GLOSSARY

Active mount The use of an actuator in a mounting system to continuously deform the mount so that no vibrational forces are passed through the mount at specific frequencies.

Adaptive filters A signal-processing technique (usually digital) in which filter parameters are continuously modified to optimize some aspect of system performance.

Antinoise sound that is identical to, but exactly opposite to, a disturbing sound. If heard alone, it would sound identical to the original noise, but it cancels the offending sound, thereby reducing the noise level.

Causality In the real world you cannot have a result that precedes a cause. In an antinoise system that deals with broadband noise, the reference signal must be derived from a position in the system where noise that is correlated to the observed noise exists earlier in time.

Harmonic number Narrowband sound, such as musical notes or noise from rotating machines, consists of a number of components at frequencies that are multiples of a fundamental frequency. The harmonic number is the ratio between the frequency of a particular component and the fundamental frequency.

LMS The least mean squares measure of the error in a system.

Noise cycle The repetitive cycle of a noise source. It is two revolutions in a four-stroke engine.

Residual noise The noise that remains after the antinoise meets the noise.

Resonance A phenomenon that occurs in low-loss systems where reflections reinforce the original energy. Energy storage in resonant structures can make noise problems much worse.

Sound field The distribution of sound energy in a defined space. It can be quite complex when resonances are present.

SPL The sound pressure level is the peak variation in air pressure due to a sound.

Subwoofer A speaker that is designed to only produce sound below 200 Hz. A crossover filter is used to pass low-frequency energy to the subwoofer and all higher-frequency energy to other speakers.

Tonal noise Noise that is made up of pure sinusoidal components with frequencies that are all multiples of a fundamental frequence.

Turbulence The random mixing in an air flow that causes noise. A perfectly smooth flow is called laminar.

BIBLIOGRAPHY

Air Movement and Control Association, Inc., *Fans and Systems,* ACMA Publication 201-90, 1990.

Chaplin, G. B. B., "Anti-noise—the Essex breakthrough," *Chartered Mechanical Engineering,* vol. 30, 1983, pp. 41–47.

Denenberg, J., "Anti-noise," *IEEE Potentials,* vol. 11, no. 2, April 1992, pp. 36–40.

Eghtesadi, Kh., and H. G. Leventhal, "Comparison of active attenuators of noise in ducts," *Acoustics Letters,* vol. 4, no. 10, 1981, pp. 204–209.

Eghtesadi, Kh., and J. W. Gardner, "Experimental results of the nonrestrictive electronic muffler on internal combustion engines," *Acoustics Letters,* vol. 4, no. 4, 1990, pp. 70–73.

PETITIONER'S EXHIBIT 1002
US PATENT NO. 6,557,540

Eghtesadi, Kh., M. McLoughlin, and E. W. Ziegler, "Development of the simulation model of the multiple interacting sensors and actuators (MISACT) for an active control system," *Recent Advances in Active Control of Sound and Vibration,* C. A. Rogers and C. R. Fuller (eds.), Virginia Polytechnic Institute, April 15–17, 1991, pp. 246–257.

Lemme, H., and J. Denenberg, "Larm Kontra Larm," *Elektronic Magazine,* vol. 41, no. 19, Sept. 1992, pp. 42–48.

Mendat, D., et al, "Active control of centrifugal fan noise," *Fan Noise—An International INCE Symposium,* CETIM Senlis, France, Sept. 1–3, 1992, pp. 455–462.

Nelson, P. A., "Causal constraints in the active control of sound," *IEEE Conference on Acoustic Speech and Signal Processing,* vol. 1, April 1987.

Nelson, P., and S. Eliot, *Active Control of Sound,* Academic Press, 1992.

"Reducing the annoyance of noise," *Proceedings of NOISE-CON 90,* University of Texas at Austin, Oct. 1990.

Ross, C., "Quieter air travel takes off with active noise control technology," *Noise and Vibration Worldwide,* 1993.

Ross, Colin, "The control of noise inside passenger vehicles," *Recent Advances in Active Control of Sound and Vibration,* C. A. Rogers and C. R. Fuller (eds.), Virginia Polytechnic Institute, April 15–17, 1991, pp. 671–681.

Warneka, G. E., "Active attenuation of noise—the state of the art," *Noise Control Engineering Journal,* **18** (3), 1982, pp. 100–110.

Widrow, P., and S. D. Stearns, *Adaptive Signal Processing,* Prentice-Hall, 1985.

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CHAPTER 32
FUTURE VEHICLE ELECTRONICS

Randy Frank and Salim Momin
Motorola Semiconductor Products

32.1 RETROSPECTIVE

Both the content and complexity of semiconductor technology for computing, power control sensing, communications, signal conditioning, and transient suppression is destined to increase in future vehicles. Therefore, this final chapter will tackle the difficult subjects of identifying potential technology developments and trends for future systems and consolidating previously mentioned development activities in areas relative to vehicle electronics. The terminology of the future generations of electronics (refer to the glossary at the end of this chapter) is a strong indication of how different emphasis will be placed in future vehicles.

Semiconductor technology is being applied to sensors in several automotive applications. Semiconductor technology is also at the heart of digital electronics including MCU (microcontroller unit), MPU (microprocessor unit), and DSP (digital signal processing) technology. Outputs of several systems have been controlled by power MOSFETs, smart power, and even IGBT (insulated gate bipolar technology) power devices. Communications, not only to the vehicle but from the vehicle, will cause major changes which will require high-frequency semiconductors. However, high-level digital electronics in MCU, MPU, and DSP will continue to determine the future of automotive electronics. Their growth from two MCUs per vehicle in 1980 to 14 per vehicle in 1990 and expected use of 35 per vehicle by 2000 will dominate automotive electronics content no matter which vehicle subsystem is involved.

32.2 IC TECHNOLOGY

Since the advent of integrated circuit (IC) technology, the automotive engineer has been designing more and more complex electronic modules—partially to meet government-mandated regulations for pollution control and fuel economy but also to provide increased performance and creature comforts. Table 32.1 is a summary of the control systems and subsystems being used or developed for modern vehicles. Transitions to higher levels of complexities are already underway as car companies worldwide migrate their engine management ECUs from 8-/16-bit microcontrollers to 32-/64-bit CISC/RISC based processors with more than one execution engine on-chip, such as Motorola's MC68332.

