes. Although the deviation of the air/fuel ratio during this limit-cycle operation is about ±1.0, the *average* air/fuel ratio is held to within ±0.05 of the desired value of 14.7.

Generally, the maximum deviation decreases with increasing engine speed because of the corresponding decrease in transport delay. The parameters of the

Figure 5.18 Typical Limit-Cycle Frequency versus RPM



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control system are adjusted such that at the worst case the deviation is within the required acceptable limits for the TWC used.

The preceding discussion applies only to a simplified idealized fuel control system. Chapter 7 explains the operation of practical electronic fuel control systems in which the main signal processing is done with digital techniques.

OPEN-LOOP MODE

Fuel control systems in open-loop mode must maintain the air/fuel mixture at or near stoichiometry, but must do it without the benefit of feedback.

The open-loop mode of fuel control must accomplish the same thing as the closed-loop mode; that is, it must maintain an air/fuel ratio very close to stoichiometry for efficient system operation with the TWC used. However, it must do it without feedback from the EGO sensor output, which senses the actual air/fuel ratio. Recall from the previous discussion that open-mode operation precedes closed-mode operation.

Although the open-loop mode of operation varies somewhat from one model to the next, many features of this mode of operation are common to all models. In reading the following discussion it is important to realize that the throttle (under driver control) actually controls the flow of *air* into the engine. The correct *fuel* flow is determined by the engine control system.

ANALYSIS OF INTAKE MANIFOLD PRESSURE

The air and fuel mixture enters the engine through the *intake manifold*, a series of channels and passages that directs the air and fuel mixture to the cylinders. One very important engine variable associated with the intake manifold is the manifold absolute pressure (MAP). The sensor that measures this pressure is the manifold absolute pressure sensor—the MAP sensor. This sensor develops a voltage that is approximately proportional to the average value of intake manifold pressure.

The MAP sensor output voltage is proportional to the average pressure within the intake manifold.

Figure 5.19 is a very simplified sketch of an intake manifold. In this simplified sketch, the engine is viewed as an air pump drawing air into the intake manifold. Whenever the engine is not running, no air is being pumped and the intake MAP is at atmospheric pressure. This is the highest intake MAP for an unsupercharged engine. (A supercharged engine has an external air pump called a supercharger.) When the engine is running, the air flow is impeded by the partially closed throttle plate. This reduces the pressure in the intake manifold so it is lower than atmospheric pressure; therefore, a partial vacuum exists in the intake.

The manifold absolute pressure varies from near atmospheric pressure when the throttle plate is fully opened to near zero pressure when the throttle plate is closed.

If the engine were a perfect air pump and if the throttle plate were tightly closed, a perfect vacuum could be created in the intake manifold. A perfect vacuum corresponds to zero absolute pressure. However, the engine is not a perfect pump and some air always leaks past the throttle plate. (In fact, some air must get past a closed throttle or the engine cannot idle.) Therefore, the intake MAP fluctuates during the stroke of each cylinder and as pumping is switched from one cylinder to the next.

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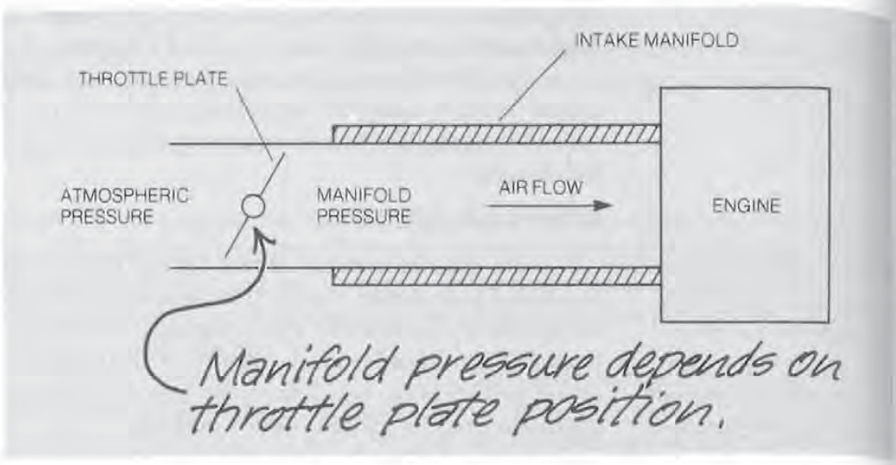


Figure 5.19 Simplified Intake System

Each cylinder contributes to the pumping action every second crankshaft revolution. For an N-cylinder engine, the frequency f_p, in cycles per second, of the manifold pressure fluctuation for an engine running at a certain RPM is given by

$$f_p = \frac{N \times \text{RPM}}{120}$$

Figure 5.20 shows manifold pressure fluctuations as well as average MAP.

For a control system application, only average manifold pressure is required. The torque produced by an engine at a constant RPM is approximately proportional to the average value of MAP. The rapid fluctuations in instantaneous MAP are not of interest to the engine controller. Therefore, the manifold pressure measurement method should filter out the pressure fluctuations at frequency f_p and measure only the average pressure. One way to achieve this filtering is to connect the MAP sensor to the intake manifold through a very small diameter tube. The rapid fluctuations in pressure do not pass through this tube, but the average pressure does. The MAP sensor output voltage then corresponds only to the average manifold pressure.

Measuring Air Mass

A critically important aspect of fuel control is the requirement to measure the mass of air that is drawn into the cylinder (i.e., the air *charge*). The amount of fuel delivered can then be calculated such as to maintain the desired air/fuel ratio. There is no practically feasible way of measuring the mass of air in the cylinder directly. However, the air charge can be determined from the mass flow

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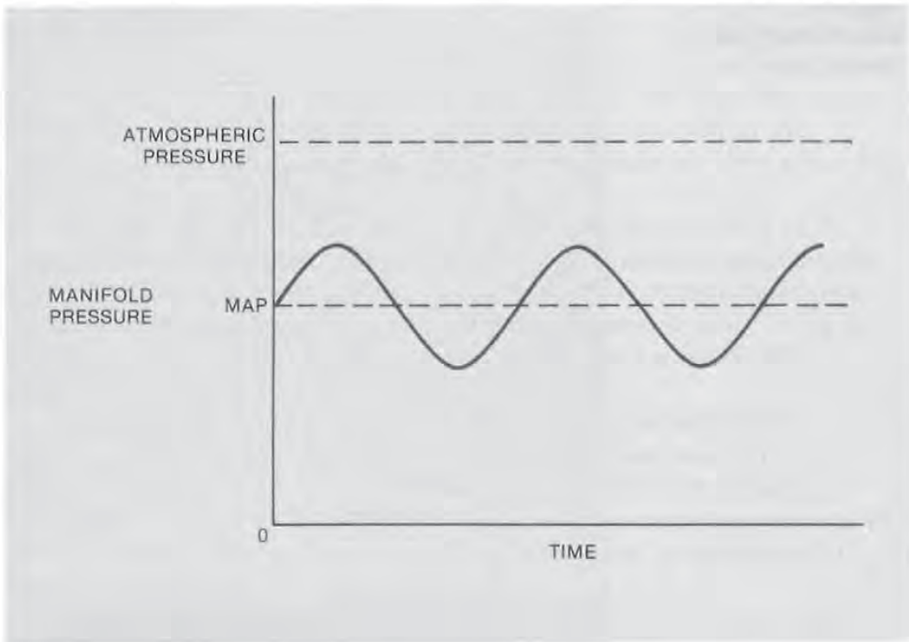


Figure 5.20 Intake Manifold Pressure Fluctuations

rate of air into the engine intake since all of this air eventually is distributed to the cylinders (ideally uniformly).

There are two methods of determining the mass flow rate of air into the engine. One method uses a single sensor that directly measures mass air flow rate. The operation of this sensor is explained in Chapter 6. The other method uses a number of sensors that provide data from which mass flow rate can be computed. This method is known as the speed-density method.

Speed-Density Method

The concept for this method is based on the mass density of air as illustrated in Figure 5.21a. For a given volume of air (V) at a specific pressure (p) and temperature (T), the density of the air (d_a) is the ratio of the mass of air in that volume (M_a) divided by V:

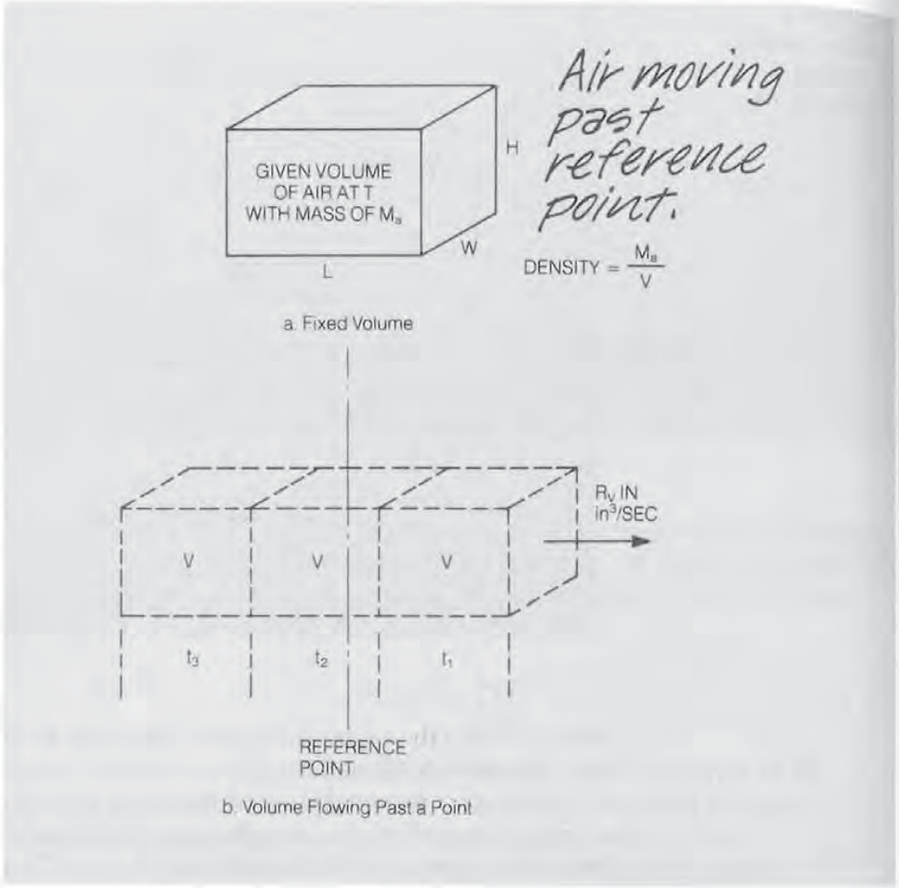
$$d_a = \frac{M_a}{V}$$

Another way of looking at this is that the mass of air in the volume V is the product of its density and volume:

$$M_a = d_a V$$

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Figure 5.21
Volume Flow Rate Calculation



This concept can be extended to moving air, as depicted in Figure 5.21b. Here air is assumed to be moving through a uniform tube (e.g., the intake pipe for an engine) past a reference point for a specific period of time. This is known as the volume flow rate. The mass flow rate is the product of the volume flow rate and the air density. The air density in the intake manifold can be computed from measurements of the intake manifold absolute pressure and the intake manifold air temperature (T_i).

In mathematical terms, if we define

R_m = mass flow rate of air flowing through the intake manifold
R_v = volume flow rate of air flowing through the intake manifold
d_a = air density in the intake manifold

then the following equation expresses the relationship between R_m, R_v, and d_a:

$$R_m = R_v d_a$$

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The intake manifold air density is determined by the absolute pressure and temperature of the intake air. The intake manifold absolute pressure is determined by the ambient air pressure (i.e., the air outside the engine), the throttle position as set by the driver, the RPM, and by the shape and size of the intake manifold. The intake air temperature is determined by the ambient air temperature and by the pressure change from ambient across the throttle.

The intake air density can be computed from the basic physics of air known as the perfect gas law. The density of any gas (including air) is directly proportional to pressure and inversely proportional to absolute temperature. (Absolute temperature is the temperature relative to absolute zero.) Using the Fahrenheit scale, absolute temperature is the temperature added to 459° in degrees Fahrenheit.

The intake air can be computed relative to a standard condition. Normally, the standard condition is sea level on a so-called standard day (SLSD). The SLSD conditions are denoted d_o, p_o, T_o, referring to density, absolute pressure, and absolute temperature. These parameters are constants for air for the entire planet and are known to great precision. In mathematical terms, the intake air density is given by

$$d_a = d_o \times \left(\frac{p}{p_o}\right) \times \frac{T_o}{T_i}$$

That is, intake air density is found by multiplying standard density by the ratio of intake manifold pressure to standard pressure and by the ratio of standard temperature to intake manifold air temperature. Such a calculation is readily performed in a digital engine controller based on measurements of intake manifold absolute pressure (MAP) and intake air absolute temperature (IAT).

A relatively close estimate of R_v can be made using inexpensive sensors. As discussed previously, the engine acts like an air pump during intake. If it were a perfect pump, it would draw in a volume of air equal to its displacement for each two complete crankshaft revolutions. Then, for this ideal engine, the volume flow rate would be

$$R_v = \left(\frac{\text{RPM}}{60}\right)\left(\frac{D}{2}\right) \text{ ideal volume flow rate}$$

where

R_v is the volume flow rate
D is the engine displacement
RPM is the engine speed

For this ideal engine, with D known, R_v could be obtained simply by measuring RPM.

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Unfortunately, the engine is not a perfect air pump. In fact, the actual volume flow rate for an engine having displacement D and running at speed RPM is given by

$$R_v = \left(\frac{\text{RPM}}{60}\right)\left(\frac{D}{2}\right)n_v$$

where n_v is the volumetric efficiency.

Volumetric Efficiency

Volumetric efficiency varies with MAP and engine speed. A table of values representing volumetric efficiency for given speeds and MAP values can be stored in memory as a lookup table.

The volumetric efficiency is a number between 0 and 1 that depends on intake manifold pressure (MAP) and RPM for all engine operating conditions. For any given engine, the value of n_v can be measured for any set of operating conditions. A table of values of n_v as a function of RPM and MAP can be prepared from this data. In a digital system, the table can be stored in memory as a lookup table. By knowing the displacement of the engine, measuring the RPM and MAP, and looking up the value of n_v for that RPM and MAP, the R_v can be computed using the previous equation.

Including EGR

Exhaust gas recirculation also must be considered when calculating volume flow rate. The true volume flow rate of air is calculated by subtracting the volume flow rate of EGR from the total volume flow rate.

Calculating R_v is relatively easy for a computer, but another factor must be taken into account. Exhaust gas recirculation requires that a certain portion of the charge into the cylinders be exhaust gas. Because of this, a portion of the displacement D is exhaust gas; therefore, the volume flow rate of EGR must be known. A valve-positioning sensor in the EGR valve can be calibrated to provide the flow rate.

From this information, the true volume flow rate of air, R_a, can be determined by subtracting the volume flow rate of EGR (R_{EGR}) from R_v. The total cylinder air charge is thus given as follows:

$$R_a = R_v - R_{EGR}$$

The volume flow rate of EGR is known from the position of the EGR valve and from engine operating conditions, as explained in Chapter 7.