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TABLE 32.1 Pervasiveness of Electronics in Modern Control Systems

Safety & chassis	Powertrain	Entertainment	Driver information	Convenience & body control
Traction control	Dynamic engine mount	Noise reduction systems	Digital & analog gauges	Multiplexed wiring
Antilock brakes	Electronic camshaft	Cellular radio/telephone	Engine diagnostic display	Intermodule network
Load-sense braking	Ignition timing	CD & optical disc players	Service reminders	Body system diagnostics
Air bag restraints	Spark distribution	CB radio	Digital clock	Smart power drivers
Dynamic ride control	Fuel delivery control	Digital audio tape	Trip computers	Antitheft device
Active suspension	Turbo control		Navigational computers	Climate control
Load leveling	Emissions monitor		Intelligent highways	Keyless entry
Electronic steering	Voltage regulator		Collision avoidance	Light reminder
	Alternator		Drowse/DWI alert	Memory seat
	Transmission shift			Sensory wipers
	On-board diagnostics			Auto door lock
	Operational adaptation			Headlight dimming
	Energy recovery			Window control
	Electronic muffler			
	Cruise control			

DSP technology is being used in audio and suspension control algorithms with new applications such as noise cancellation just on the horizon. Semiconductor technology, and specifically the integrated circuit, is the enabling technology. Thus, before we can discuss the future of automotive electronics, the future developments in semiconductor technology along with its critical success factors must be understood since they will have a profound impact not only on what systems get designed but, more importantly, on how they get designed.

The 1992 SIA Semiconductor Technology Workshop established a 15-year roadmap for key IC device characteristics such as feature size, chip size, defect density, power dissipation, and number of I/Os (Table 32.2). Based on this roadmap, the design engineers at the turn of the century will be dealing with ICs which will integrate 50 to 100 million transistors on a chip with clock speeds in excess of 250 MHz. This is based solely on extrapolation of today's technologies and does not take into account dramatic breakthroughs in technologies such as *quantum effect transistors,* which could increase device complexities by several orders of magnitude. There is already some work being done at the Massachusetts Institute of Technology and Texas Instrument R&D laboratories on *3-D quantum ICs* with complexities of 20 billion transistors. Today's more complex circuits have three to four metal layers, but future circuits will have six to seven metal layers for interconnect and power routing by the year 2005. Three-dimensional interconnections are key to denser electronic circuits. Thin circuits that can be lifted off an underlying substrate may allow not only faster circuits, but combinations of otherwise too-complex processes to be achieved and circuit placement in more varied packaging shapes including remote displays, sensors, or actuators.

TABLE 32.2 General Technology Roadmap

Characteristic	1992	1995	1998	2001	2004	2007
Feature size	0.5	0.35	0.25	0.18	0.12	0.1
Gates per chip	300K	800K	2M	5M	10M	20M
Wafer processing cost ($/cm^2)	$4.00	$3.90	$3.80	$3.70	$3.60	$3.50
Chip size (mm^2)	250	400	600	800	1000	1250
Wafer diameter (mm)	200	200	200–400	200–400	200–400	200–400
Defect density (defects/cm^2)	0.1	0.05	0.03	0.01	0.004	0.002
Number of interconnect levels	3	4–5	5	5–6	6	6–7
Power supply voltage (V)	5	3.3	2.2	2.2	1.5	1.5
No. of I/Os	500	750	1500	2000	3500	5000
Performance (MHz)	120	200	350	500	700	1000

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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.

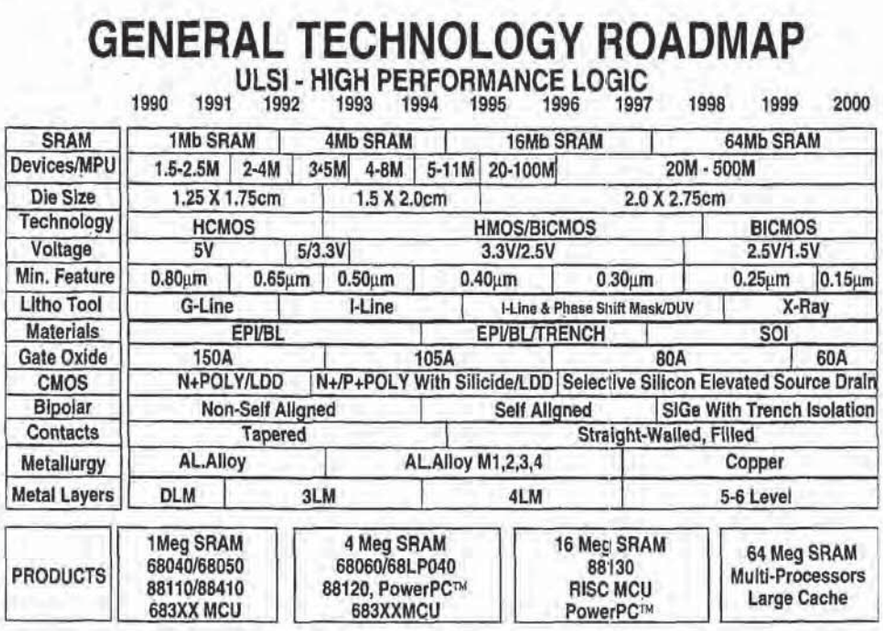


FIGURE 32.1 Operating frequencies/feature size/integration level.

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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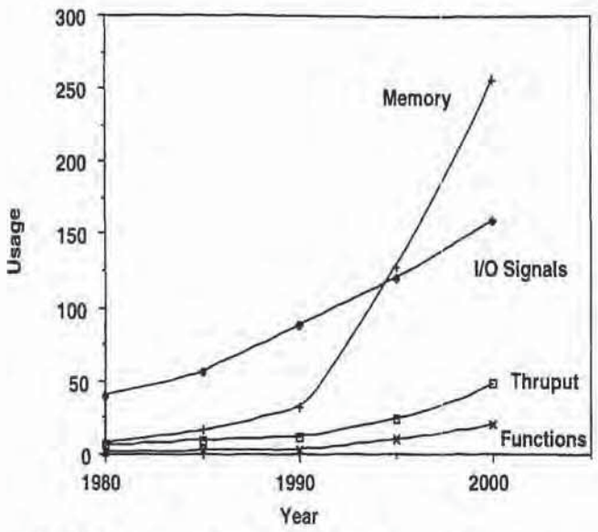


FIGURE 32.2 Automotive usage of microcontroller technology.

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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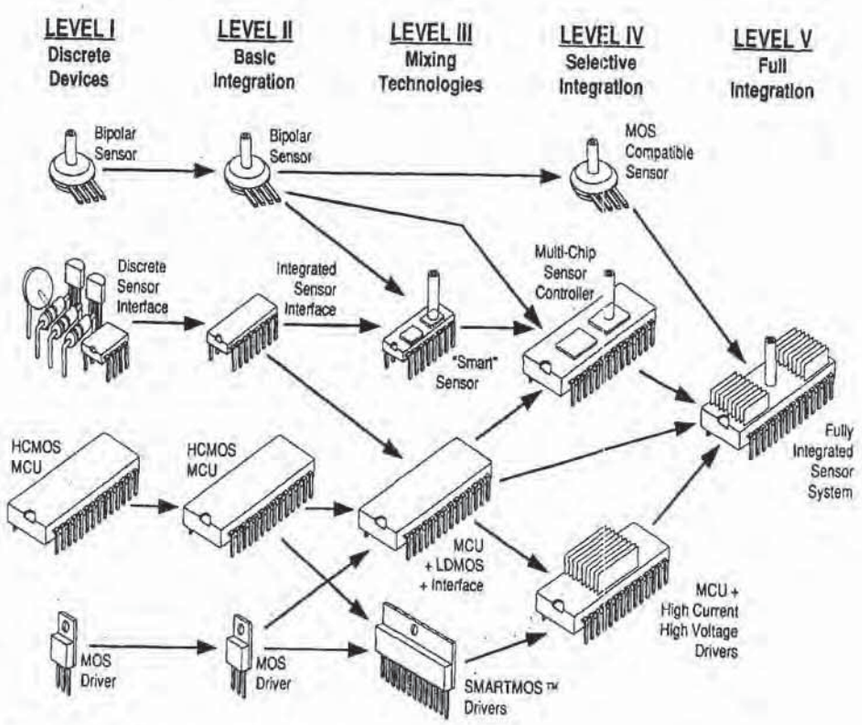


FIGURE 32.3 Sensor technology migration path.

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.

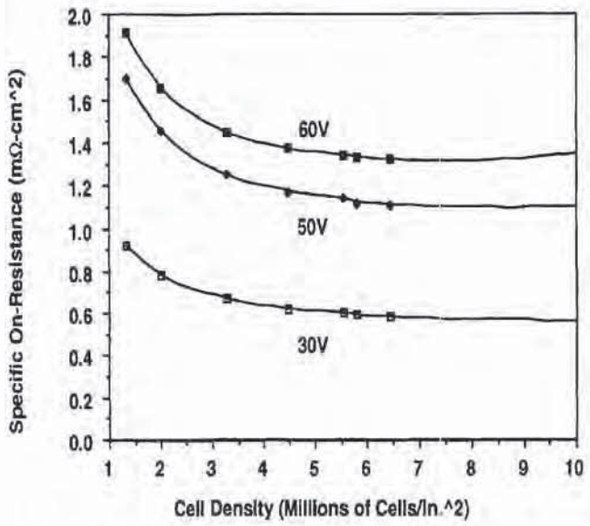


FIGURE 32.4 Power efficiency vs. voltage.

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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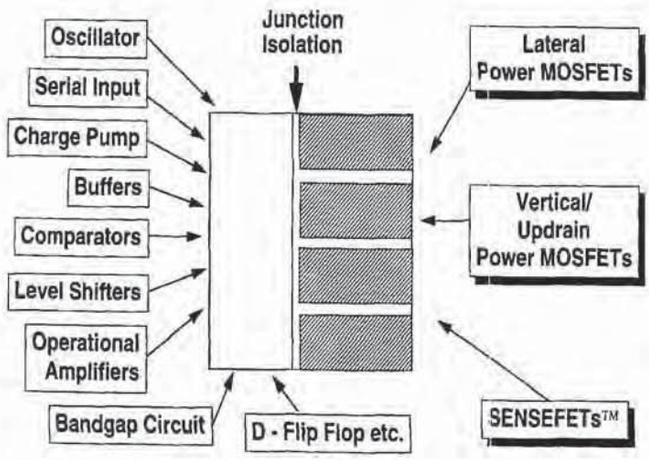


FIGURE 32.5 SMARTMOS™ technology cells.

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.

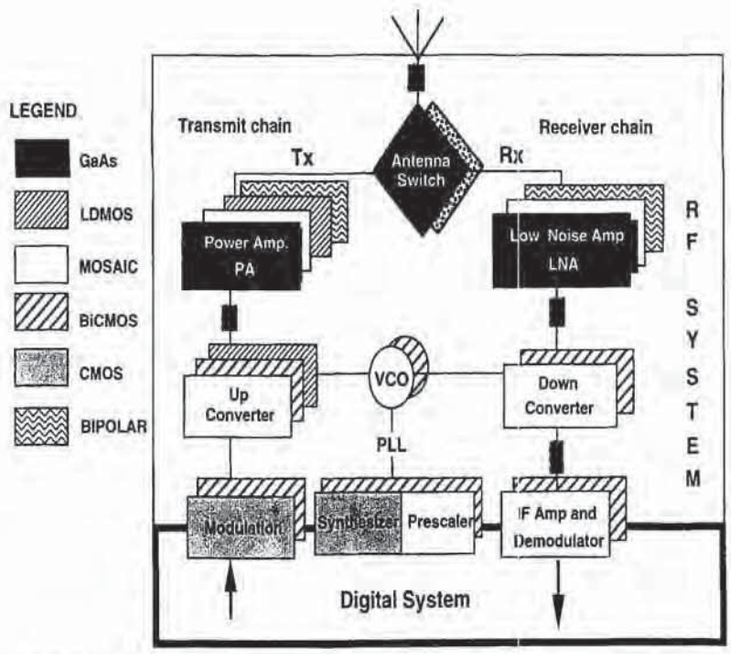


FIGURE 32.6 RF semiconductor technologies.

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.

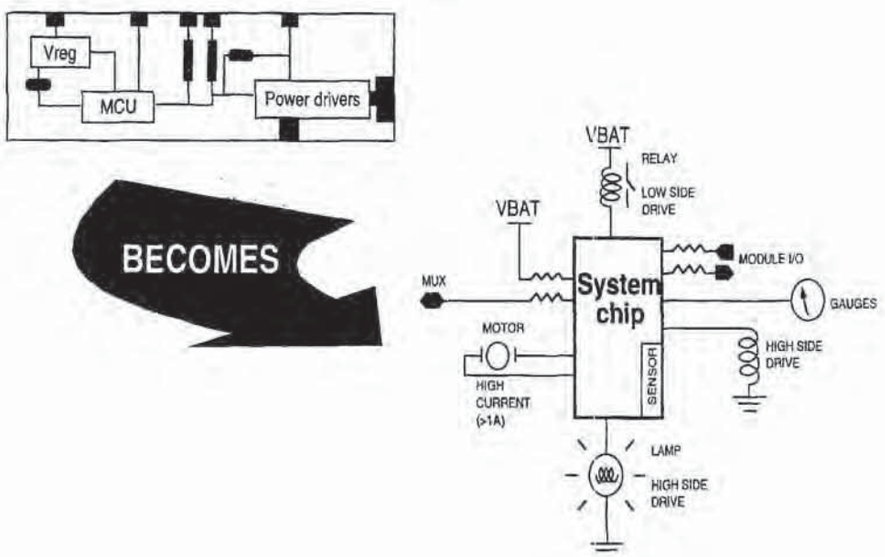


FIGURE 32.7 System Chip™ integrated solution.