Substituting the equation for R_v, the volume flow rate of air is

$$R_a = \left[\left(\frac{\text{RPM}}{60}\right)\left(\frac{D}{2}\right)n_v\right] - R_{EGR}$$

Knowing R_a and the density d_a gives the mass flow rate of air R_m as follows:

$$R_m = R_a d_a$$

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

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

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

ELECTRONIC IGNITION

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

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

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

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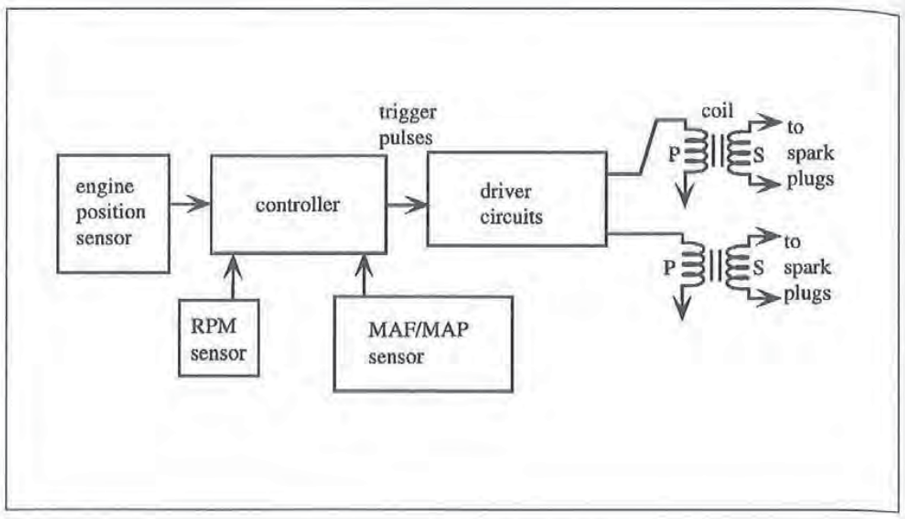


Figure 5.22 Electronic Distributorless Ignition System

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

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

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Quiz for Chapter 5

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

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

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

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

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

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

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

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

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

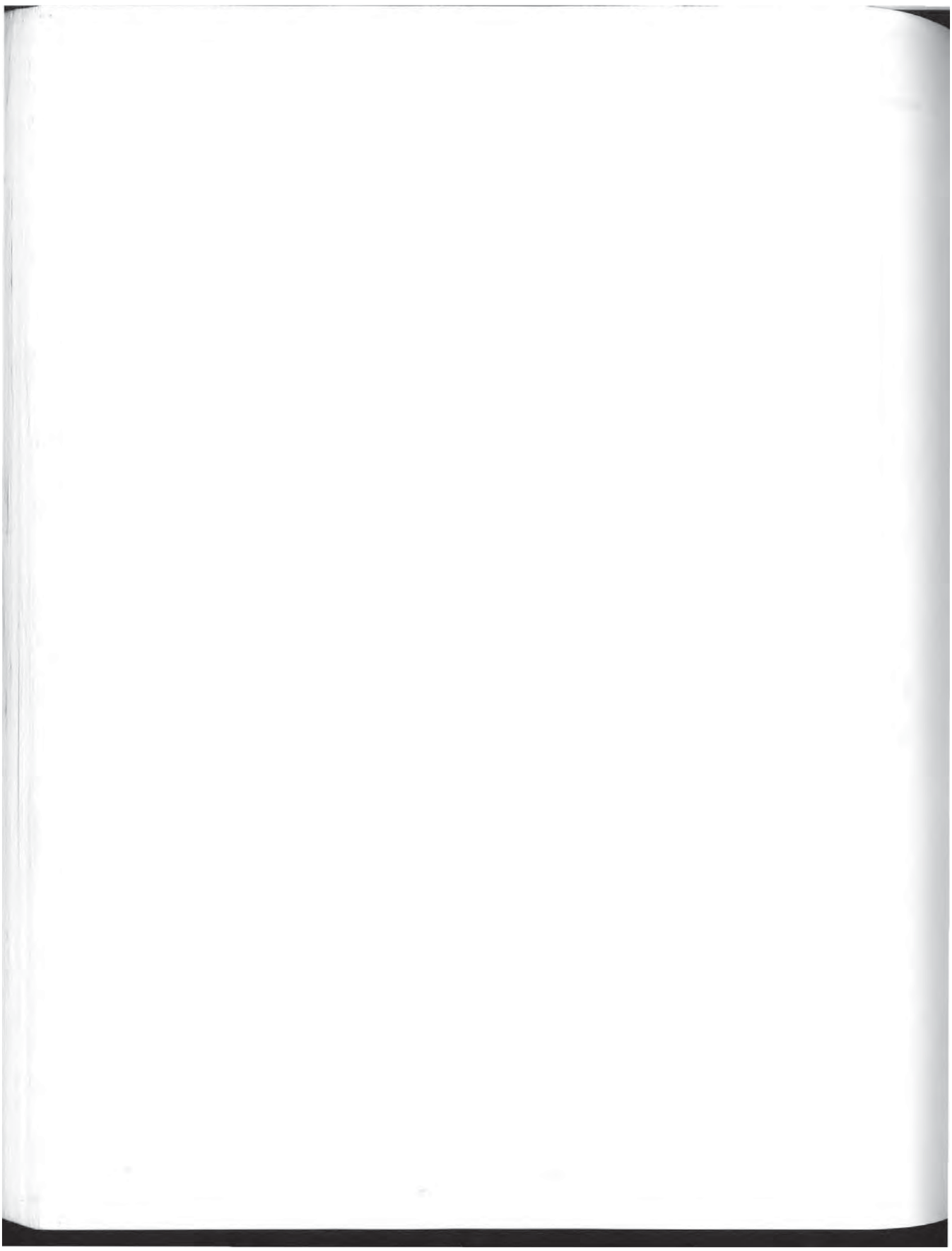
17. In an electronic fuel control system, what causes the time delay between fuel metering and the EGO sensor response?
   a. dynamic response of the electronics
   b. transport time of the air and fuel through the engine
   c. limit-cycle theory
   d. none of the above

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

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

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Sensors and Actuators

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

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

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

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

AUTOMOTIVE CONTROL SYSTEM APPLICATIONS OF SENSORS AND ACTUATORS

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

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

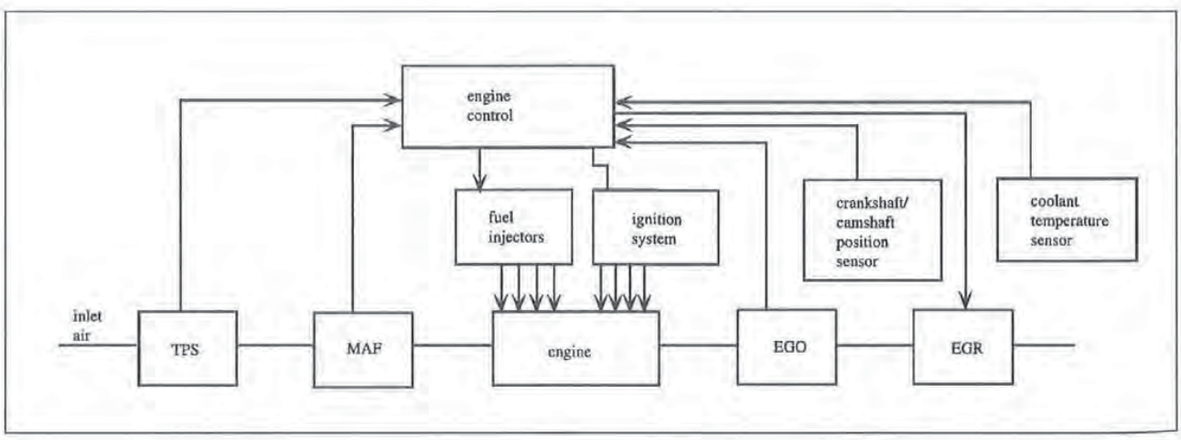
The sensors and actuators that are available to a control system designer are not always what the designer wants, because the ideal device may not be commercially available at acceptable costs. For this reason, often special signal processors or interface circuits are designed to adapt to an available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

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

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

Figure 6.1
Typical Electronic Engine Control System



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Variables to be Measured

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

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

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

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

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

AIR FLOW RATE SENSOR

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

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

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

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

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

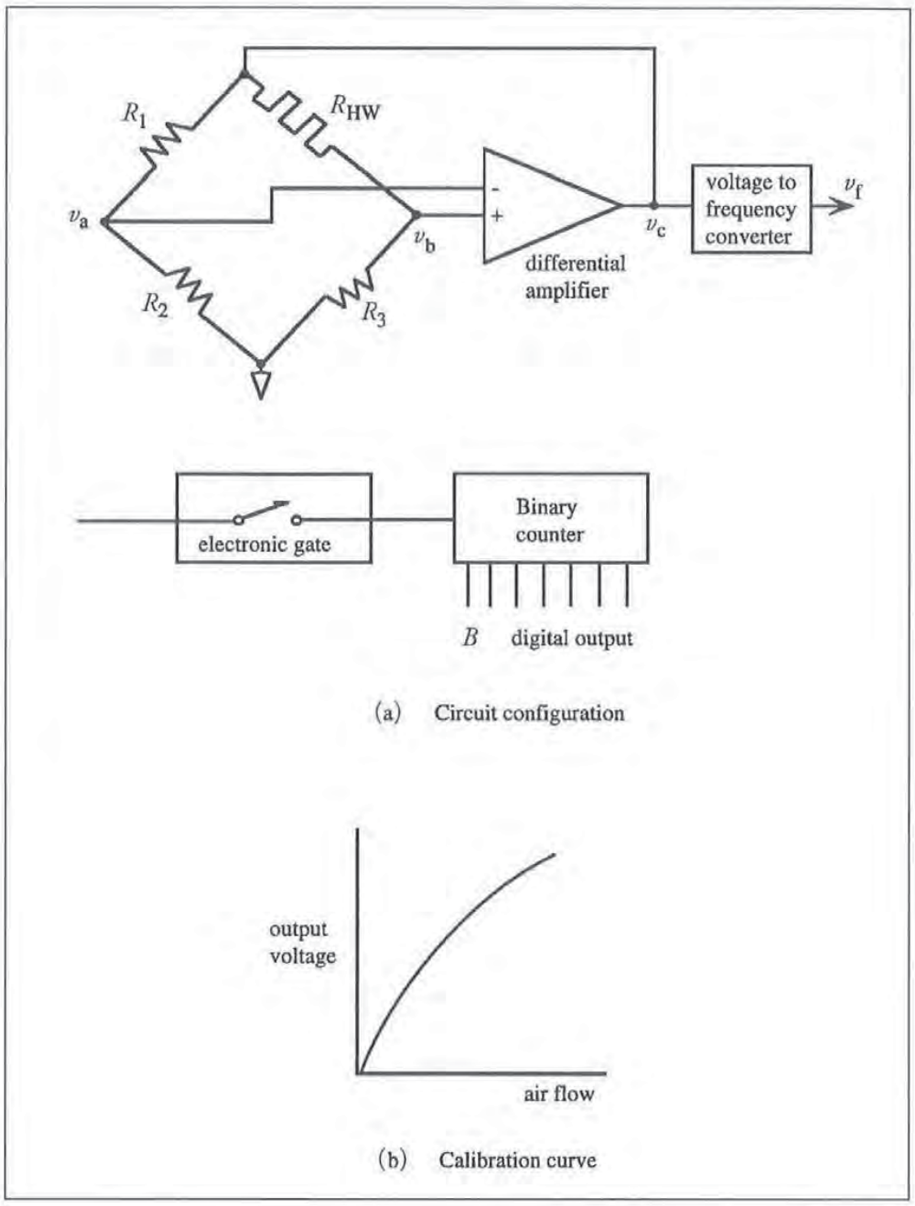
The amplifier output voltage v_c varies with MAF and serves as a measure of R_m. Typically the conversion of MAF to voltage is slightly nonlinear, as indicated by the calibration curve depicted in Figure 6.2b. Fortunately, a modern digital engine controller can convert the analog bridge output voltage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

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

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

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Figure 6.2
Mass Air Flow Sensor



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

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

$$B = ft$$

where

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

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

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

Indirect Measurement of Mass Air Flow

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

MAP Sensor Concepts

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

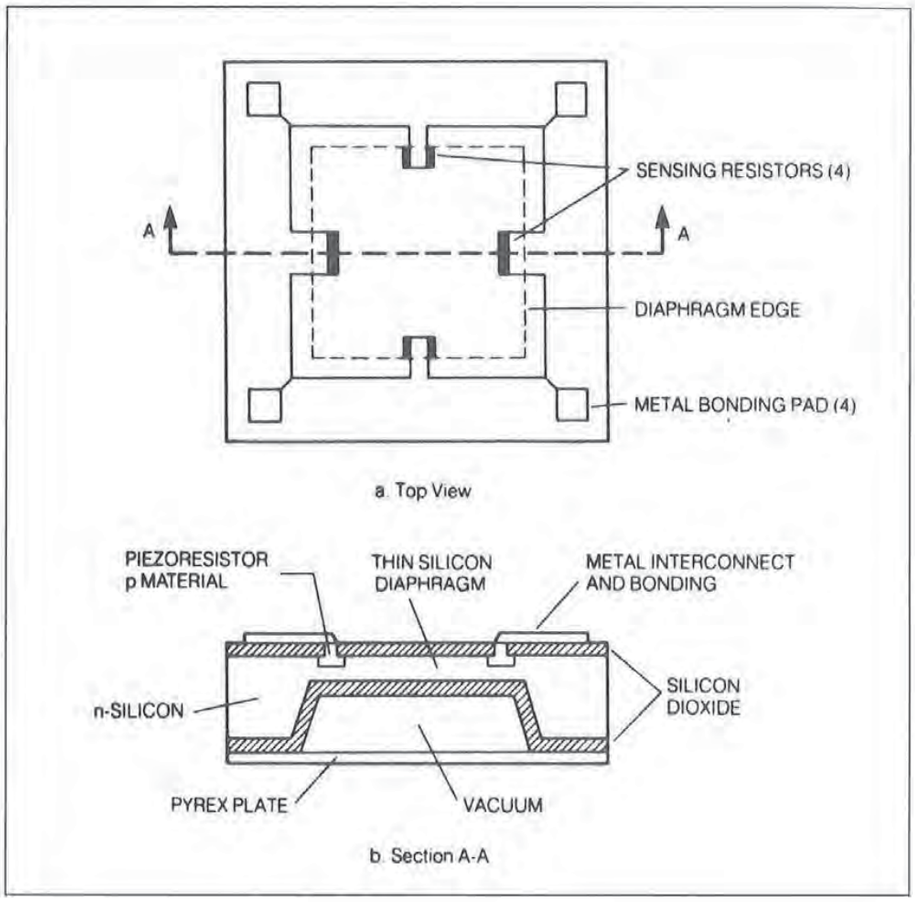
It is interesting to note that none of the MAP sensors in use measure manifold pressure directly, but instead measure the displacement of a diaphragm that is deflected by manifold pressure. The details of the diaphragm displacement and the measurement of this displacement vary from one configuration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

Strain Gauge MAP Sensor

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

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Figure 6.3 Typical Silicon-Diaphragm Strain Gauge MAP Sensor



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

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

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

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

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

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

ENGINE CRANKSHAFT ANGULAR POSITION SENSOR

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

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

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

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

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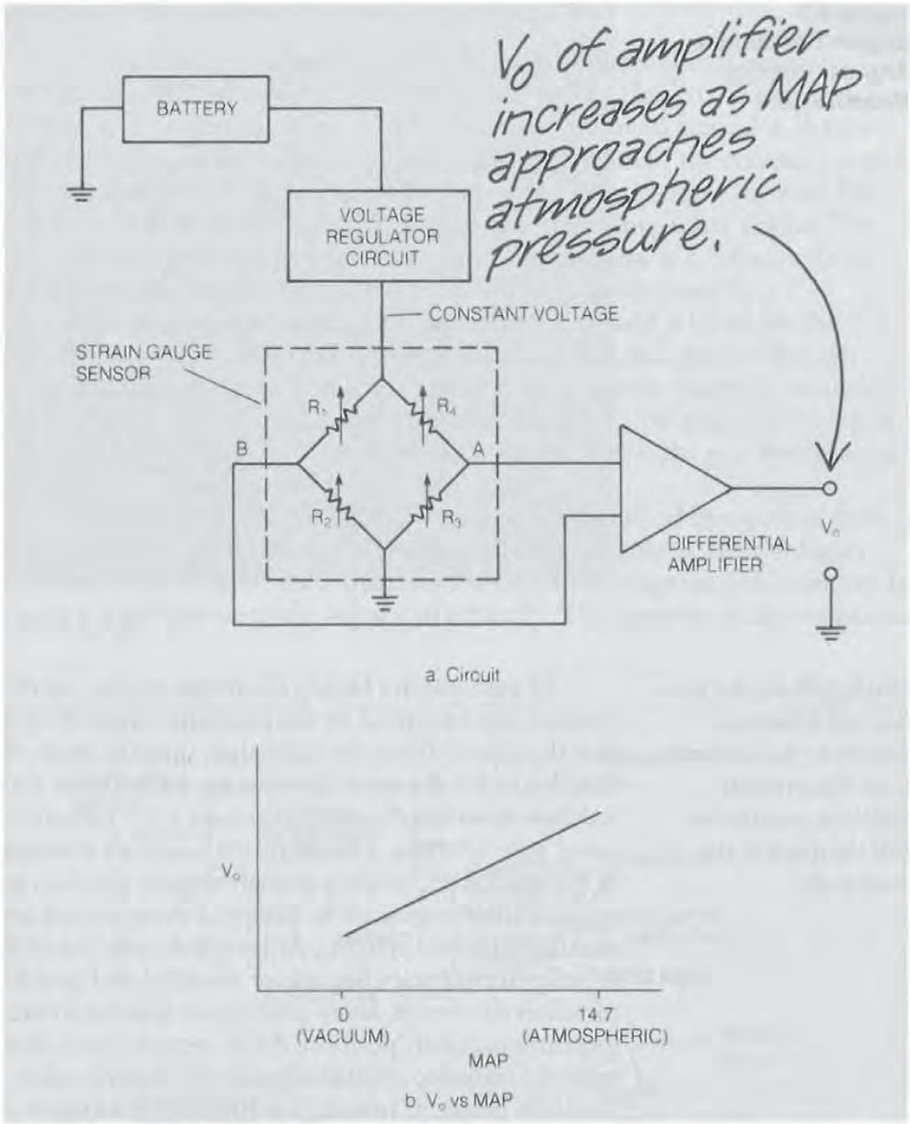
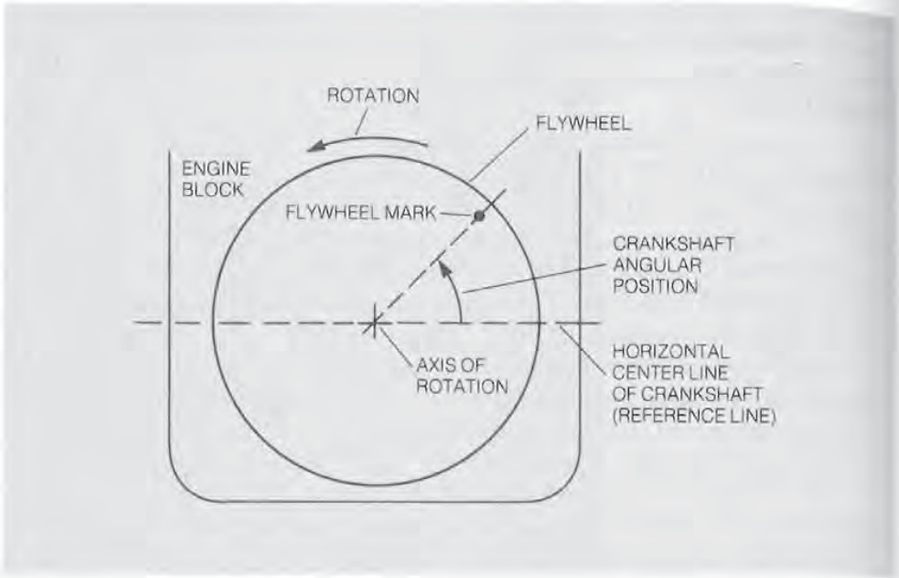


Figure 6.4
Circuit Diagram for MAP Sensor Using Strain Gauges

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

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Figure 6.5
Engine Crankshaft Angular Position Measurement



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

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

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

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Magnetic Reluctance Position Sensor

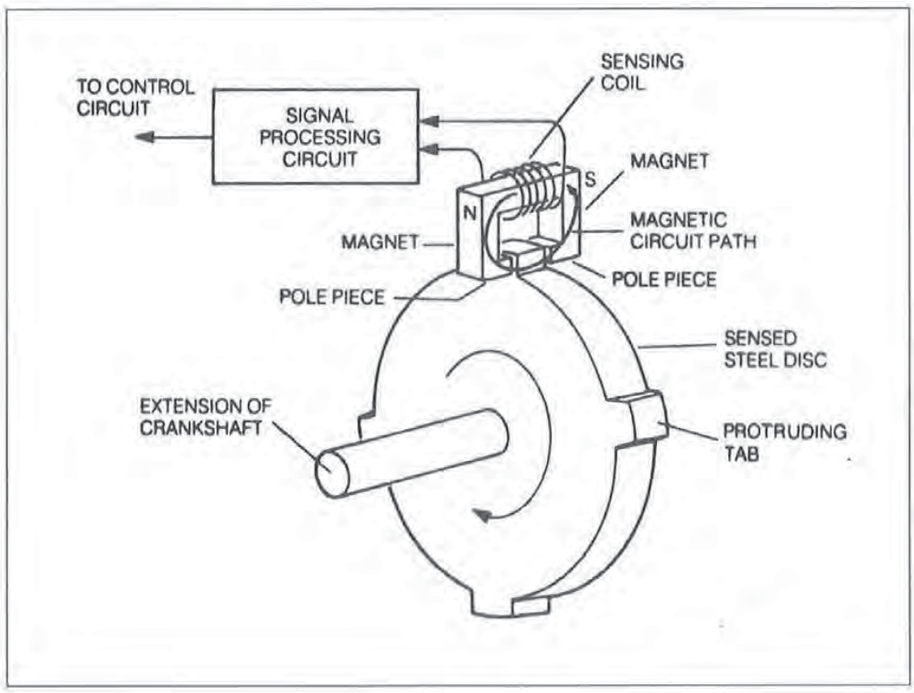
In the magnetic reluctance position sensor, a coil wrapped around the magnet senses the changing intensity of the magnetic field as the tabs of a ferrous disk pass between the poles of the magnet.

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

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

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

Figure 6.6
Magnetic Reluctance Crankshaft Position Sensor



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

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

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

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

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

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

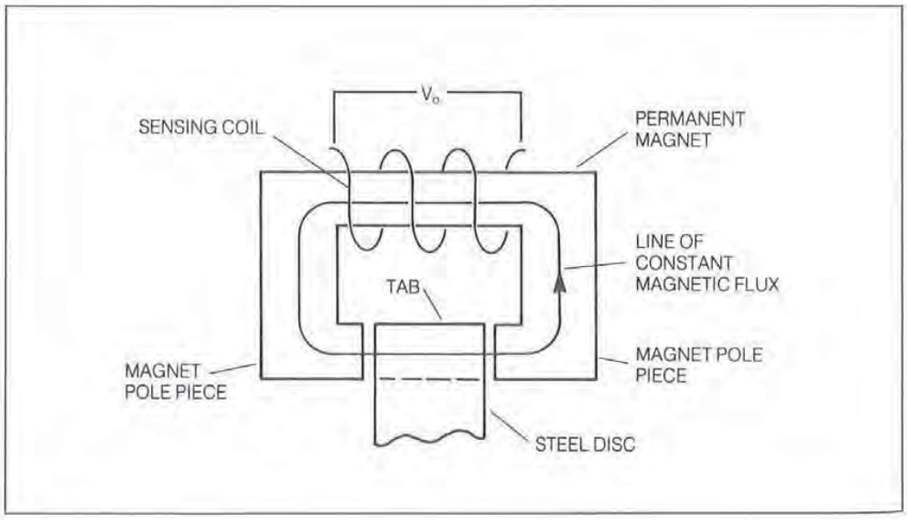


Figure 6.7 Magnetic Circuit of the Reluctance Sensor

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

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

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

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

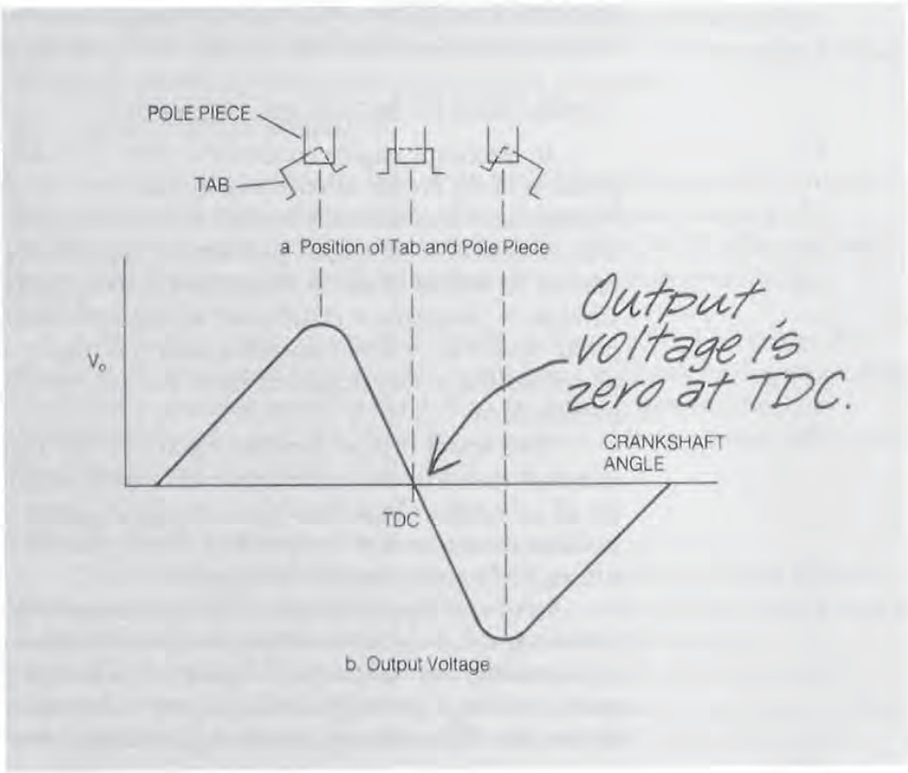


Figure 6.8 Output Voltage Waveform from the Magnetic Reluctance Crankshaft Position Sensor Coil

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

Engine Speed Sensor

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

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

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

Timing Sensor for Ignition and Fuel Delivery

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

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

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

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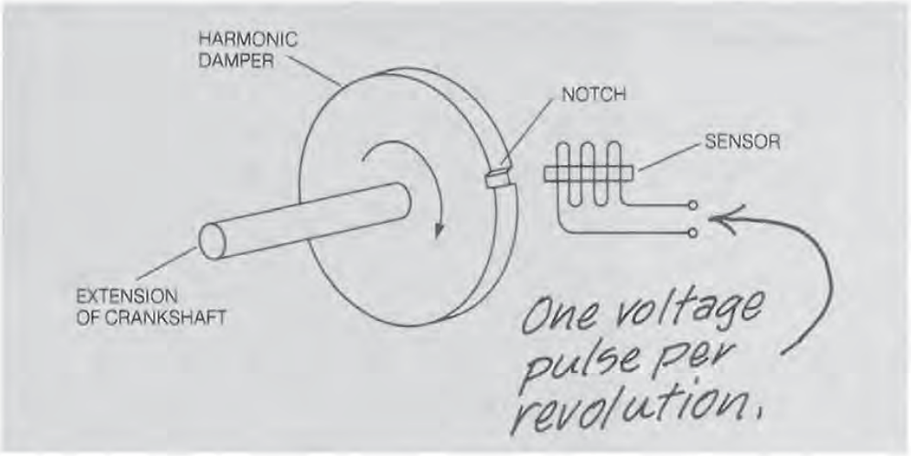


Figure 6.9
Crankshaft Position Sensor

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

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

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

Hall-Effect Position Sensor

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

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

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

The Hall Effect

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

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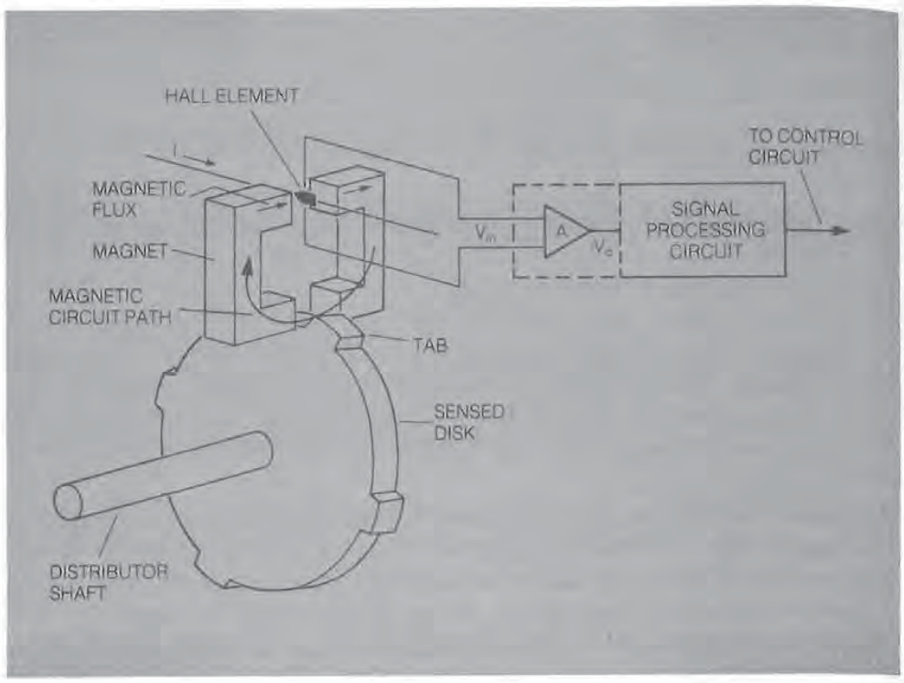


Figure 6.10
Hall-Effect Position Sensor

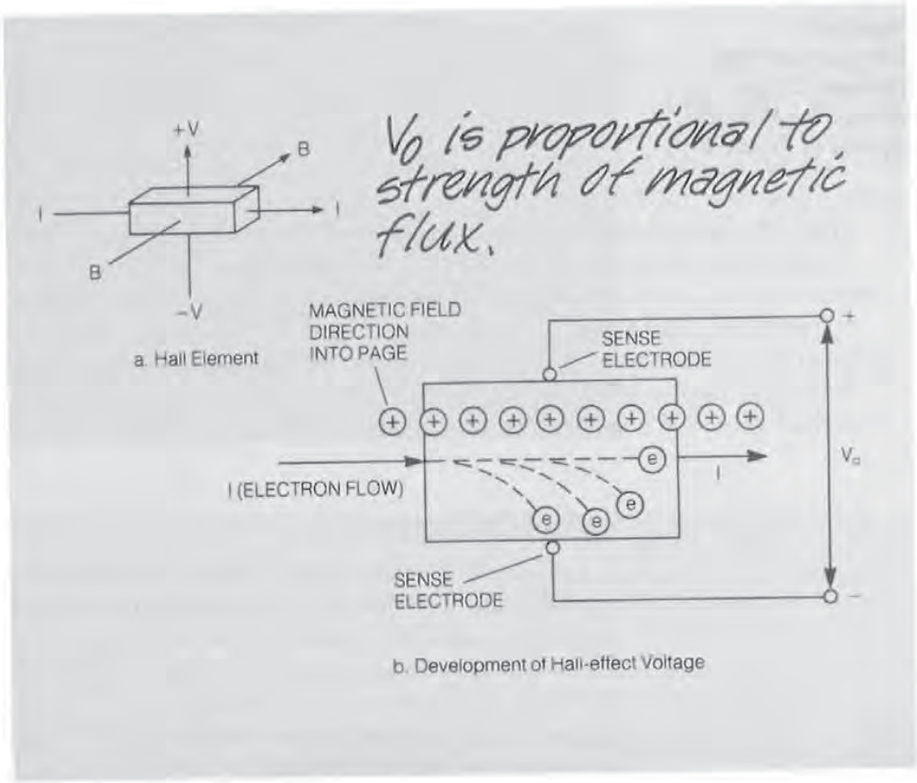
generation of a voltage that is dependent on a magnetic field—is called the *Hall effect.*

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

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

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Figure 6.11
The Hall Effect



V_0 is proportional to strength of magnetic flux.