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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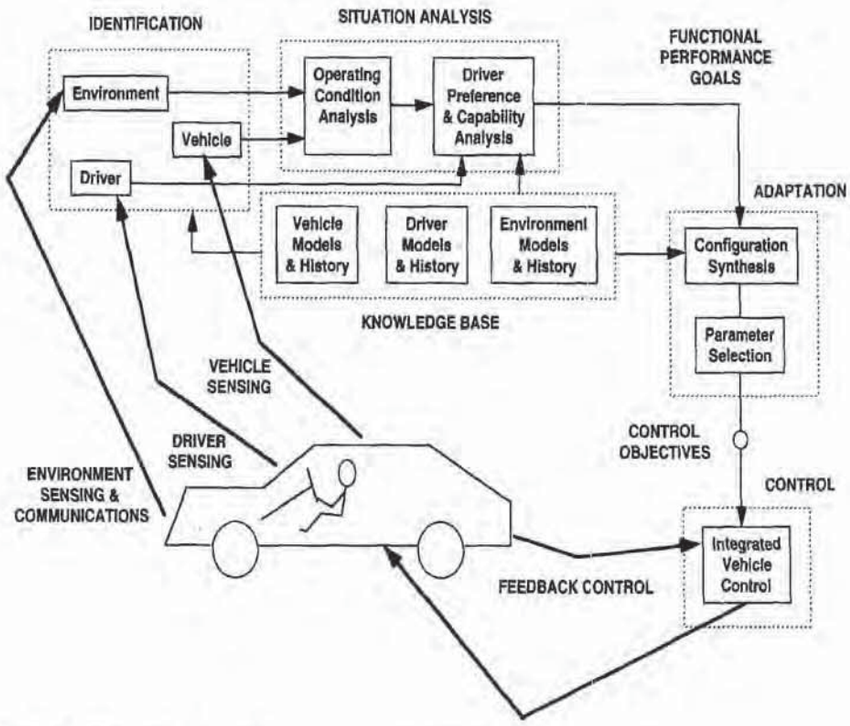


FIGURE 32.8 Vehicle, driver, and environment interrelationships.

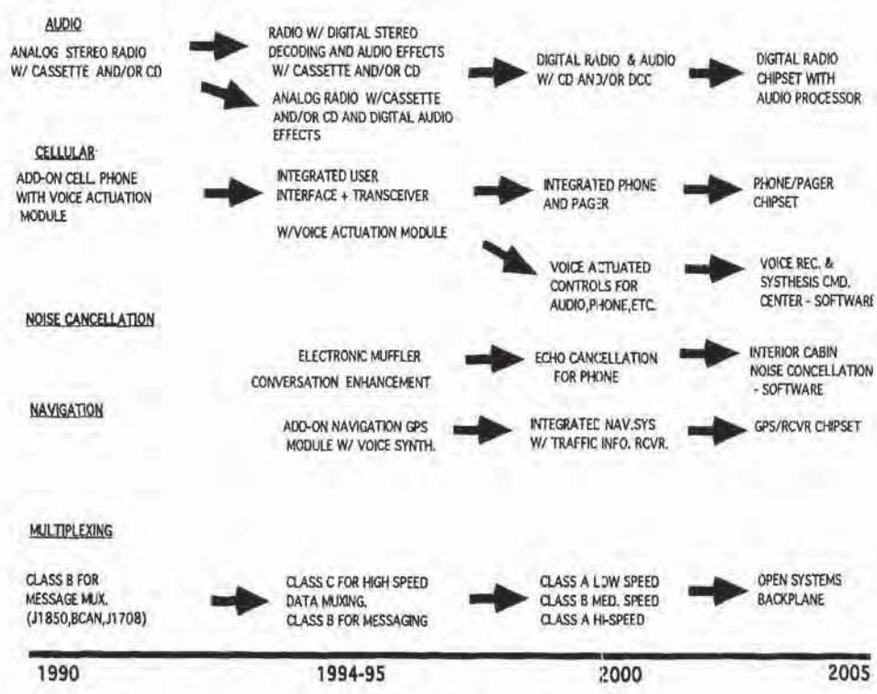


FIGURE 32.9 Audio, communication, navigation systems evolution.

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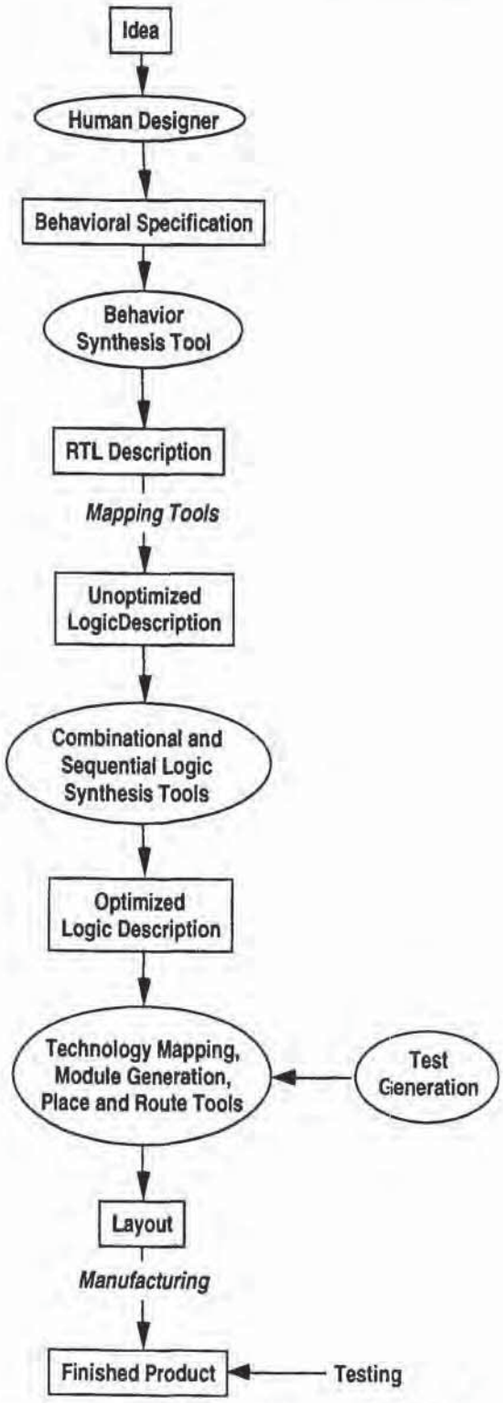


FIGURE 32.10 Typical synthesis pipeline of today's design of VLSI silicon chip.

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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.

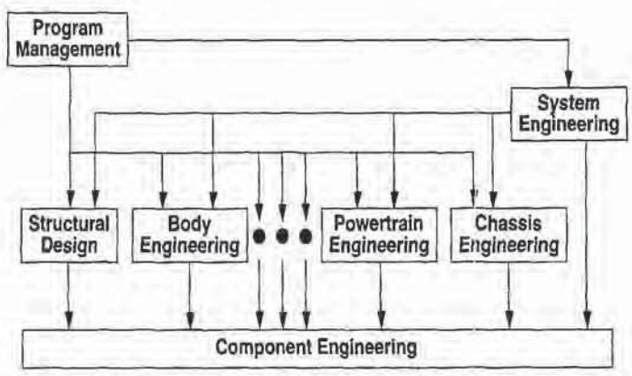


FIGURE 32.11 Product development with system engineering operation.

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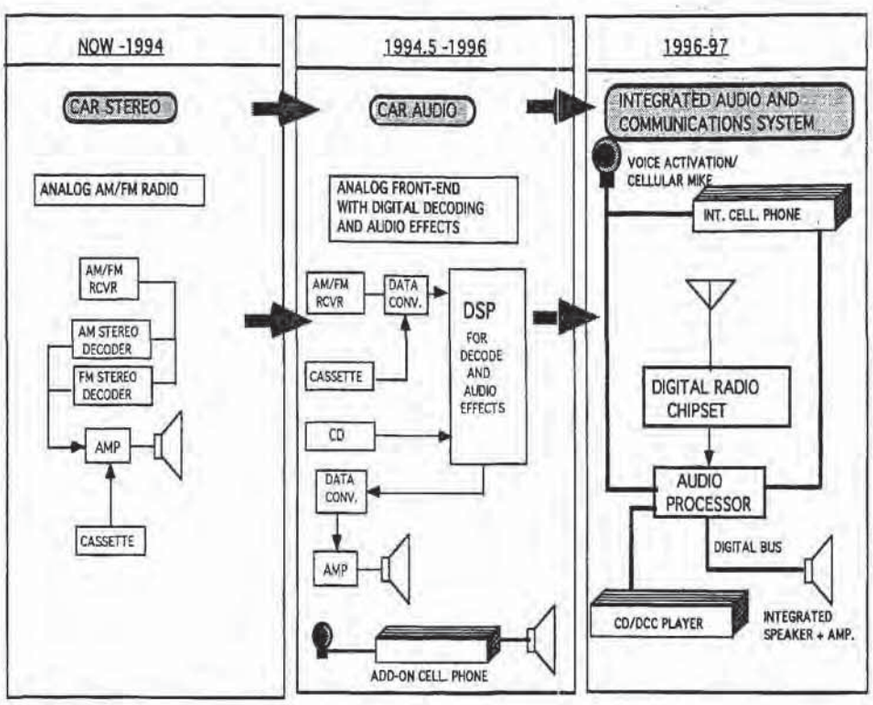


FIGURE 32.12 Audio evolution.

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.

BIBLIOGRAPHY

"Behavior Synthesis Yields Working Silicon," *Electronic Design,* Dec. 2, 1993, p. 28.

Benson, M., R. Frank, J. Jandu, and M. Shaw, *Proceedings of Sensors Expo 1993,* Philadelphia, Pa., Oct. 26–28, 1993, pp. 133–143.

"Circuits don't need substrates at UCLA," Technology News section of *Solid State Technology,* Dec. 1993, pp. 18–19.

Devadas, S., "Microelectronic System Design Skills for the Year 2000 and Beyond," *Journal of Microelectronic Systems Integration,* vol. 1, no. 1, 1993, pp. 85–95.

"EDA: An Emerging Competitive Weapon," *The Hansen Report,* July/August 1992.

Faubert, R., "Mainstream logic designers need to master new hardware and software design skills," *IEEE Spectrum,* p. 57.

Fleming, William, "Automotive Electronics," *IEEE Vehicular Technology Society News,* May 1993, pp. 32–34.

Gates, M., "EPA nominee is tough on environment, open to ideas," *Automotive News,* July 26, 1993, p. 4.

Schilke, N. A., et al., "Integrated Vehicle Controls," *Proceedings of 1988 International Congress on Transportation Electronics,* IEEE 88CH2533-8, Dearborn, Mich., Oct. 17–18, 1988, pp. 97–106.

SIA Semiconductor Technology, Workshop Working Group Reports, San Jose, Calif., 1993.

"Systems Engineering: and Update," *Automotive Engineering,* Feb. 1992, pp. 65–66.

Wilhelm, R. V., E. M. Norppa, and K. D. Casey, "Voice of the Customer Linkages to Powertrain Controller Design," *Proceedings of 1992 International Congress on Transporation Electronics,* SAE, Warrendale, Pa., Oct., 1992, pp. 253–258.

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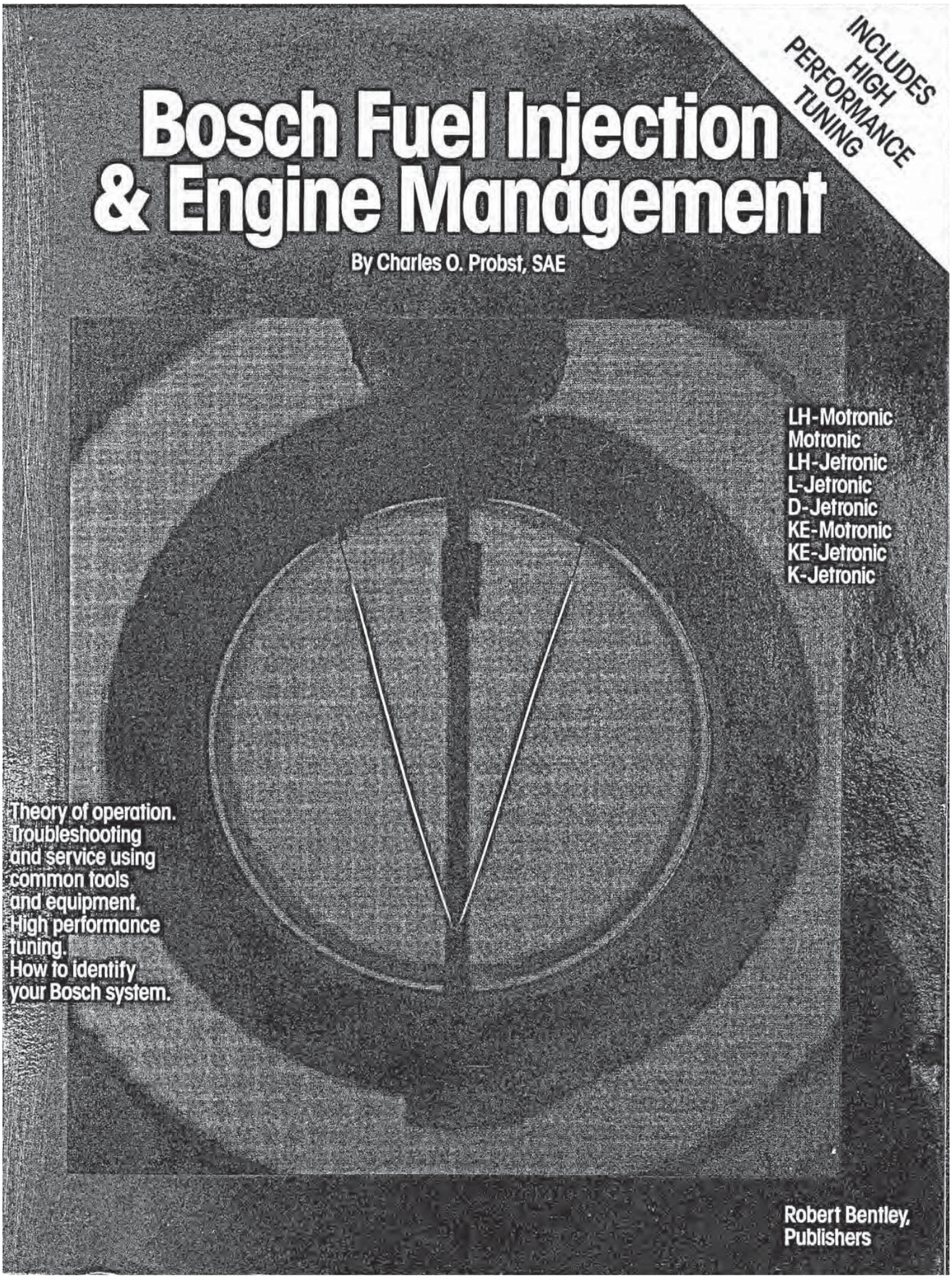
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Chapter 2