Output Waveform

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

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

The voltage waveform V_0 that is produced by the Hall element in the position sensor of Figure 6.10 is illustrated in Figure 6.12. Since V_0 is proportional to the magnetic flux density, it reaches maximum when any of the tabs is symmetrically located between the magnet pole pieces (corresponding to TDC of a cylinder). If the disk is driven by the camshaft, then the disk must have as many tabs as the engine has cylinders. Therefore, the disk shown would be for a 4-cylinder engine. It is important to realize that voltage output versus crankshaft angle is independent of engine speed. Thus, this sensor can be used for setting the engine timing when the engine is not running (e.g., when it is being motored at the end of an assembly line).

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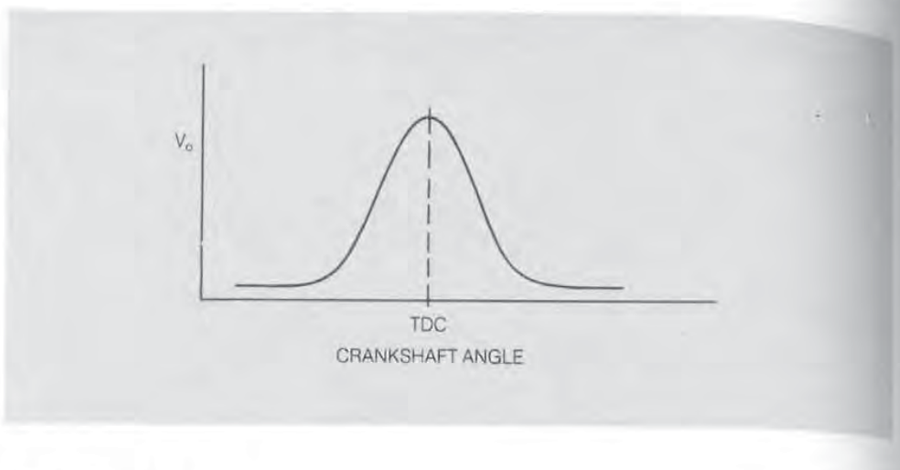


Figure 6.12 Waveform of Hall Element Output Voltage for Position Sensor of Figure 6.10

Shielded-Field Sensor

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

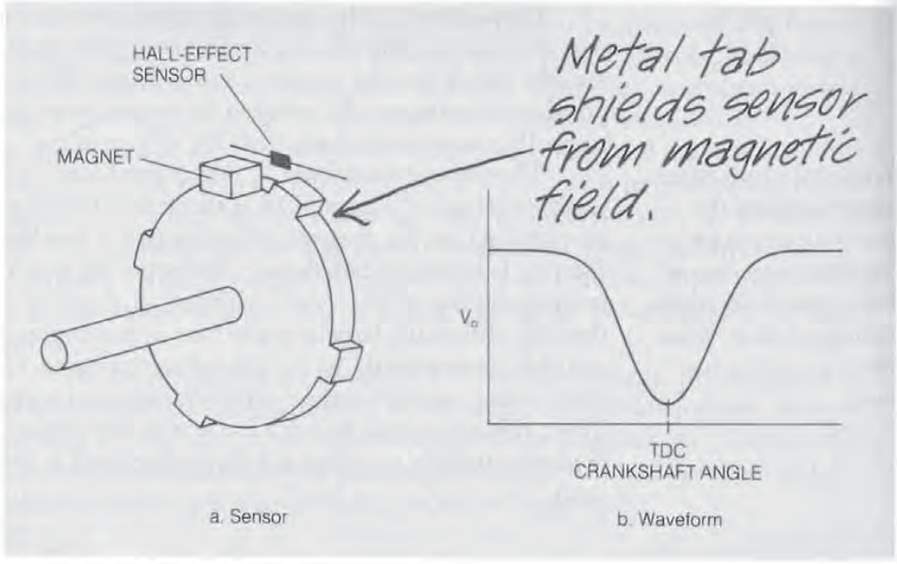


Figure 6.13 Hall-Effect Position Sensor That Shields the Magnetic Circuit

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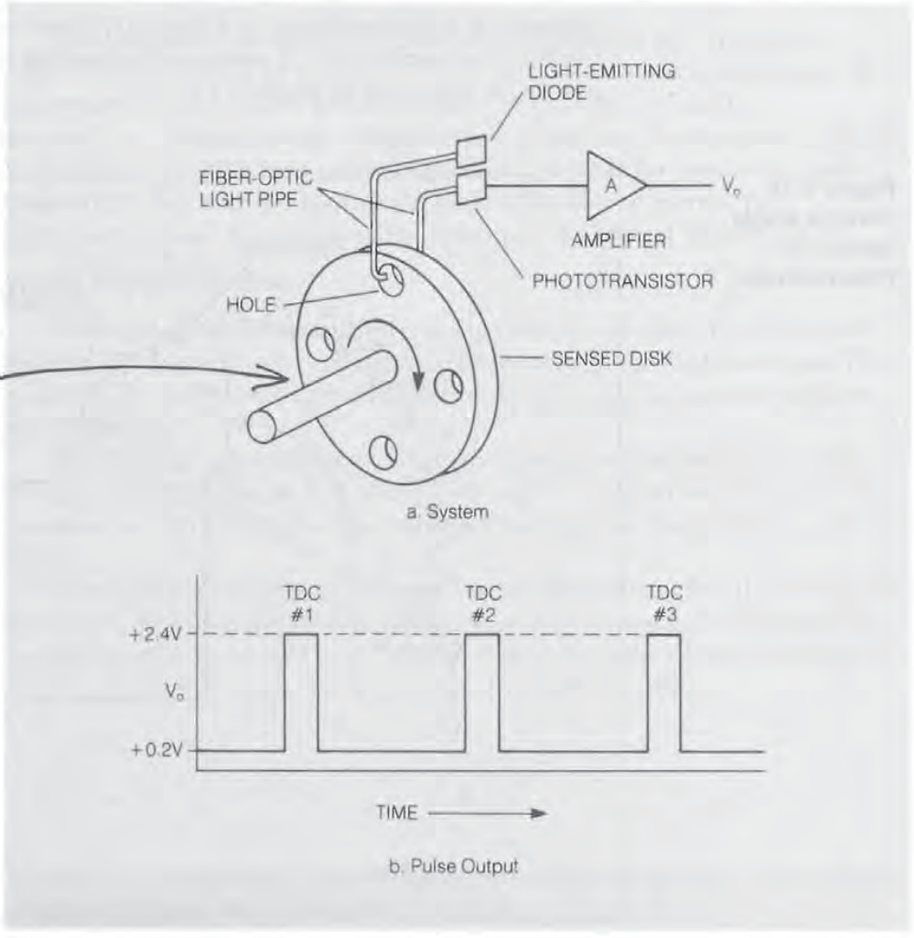
Optical Crankshaft Position Sensor

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

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

Figure 6.14
Optical Position Sensor

Rotation of disk causes alternate blocking and transmission of light.



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

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

THROTTLE ANGLE SENSOR

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

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

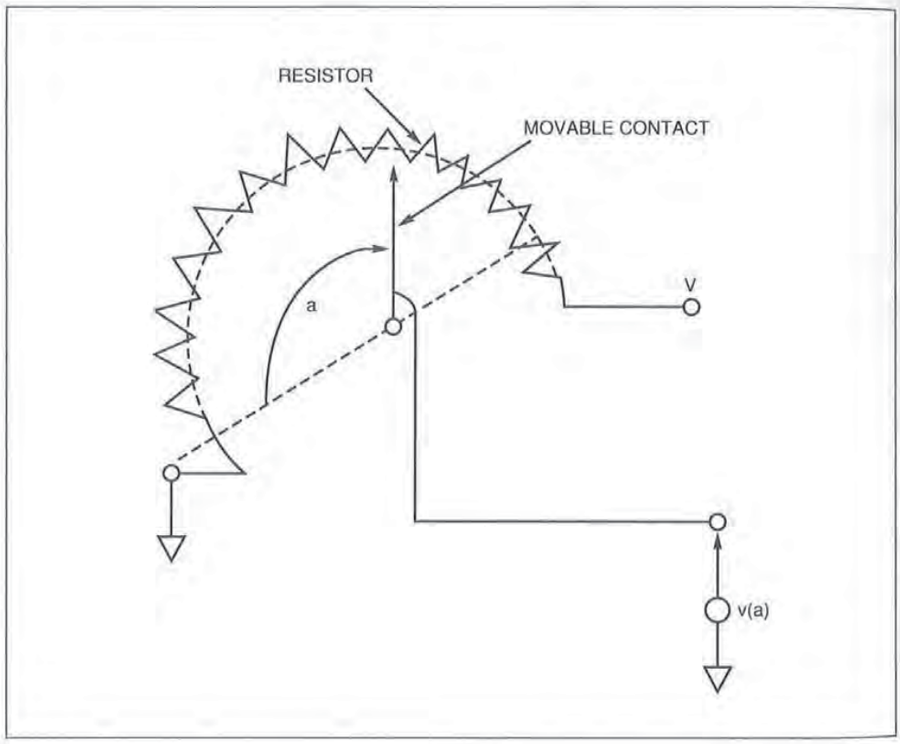


Figure 6.15 Throttle Angle Sensor: A Potentiometer

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

$$v(a) = ka$$

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

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

TEMPERATURE SENSORS

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

Typical Coolant Sensor

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

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

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

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

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

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

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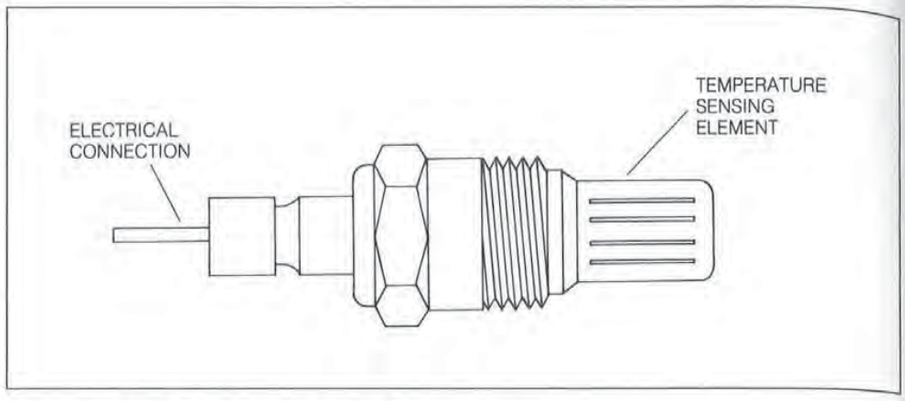


Figure 6.16
Coolant Temperature Sensor

SENSORS FOR FEEDBACK CONTROL

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

Exhaust Gas Oxygen Sensor

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

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

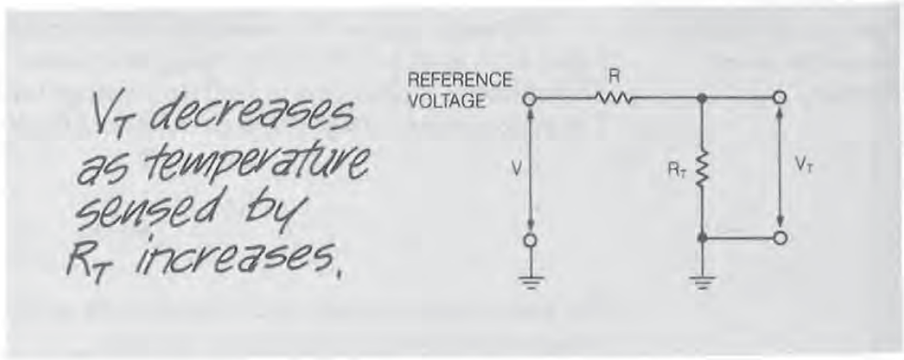


Figure 6.17
Typical Coolant Temperature Sensor Circuit

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

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

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

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

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

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

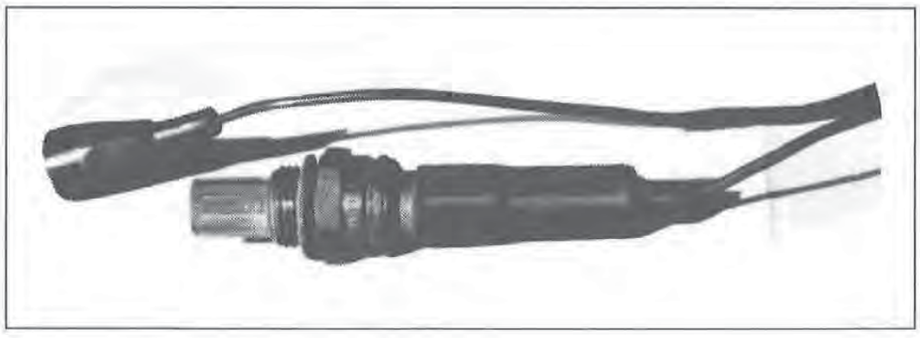
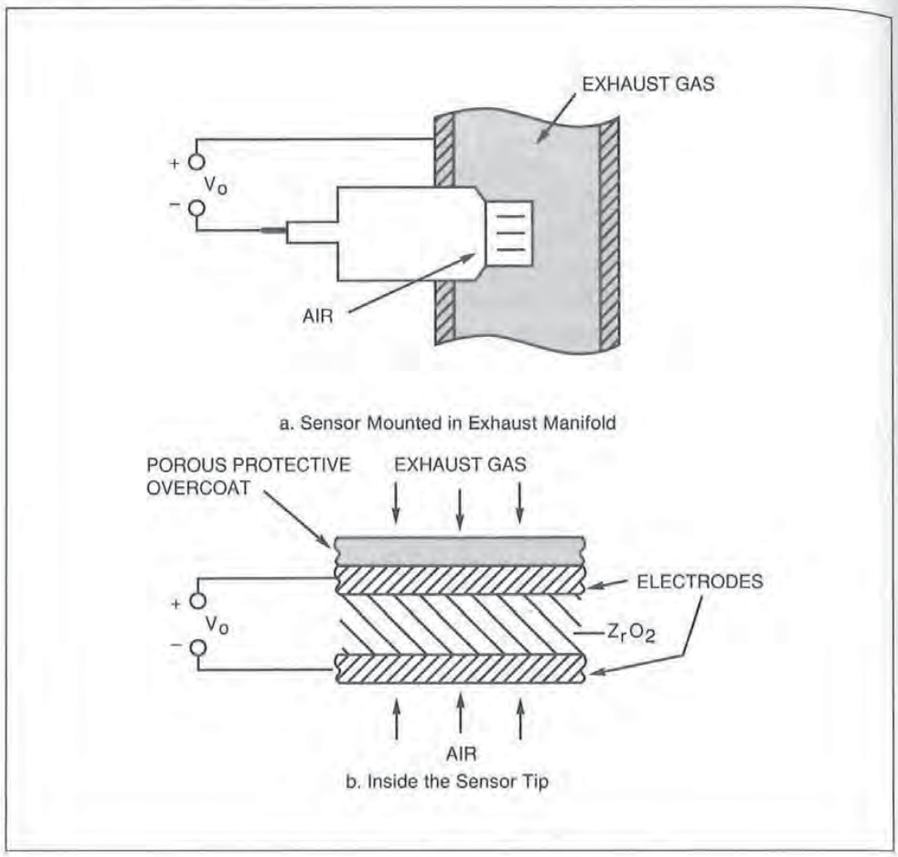