Engine Management Fundamentals

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1. INTRODUCTION

What sets fuel-injection and engine-management systems apart from other fuel delivery systems is their ability to precisely control fuel metering and adjust it in response to changing operating conditions. The key elements in the success of Bosch fuel-injection and engine-management systems are (a) a comprehensive understanding of the engine's varying fuel delivery requirements over a broad range of operating conditions, (b) extensive research into how the factors which influence the engine's fuel needs can be measured and interpreted by control systems and, (c) highly developed methods for controlling fuel metering to optimize overall performance.

In this chapter, I'll review the basic factors governing air-fuel mixture and fuel delivery, I'll describe why various engine operating conditions demand different air-fuel mixtures, and I'll explain how the air-fuel ratio can be manipulated to improve driveability and control exhaust emissions with little sacrifice of power. In chapter 3 and chapter 5, you'll see how Bosch applies these principles to the design and operation of their fuel-injection systems.

2. BASIC FACTORS

First, the basics. We'll take a closer look at air-fuel ratios and the engine's basic demands for a combustible mixture. I'll describe additional factors affecting fuel delivery which are imposed by the demands of the car-buying public, and we'll examine pressure and pressure measurement—a subject that is fundamental to understanding how Bosch fuel-injection systems work.

2.1 Air-Fuel Ratios

An engine's throttle controls the amount of air the engine takes in. The main function of any fuel delivery system is to mix fuel with that incoming air in the proper ratio. Small variations in air-fuel ratio can have dramatic effects on power output, fuel consumption, and exhaust emissions.

The Basic Combustible Mixture

Laws of physics tell us that combustion of any substance requires a sufficient ratio of surface area to mass (small enough particles), and the correct amount of oxygen (in proportion to the amount of fuel). In internal combustion engines these conditions are met by atomizing the fuel into tiny droplets, and by metering fuel in correct proportion to the intake air. In round numbers, approximately 14 parts of air are required to support complete combustion of 1 part of fuel—in other words, an air-fuel ratio of about 14:1.

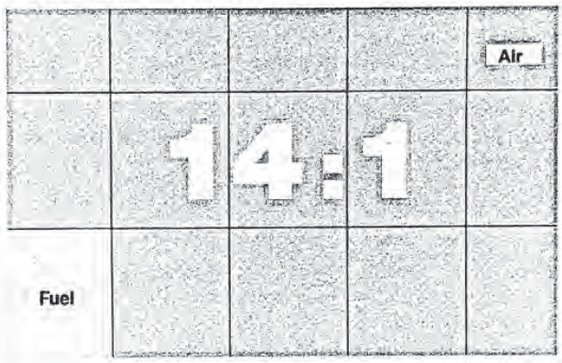


Fig. 2-1. By mass, it takes about 14 parts of air to support complete combustion of 1 part of fuel. Before today's concerns over fuel economy and emissions, an air-fuel ratio somewhere close to 14:1 was good enough.

Throughout this book, I'll follow generally accepted practice and discuss air-fuel ratios primarily in terms of mass. This is the simplest and best way to help you understand the basic factors governing fuel delivery and combustion. Many of the Bosch systems, however, measure air flow by volume. It is interesting to see that, by volume, the proportion of air to fuel is approximately 11,500:1.

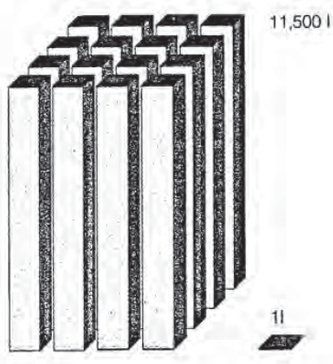


Fig. 2-2. By volume, it takes approximately 11,500 parts of air to support complete combustion of 1 part of fuel.

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Notice that I am talking about combustion that is complete – combustion that makes the best, most thorough use of fuel. Air-fuel ratios which are higher or lower than approximately 14:1 will still burn, but such combustion produces unwanted by-products and other side effects. As you read further into this chapter, you'll see what those are, and why precise control of the air-fuel ratio has become so important.

Rich and Lean Mixtures

The terms "rich" and "lean" are used to describe mixtures which deviate from the theoretically perfect air-fuel ratio and burn less efficiently.

A rich mixture is one with a lower air-fuel ratio; there is insufficient air (oxygen) to support complete combustion of the fuel. Rich mixtures increase fuel consumption and emissions of hydrocarbons (HC) and carbon monoxide (CO) – the products of incompletely burned gasoline. They tend to reduce power, increase carbon deposits and, in the extreme case, foul spark plugs and dilute the engine's lubricating oil.

"Enrichment" is the process of metering more fuel for a given amount of air to produce a richer mixture.