Figure 6.18 Zirconium Dioxide (ZrO_2) EGO Sensor

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Figure 6.19
EGO Mounting and Structure



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

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

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

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

Desirable EGO Characteristics

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

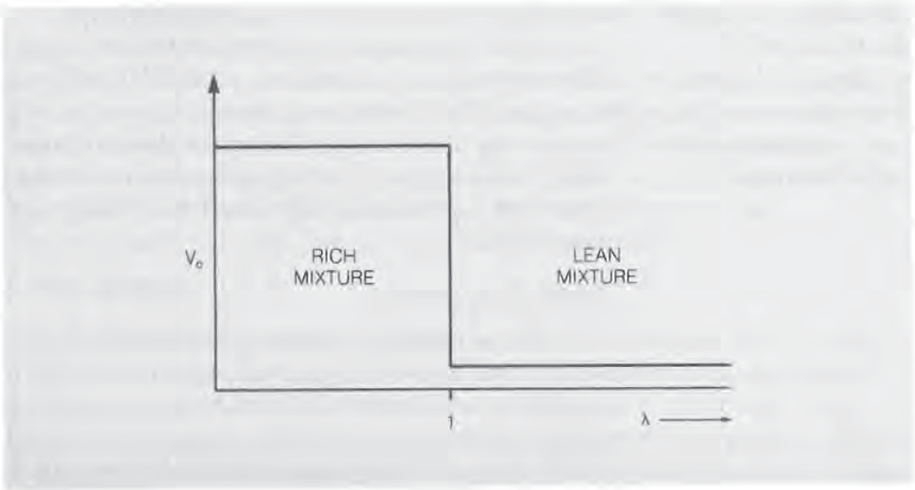
1. Abrupt change in voltage at stoichiometry
2. Rapid switching of output voltage in response to exhaust gas oxygen changes
3. Large difference in sensor output voltage between rich and lean mixture conditions
4. Stable voltages with respect to exhaust temperature

Switching Characteristics

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

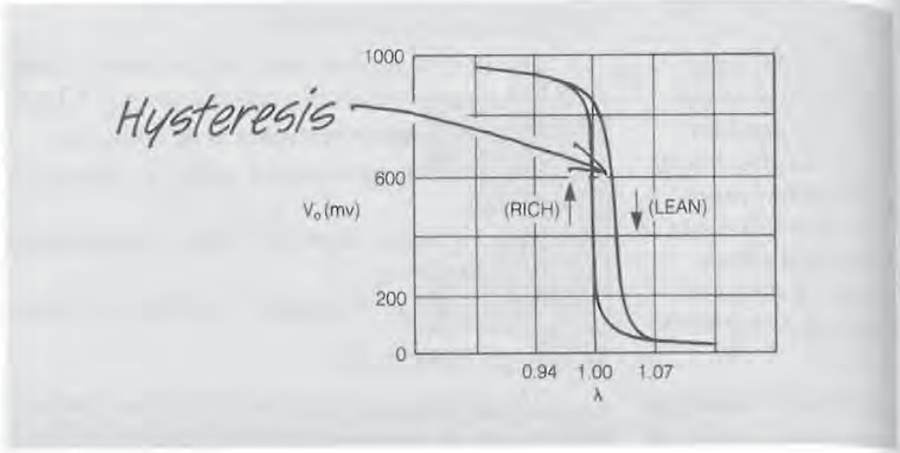
Temperature affects switching times and output voltage. Switching times at two temperatures are shown in Figure 6.22. Note that the time per division is twice as much for the display at 350°C as at 800°C. This means that the switching times are roughly 0.1 second at 350°C, whereas at 800°C they are

Figure 6.20
Ideal EGO Switching Characteristics



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Figure 6.21
Typical EGO Sensor Characteristics



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

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

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

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

Heated EGO Sensors

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

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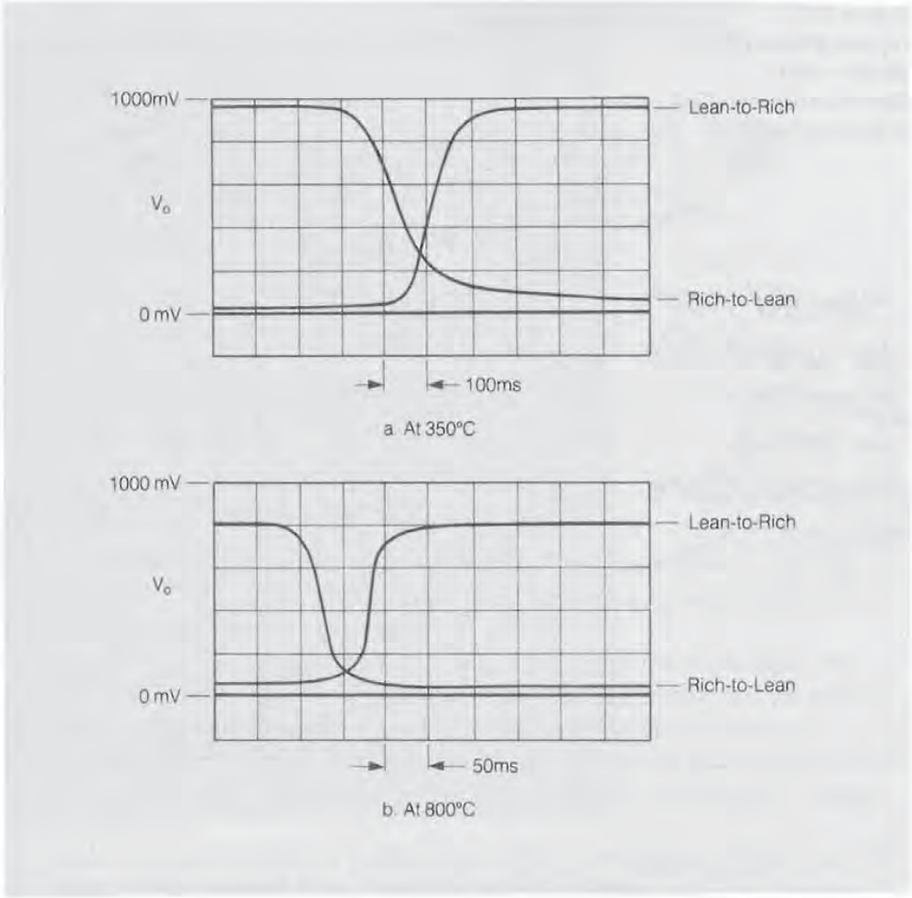


Figure 6.22
Typical Voltage Switching Characteristics of EGO Sensor

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

Knock Sensors

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

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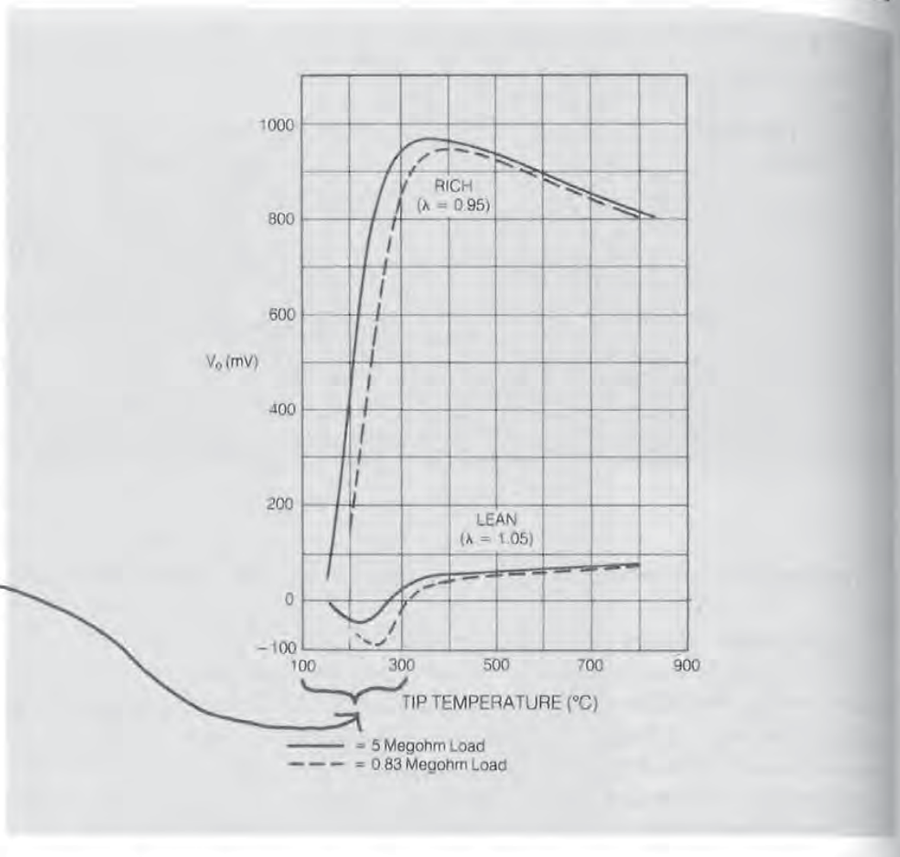


Figure 6.23
Typical Influence of Mixture and Temperature on EGO Output Voltage

Should not be used for control in this temperature range.

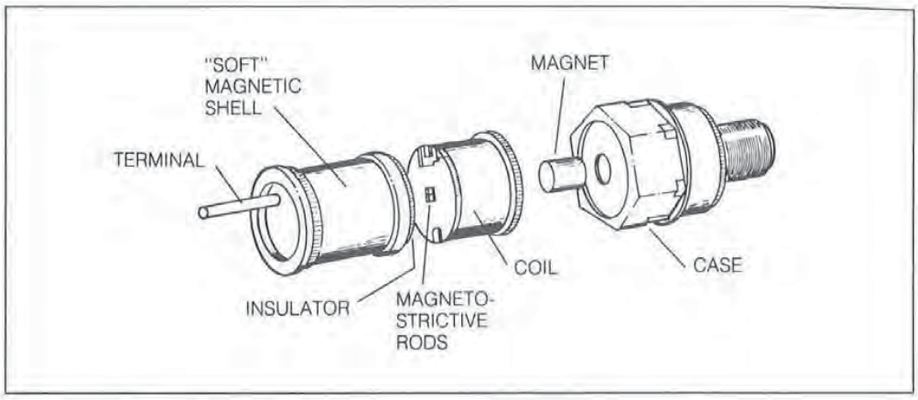
occurs most commonly with high manifold pressure and excessive spark advance. It is important to detect knock and avoid excessive knock; otherwise, there may be damage to the engine.

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

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

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Figure 6.24
Knock Sensor



AUTOMOTIVE ENGINE CONTROL ACTUATORS

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

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

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

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

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

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

Fuel Injection

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

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

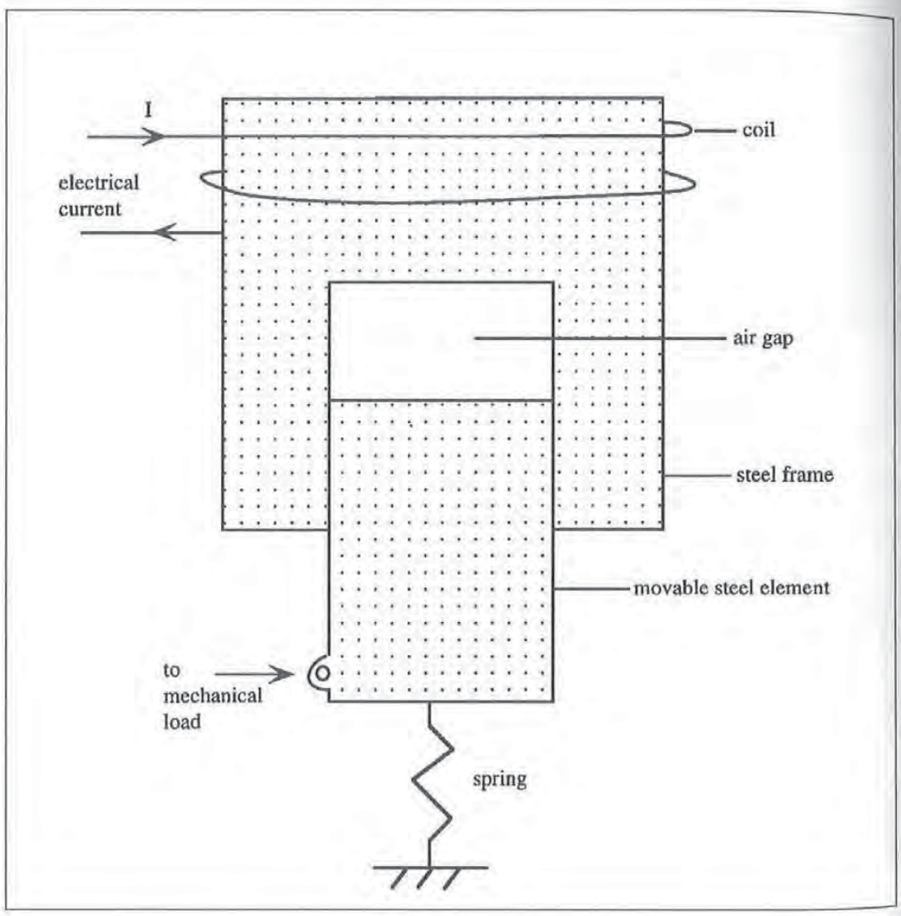


Figure 6.25
Schematic Drawing of a Solenoid

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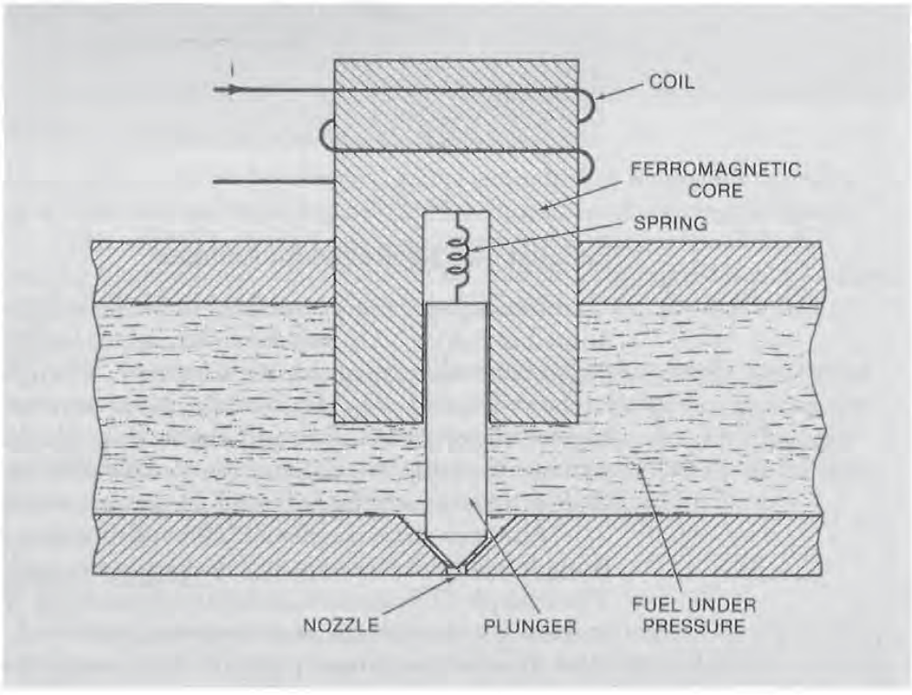
upward, the aperture is exposed, and fuel (under pressure) sprays through this aperture.

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

Fuel Injector Signal

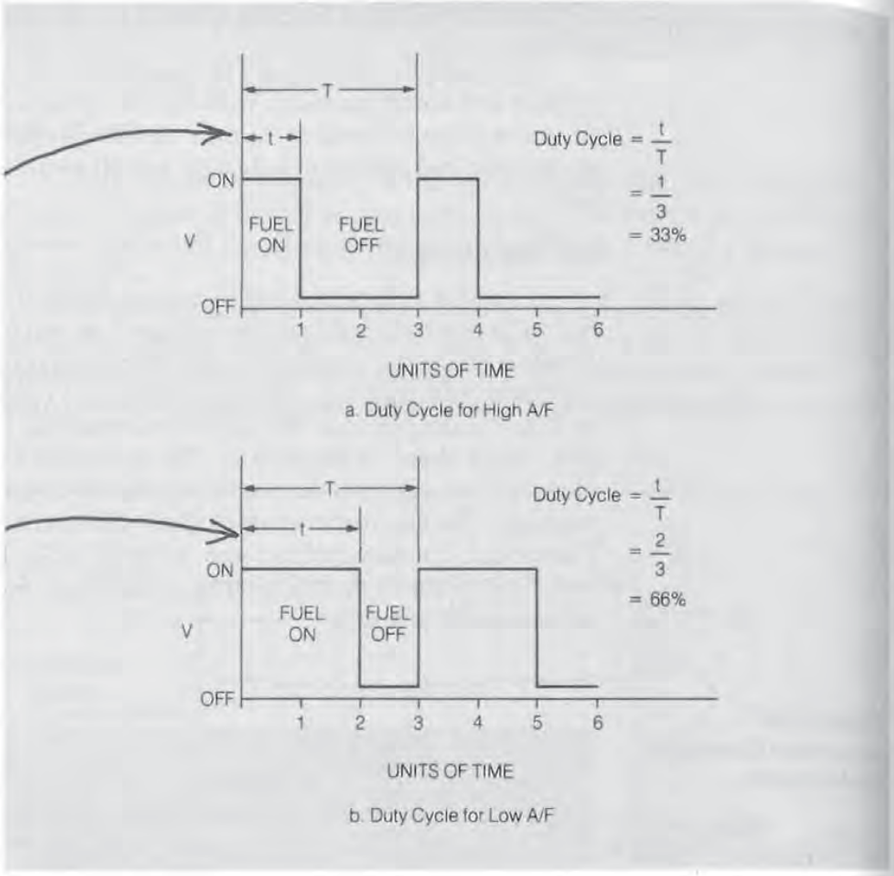
Consider an idealized fuel injector as shown in Figure 6.26, in which the injector is open when the applied voltage is on and is closed when the applied voltage is off. In this idealization, the control voltage operating the fuel injector is a binary pulse train (i.e., either on or off). For a pulse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

Figure 6.26 Schematic Drawing of Fuel Injector



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Figure 6.27
Pulse Mode Fuel Control Signal to Fuel Injector



High air-to-fuel ratio.

Low air-to-fuel ratio.

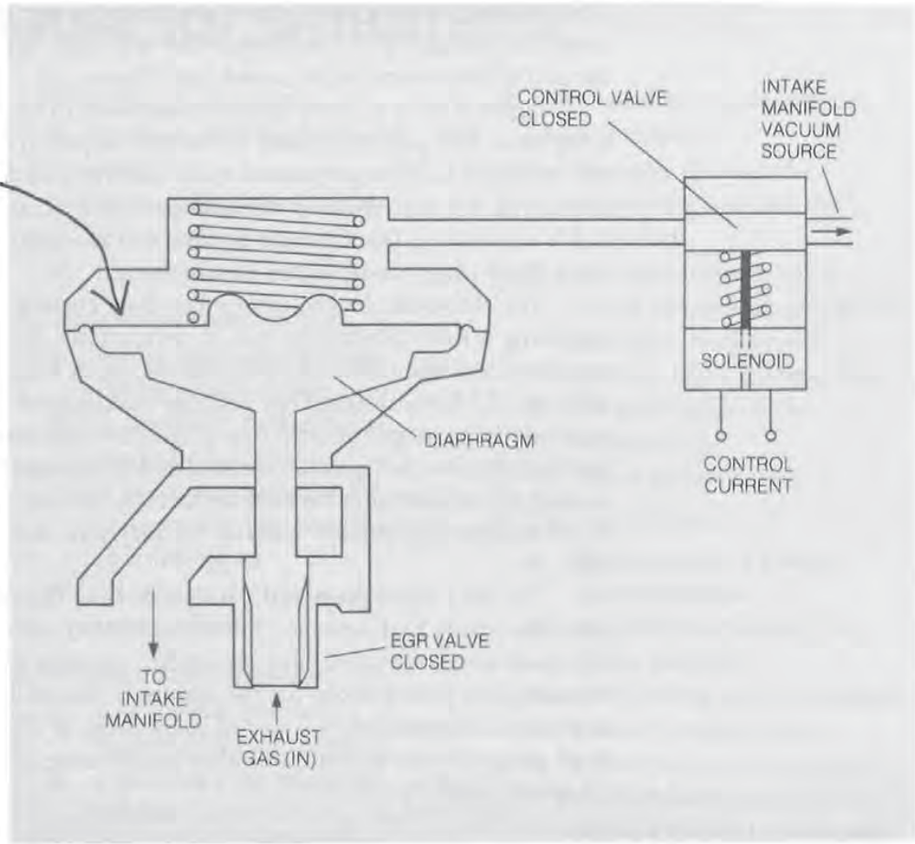
Exhaust Gas Recirculation Actuator

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

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

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Figure 6.28
EGR Actuator Control



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

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

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

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

Ignition System

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

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

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

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

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

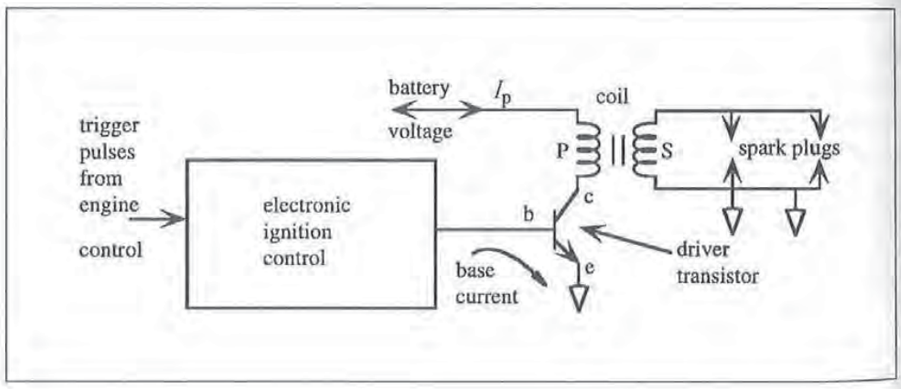


Figure 6.29
Electronic Ignition Subsystem

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Quiz for Chapter 6

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

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

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

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

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

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

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

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

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

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Digital Engine Control System

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

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

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

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

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

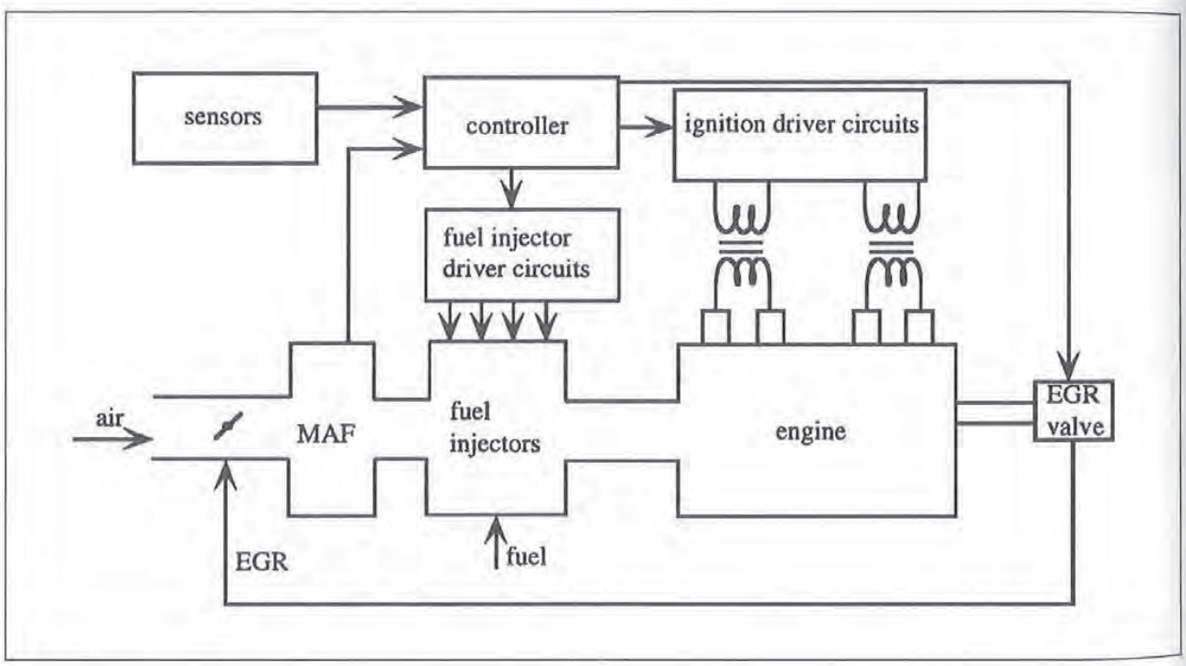
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DIGITAL ENGINE CONTROL FEATURES

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

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

Figure 7.1
Components of an Electronically Controlled Engine



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

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

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

$$F = R_f T$$

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

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

CONTROL MODES FOR FUEL CONTROL

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

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

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

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

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

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

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

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

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

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

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

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

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

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

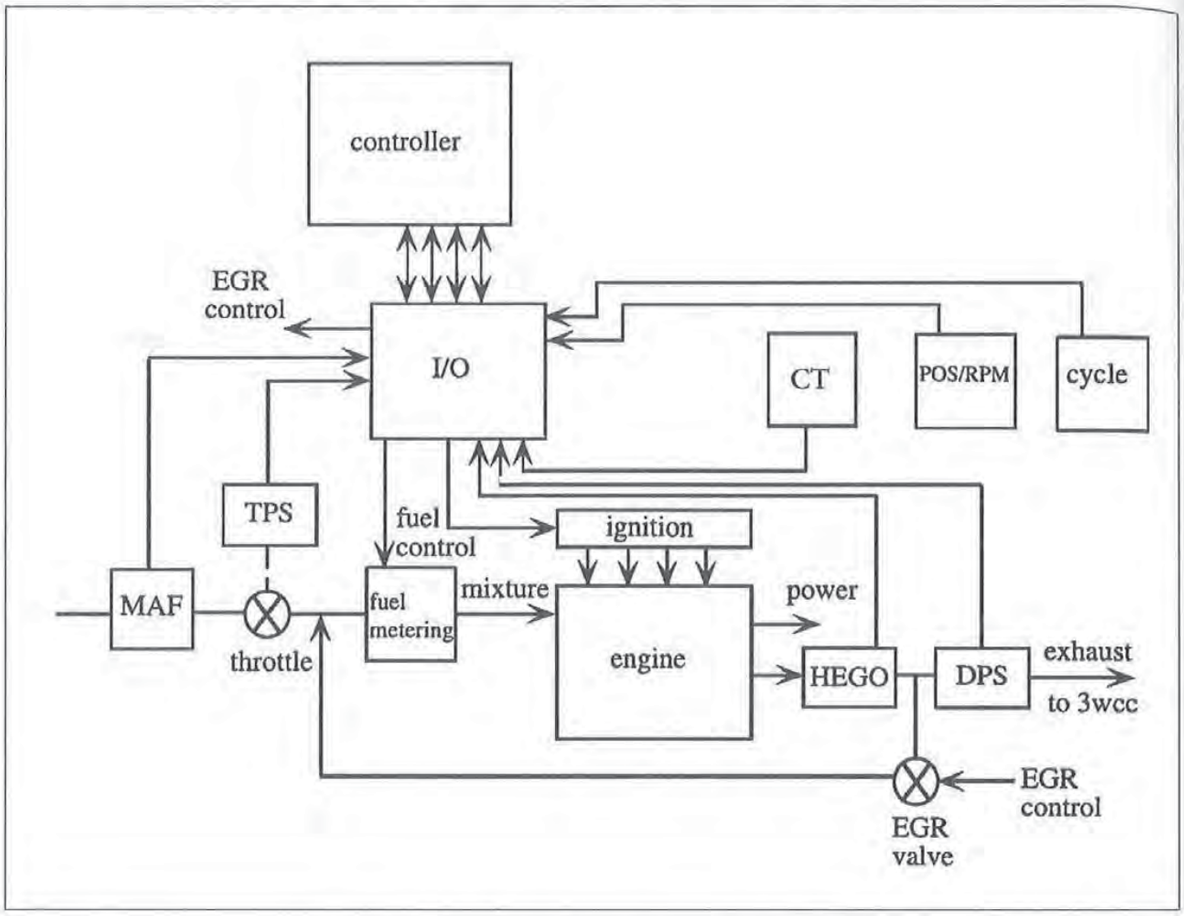
During hard acceleration or heavy engine load, the control mode selection logic chooses a scheme that provides a rich air/fuel mixture for the duration of the acceleration or heavy load. This scheme provides maximum torque but relatively poor emissions control and poor fuel economy regulation as compared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

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

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

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Figure 7.2
Digital Engine Control System Diagram



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

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

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

Engine Crank

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

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

Engine Warm-Up

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

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

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

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

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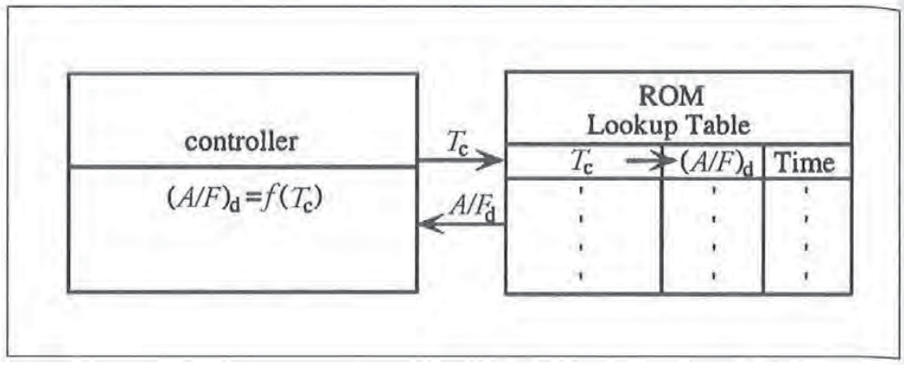