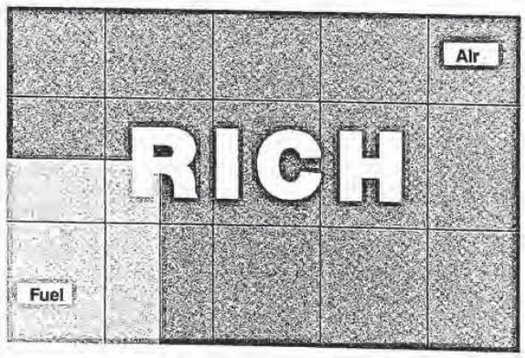


Fig. 2-3. Rich mixtures contain more fuel than can be completely burned in the given amount of air.

A lean mixture is one with a higher air-fuel ratio; there is more air than necessary for complete combustion of the fuel. The fuel will burn completely, but more slowly and at a higher combustion temperature. Lean mixtures reduce power, elevate engine temperature, and increase emissions of oxides of nitrogen (NO_x) – a product of combustion at excessively high temperature. They also tend to cause driveability problems. In the extreme case, the high temperatures resulting from lean combustion will cause pre-ignition – violent, untimed combustion of the mixture which has the potential to cause serious engine damage.



Fig. 2-4. Lean mixtures contain more air than is necessary for combustion of the fuel. Inferior combustion reduces power and can cause engine damage.

Stoichiometric Ratio

When "gas was cheap and the air was dirty," carburetors were usually set up to deliver mixtures richer than 14:1, perhaps with an air-fuel ratio as low as 12:1. As the car aged and a little excess air leaked in around the gaskets of the carburetor or the intake manifold, the engine still got a good combustible mixture. Then, too, the carburetor was farther from the end cylinders than from the middle ones. A richer mixture was some compensation for unequal fuel distribution.

There was another reason for setting up carbureted engines to run a little rich. Air-fuel mixture was less precise, and some variations were to be expected. As shown in Fig. 2-5, variations in a rich mixture have only a small effect on power, while variations in a lean mixture affect power dramatically.

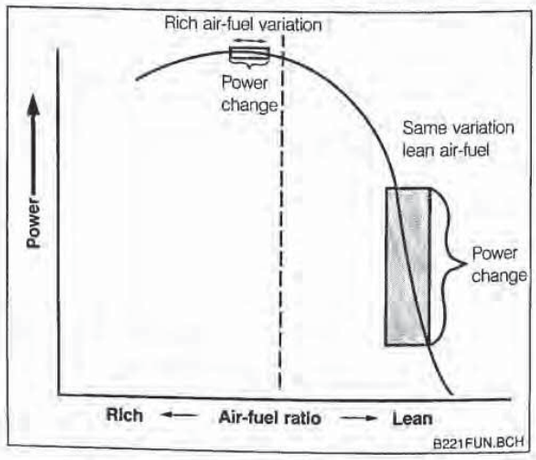


Fig. 2-5. Variation in a rich air-fuel ratio makes much less difference in power than the same variation in a lean air-fuel ratio.

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For today's engines, with the increased emphasis on fuel economy and reduced emissions, the air-fuel ratio has to be controlled much more carefully. The "ideal" air-fuel ratio—the one which yields the most complete combustion and the best compromise between lean and rich mixtures—is 14.7:1. This is called the "stoichiometric" ratio. The mixture is neither rich nor lean.

The Excess Air Factor—Lambda

The stoichiometric ratio can also be described in terms of the air requirements of the engine. Bosch calls this the "excess air factor" and represents it using the Greek letter λ (lambda). At the stoichiometric ratio—when the amount of air equals the amount required for complete combustion of the fuel and there is no excess air—lambda (λ) = 1.

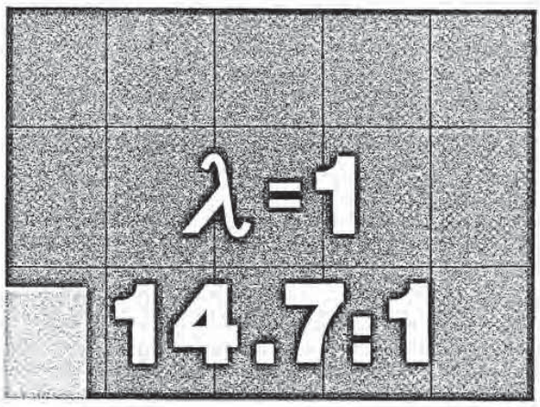


Fig. 2-6. The ideal or "stoichiometric" air-fuel ratio—when there is just enough air to burn all the fuel—is 14.7:1. This is also described as λ (lambda) = 1.

When there is excess air (air-fuel ratio leaner than stoichiometric), lambda is greater than one. When there is a shortage of air (air-fuel ratio richer than stoichiometric), lambda is less than one.

The concept of lambda (the excess air factor) was created specifically to support thinking about fuel delivery in terms of the air requirements of the engine. As you'll see later on, this concept plays a big part in controlling exhaust emissions.

2.2 Driveability and Emission Control

I've described the engine's basic requirement for a combustible mixture of air and fuel, how variations in mixture influence performance, and how older carburetor systems tended to run richer than the ideal air-fuel ratio in the interest of delivering smooth, reliable power.

While power is always a requirement, modern fuel delivery systems face additional demands. Increasing concern over the cost and availability of gasoline has resulted in greater demand for fuel economy. Environmental concerns and resulting legislation demand rigid control of harmful exhaust emissions. And, the car-buying public increasingly demands good driveability—quick-starting and smooth, trouble-free performance under any and all operating conditions. Each of these factors places different demands on the fuel delivery system, and there are trade-offs.

Adjusting the system for maximum power also means increasing fuel consumption. Minimizing fuel consumption means sacrificing power and driveability. Choosing either maximum power or minimum fuel consumption means increased exhaust emissions. The modern fuel delivery system must be able to maintain strict control of air-fuel ratio in order to achieve the best compromise and meet these conflicting demands in the most acceptable way. In general, this means slight sacrifices of power and fuel economy in exchange for optimum emissions control.

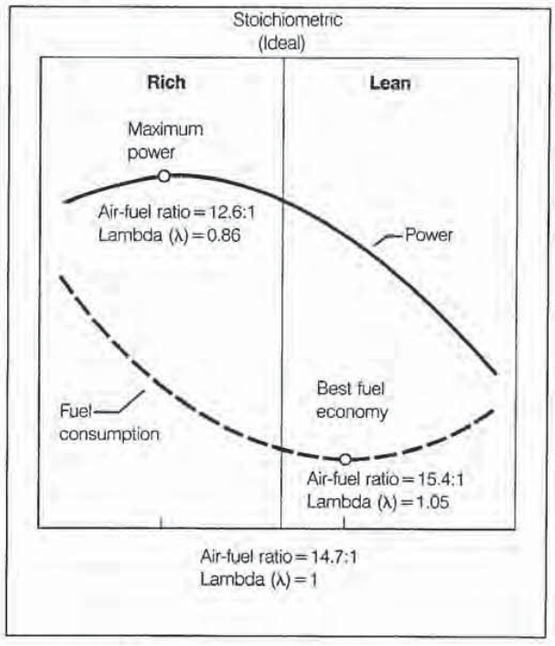


Fig. 2-7. The air-fuel ratio which delivers maximum power is slightly richer than stoichiometric; the one which delivers minimum fuel consumption is slightly more lean than stoichiometric. The stoichiometric ratio is a compromise which sacrifices very little of either.