Figure 7.3 Illustration of Lookup Table for Desired Air/Fuel Ratio

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

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

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

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

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

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

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

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

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

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

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

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

Open-Loop Control

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

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

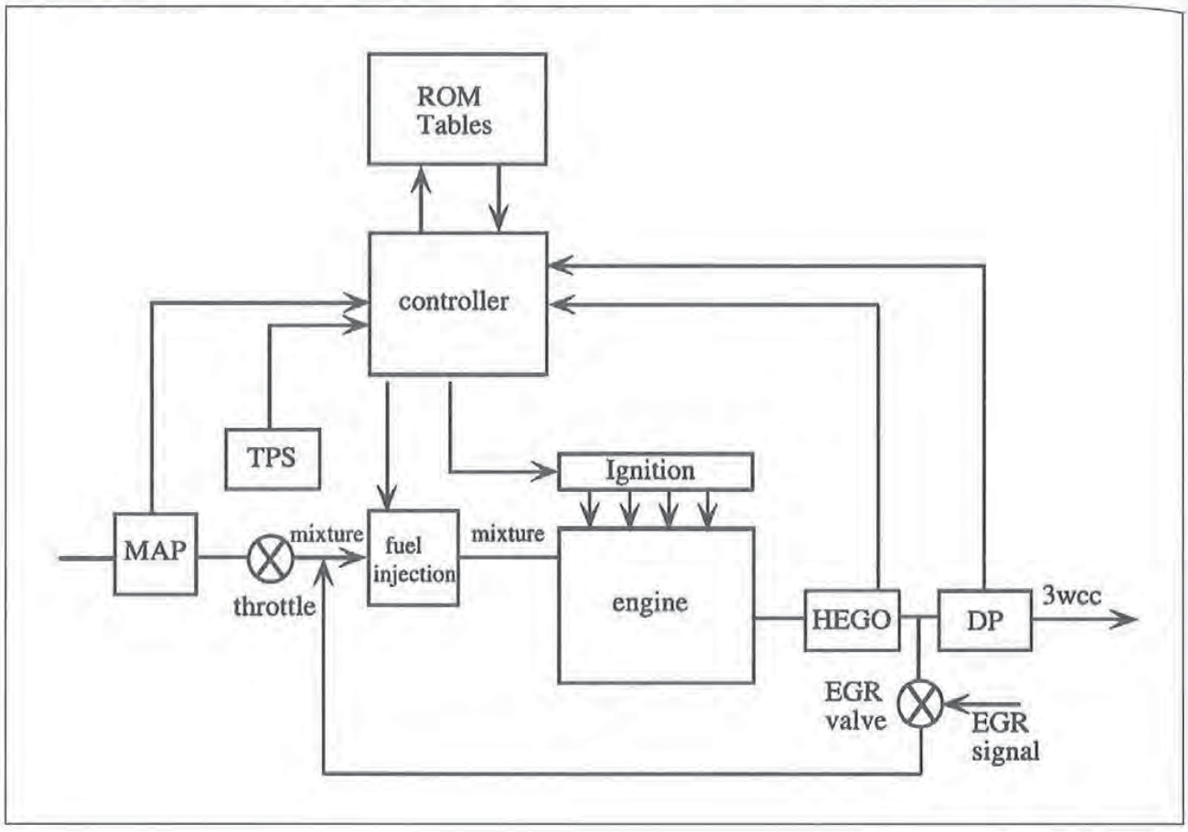
$$T_b = \frac{\text{MAF}}{r(N/s)(14.7)R_f} \qquad \text{base pulse width}$$

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

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

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Figure 7.4
Engine Control System Using the Speed-Density Method

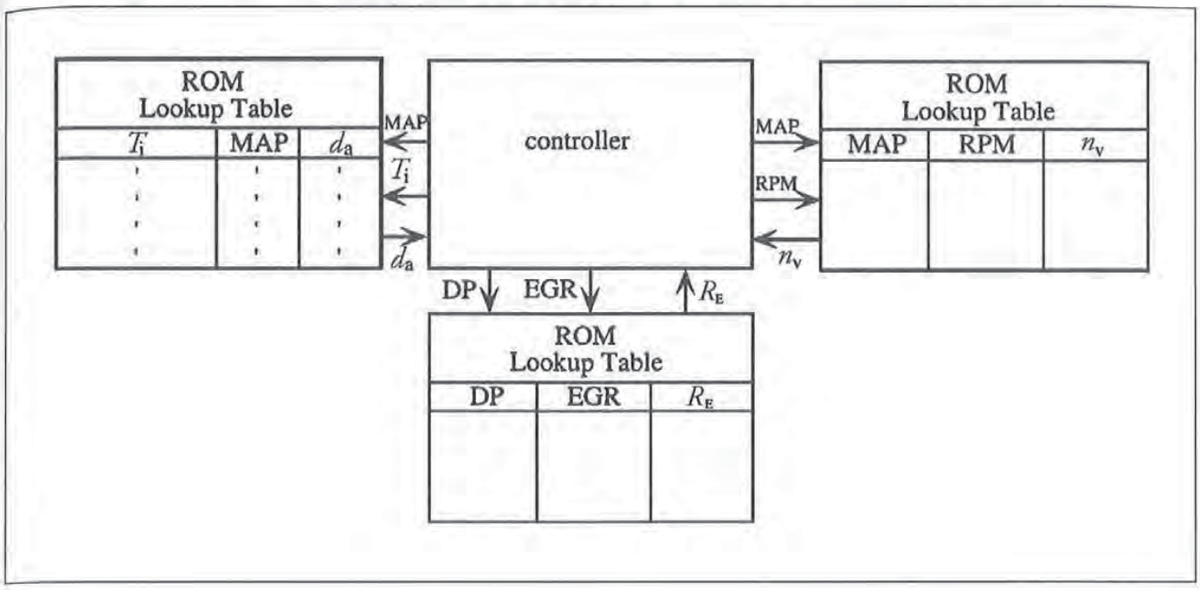


air density d_a is computed from MAP and T_i, and the volume flow rate R_v of combined air and EGR is computed from RPM and volumetric efficiency, the latter being a function of MAP and RPM. The volume rate for air is found by subtracting the EGR volume flow rate from the combined air and EGR. Finally,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

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

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



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

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

where D is the engine displacement.

Closed-Loop Control

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

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

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

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

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

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

where

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

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

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

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

where

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

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

α and β are constants

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

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

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

for a rich mixture.

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

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

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

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

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

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

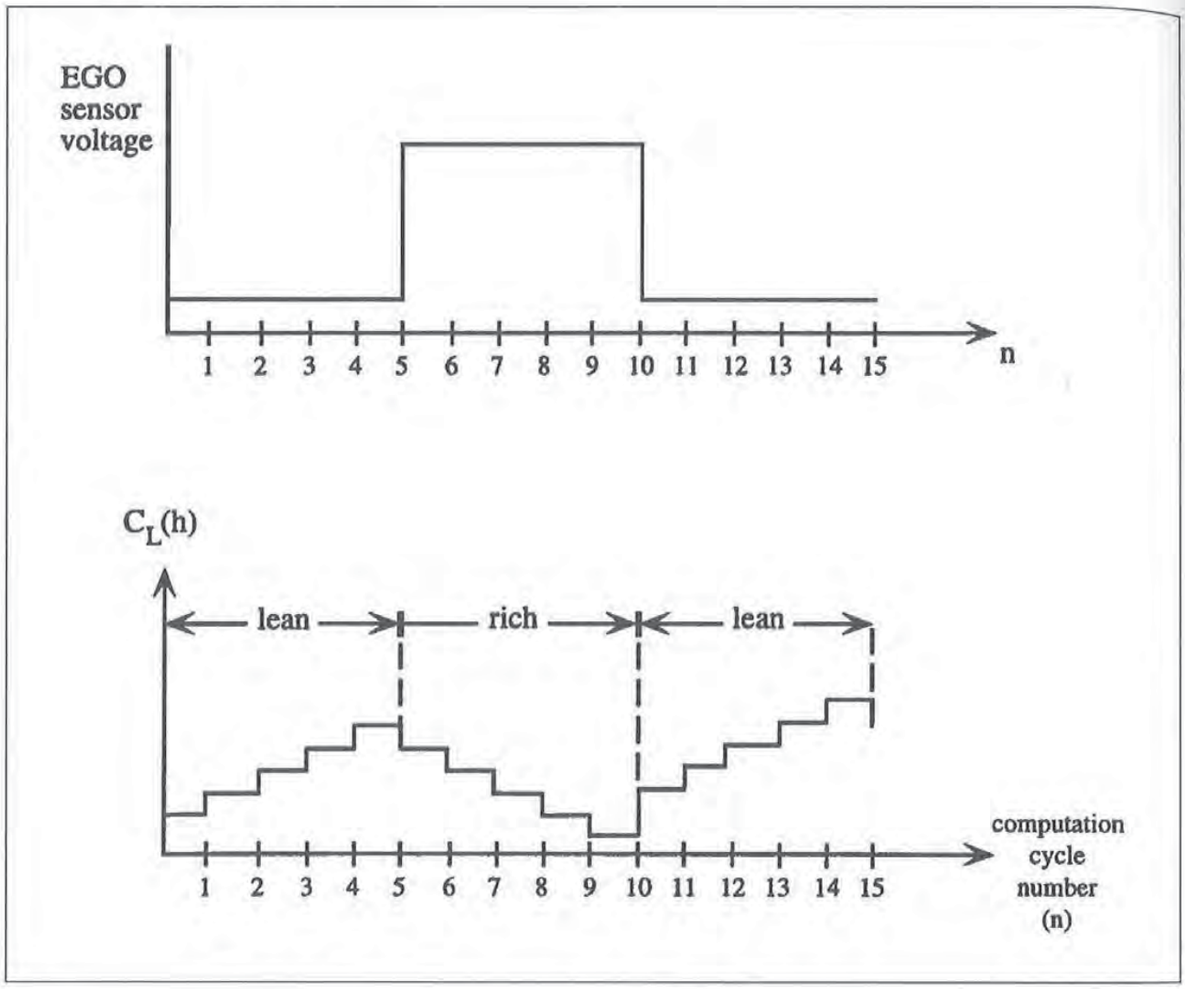
Acceleration Enrichment

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

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

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Figure 7.6
Closed-Loop Correction Factor



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

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

Deceleration Leaning

Fuel flow is reduced during deceleration with closed throttle.

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

Idle Speed Control

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

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

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

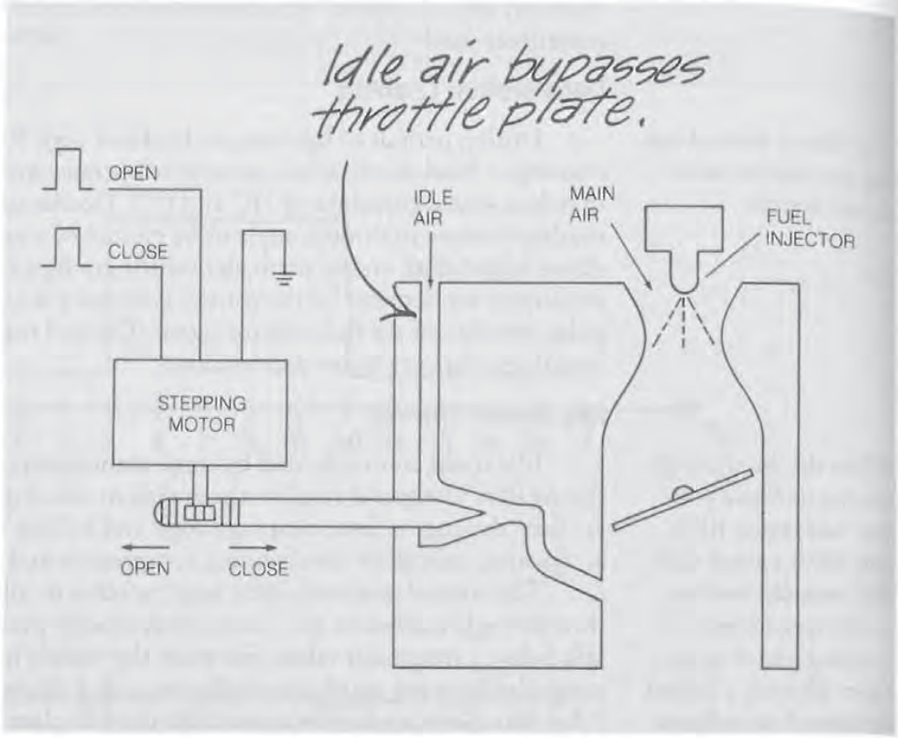
There are various schemes for operating a valve to introduce bypass air for idle control. One relatively common method for controlling the idle speed bypass air uses a special type of motor called a *stepper motor.* A stepper motor moves in fixed angular increments when activated by pulses on its two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

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

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

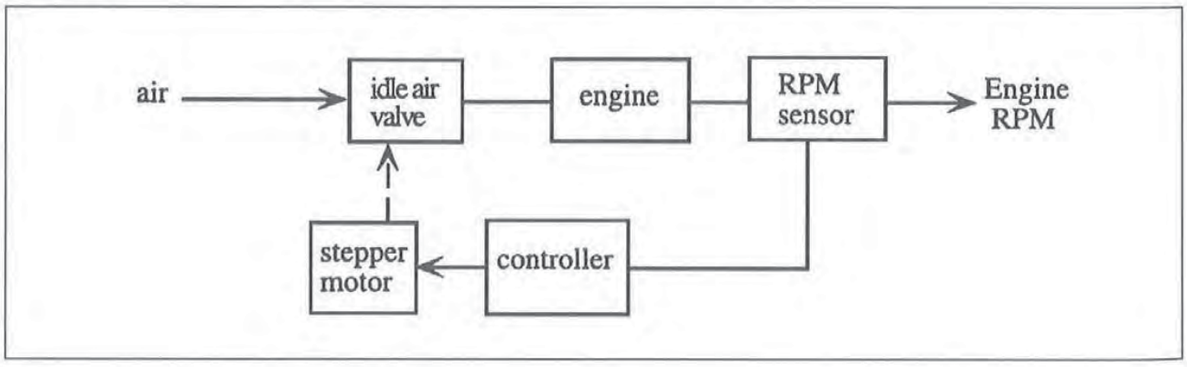
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Figure 7.7a
Idle Air Control



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

Figure 7.7b
Idle Air Control



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EGR CONTROL

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

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

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

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

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

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

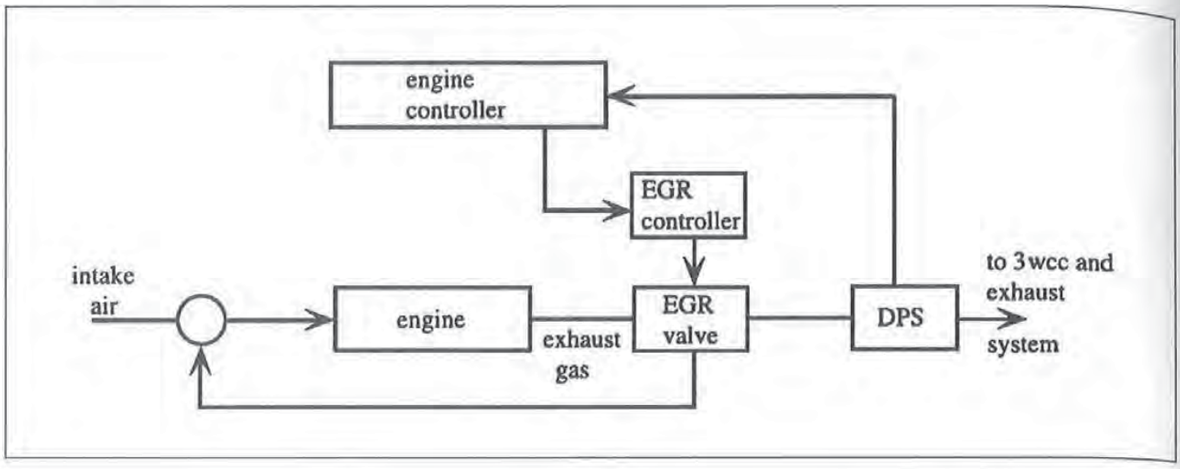
A simplified block diagram for an EGR control system is depicted in Figure 7.8. In this figure the EGR valve is operated by a solenoid-regulated vacuum actuator (coming from the intake). An explanation of this proportional actuator is given in Chapter 6. The engine controller determines the required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

ELECTRONIC IGNITION CONTROL

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

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Figure 7.8
EGR Control



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

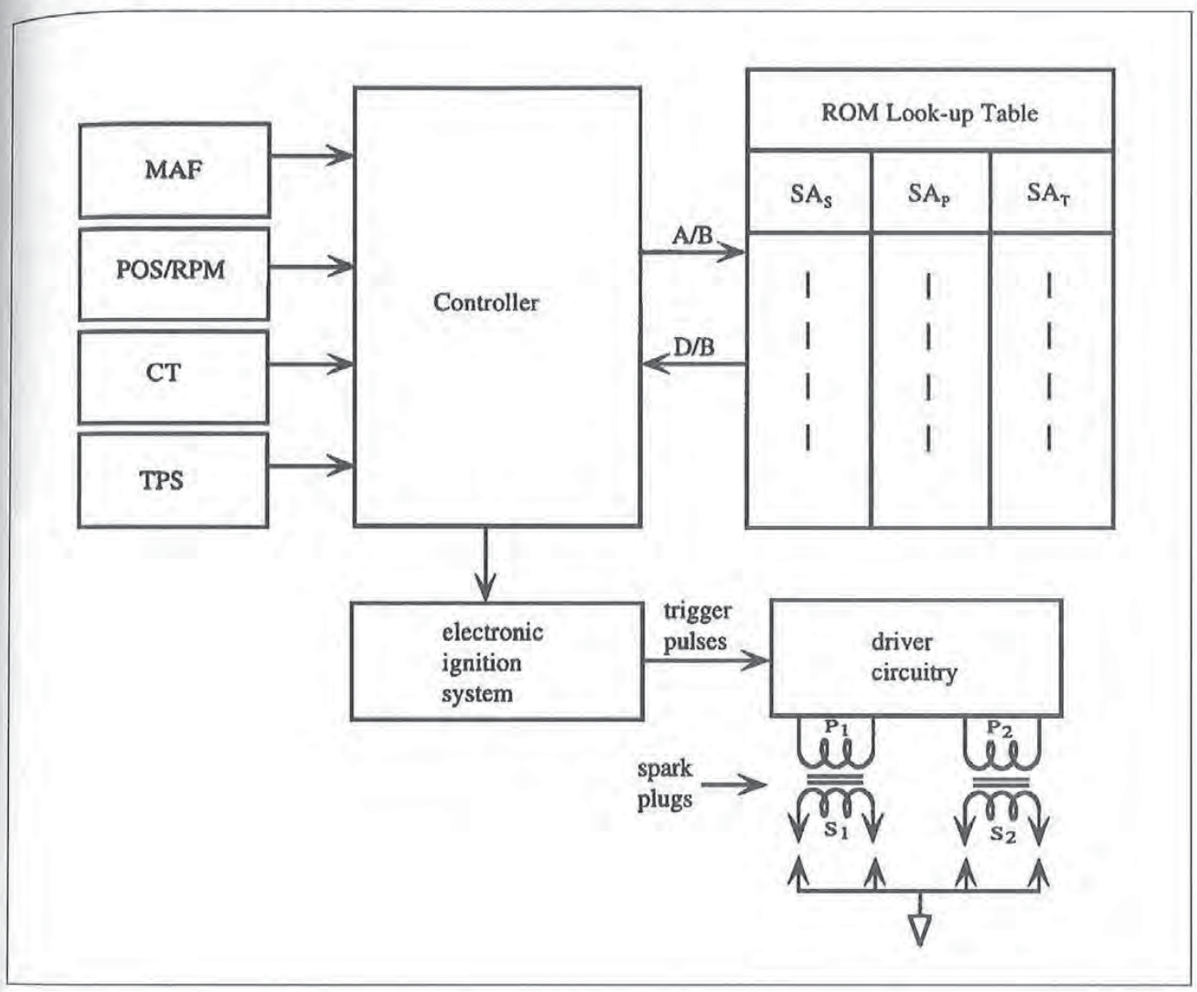
In most present-day electronically controlled engines the distributor has been replaced by multiple coils. Each coil supplies the spark to either one or two cylinders. In such a system the controller selects the appropriate coil and delivers a trigger pulse to ignition control circuitry at the correct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

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

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

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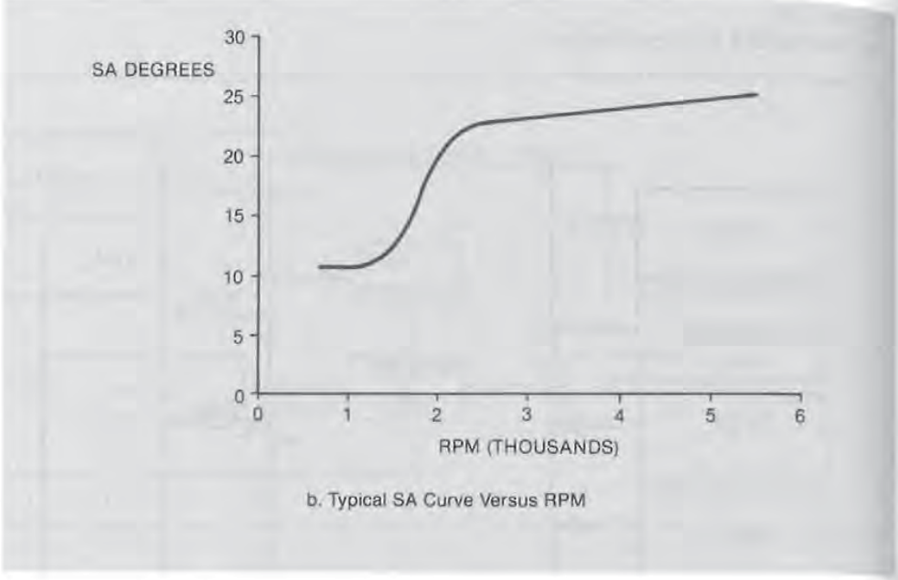
Figure 7.9a
Distributorless Ignition System



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

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Figure 7.9b Distributorless Ignition System



b. Typical SA Curve Versus RPM

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

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

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

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

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

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

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

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

$$SA = SA_S + SA_P + SA_T$$

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

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

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

Closed-Loop Ignition Timing

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

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

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

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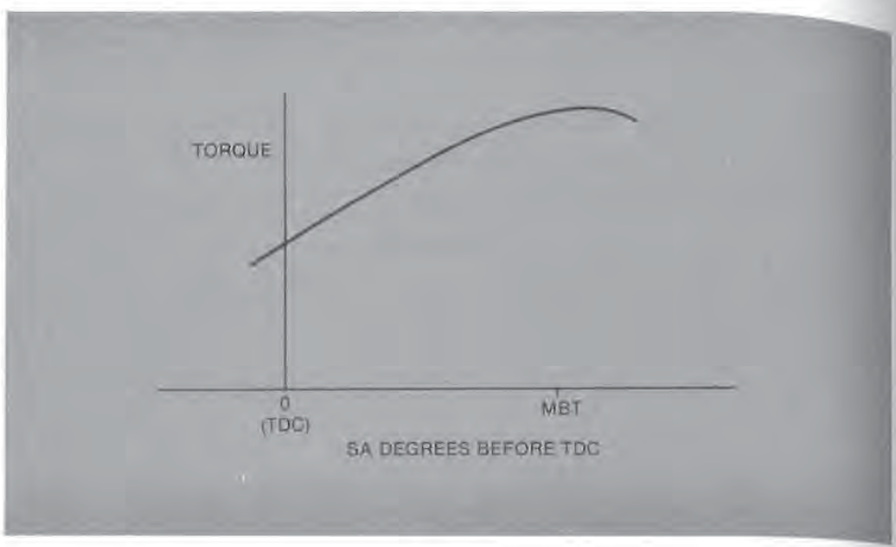


Figure 7.10
Torque versus SA for Typical Engine

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

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

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

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

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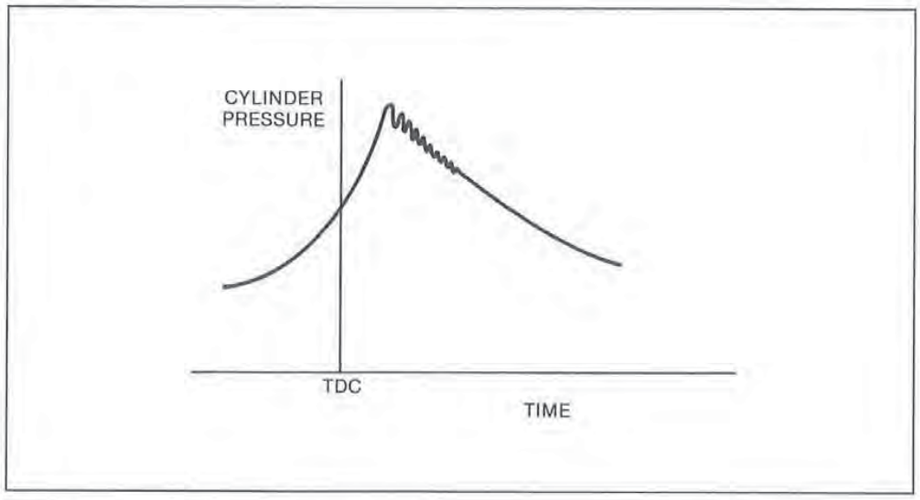


Figure 7.11
Cylinder Pressure (Knocking Condition)

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

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

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

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

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

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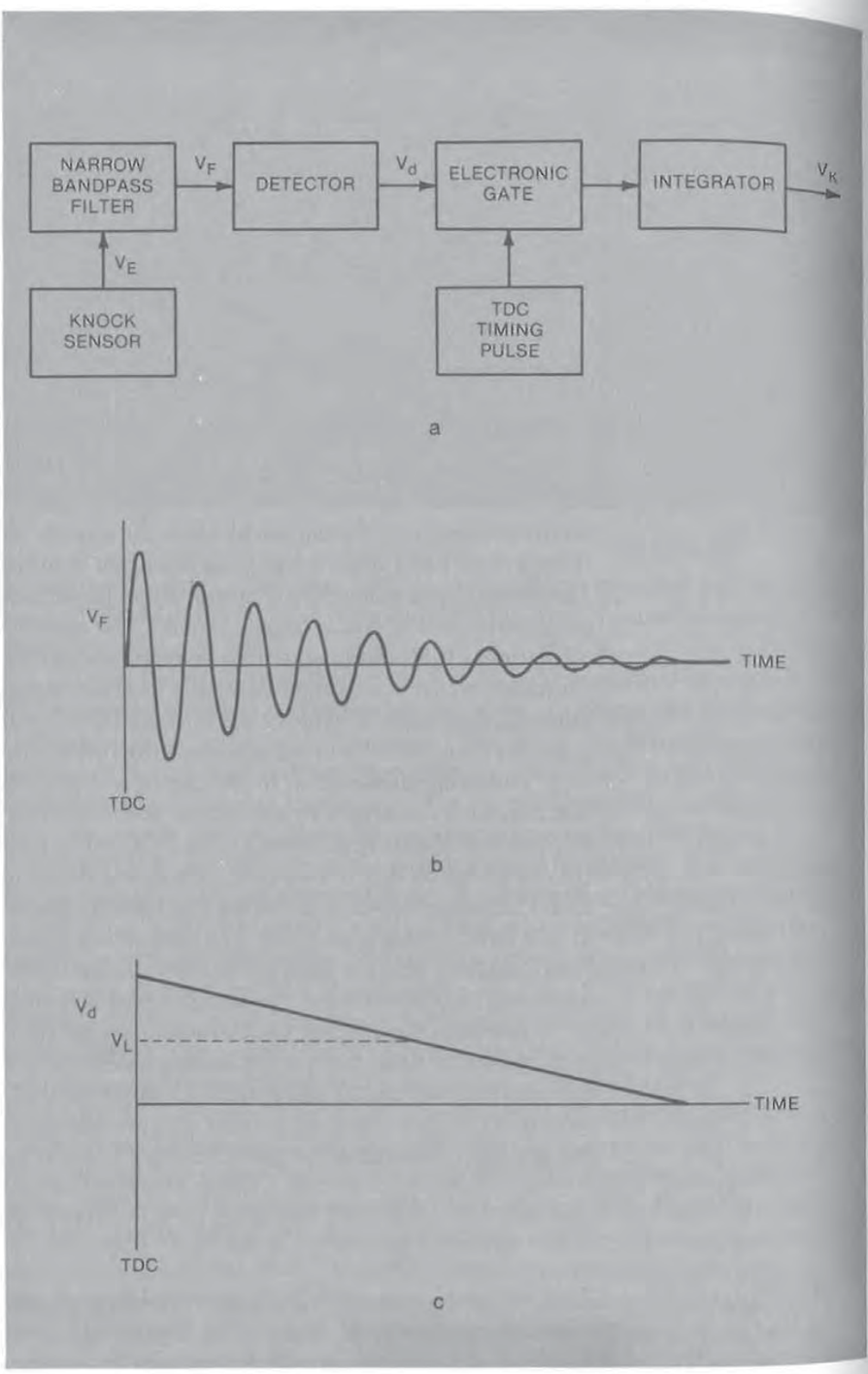
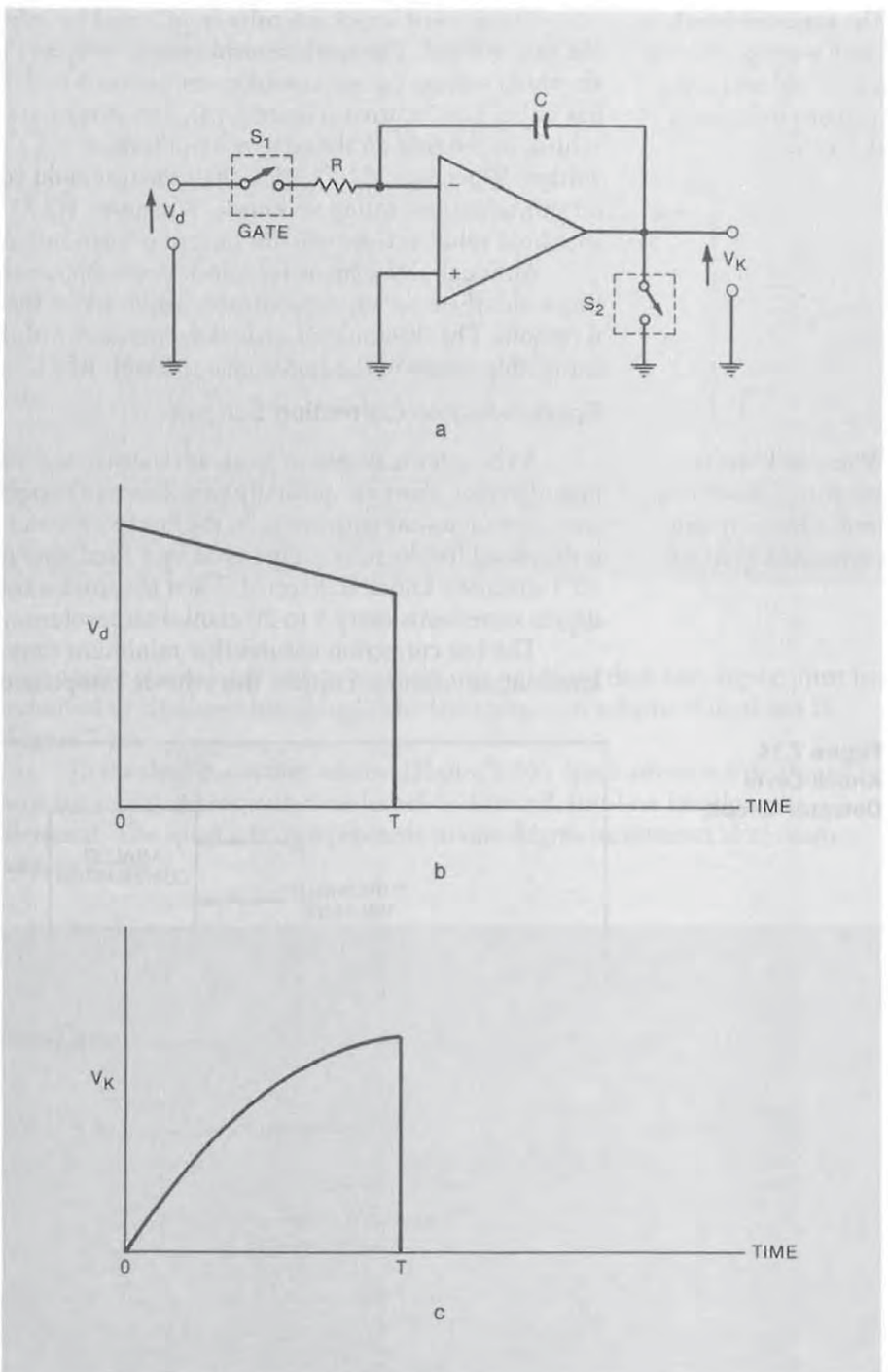


Figure 7.12 Instrumentation and Waveforms for Closed-Loop Ignition Control

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Figure 7.13
Example Integrator Circuit Diagram



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