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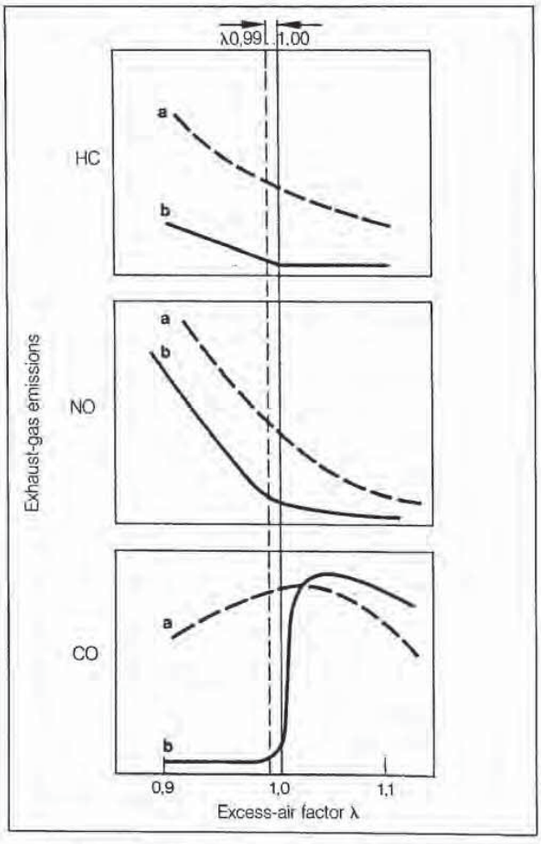


Fig. 2-8. Stoichiometric air-fuel ratio ($\lambda = 1$) yields the best compromise for control of hydrocarbon (HC), carbon monoxide (CO), and oxides of nitrogen (NO_x) emissions, before the catalytic converter (a) or after it (b).

It is fuel injection's ability to maintain the air-fuel ratio within close tolerances that makes it superior to carburetor systems. For the manufacturer, fuel-injection means better emission control and better fuel economy, both important in meeting increasingly stringent government regulation. For the owner, fuel-injection means achieving fuel economy and emission control while preserving driveability and maximum power.

Fuel Economy - CAFE

Along with the general demand for fuel economy, each manufacturer must consider another factor: mandated federal standards for rated fuel economy – the Corporate Average Fuel Economy (CAFE) standards. The industry trend in rated miles-per-gallon (mpg) turned upward beginning in 1975, as catalytic converters replaced engine de-tuning as a means of emission control. In addition, government legislation established an average mpg standard to apply to the total fleet of cars each manufacturer delivers each year. Further, the target mpg standard rose each year, starting at 18 mpg in 1978, and rising to 27.5 mpg in 1985, but cut back in 1986 to 26 mpg. Fuel injection's precise control of fuel delivery minimizes fuel consumption while still providing good driveability.

2.3 Air Flow, Fuel Delivery, and Engine Load

You know that air is drawn into the engine with each intake stroke of each piston. The piston moving down on its intake stroke increases cylinder volume and lowers pressure in the cylinder. With the intake valve open, air at higher pressure rushes in from the intake manifold to fill the cylinder. The amount of fuel necessary to create a stoichiometric mixture depends on how much air rushes in.

In simplest terms, intake air flow occurs because normal atmospheric pressure is higher than the pressure in the cylinders. Air rushes in during the intake stroke, trying to equalize the pressure. In gasoline engines, the throttle valve restricts intake air flow. As you open the throttle, the opening to atmospheric pressure raises manifold pressure. So, in practice, the amount of air that rushes into the cylinder on the intake stroke depends on the difference between the pressure in the intake manifold and the lower pressure in the cylinder. Pressure in the intake manifold depends on throttle opening.

The greatest intake air flow occurs when the throttle valve is fully open. The throttle valve causes almost no restriction, and full atmospheric pressure is admitted to the intake manifold. This creates the greatest possible difference between manifold pressure and cylinder pressure, and the greatest intake air flow.

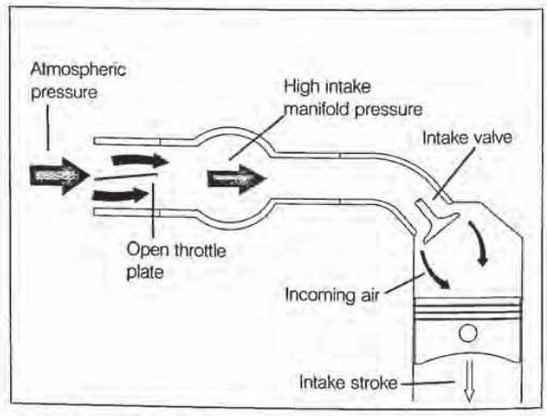


Fig. 2-9. At full throttle, nearly unrestricted atmospheric pressure raises manifold pressure. Large pressure differential between manifold and cylinders increases air flow.

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The least intake air flow occurs when the throttle is nearly closed. The restriction of the throttle valve limits the effect of atmospheric pressure. There is little difference between manifold pressure and the low pressure in the cylinders, and air flow is low.

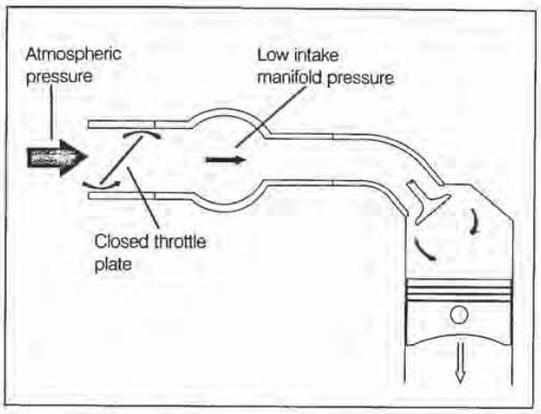


Fig. 2-10. With the throttle closed, atmospheric pressure has little effect on manifold pressure. Low pressure differential between manifold and cylinders results in little air flow.

Fuel delivery requirements depend more than anything else on how much work you are asking the engine to do—on how much of a "load" you are placing on it. To accelerate, you step down harder on the accelerator. This opens the throttle valve, increasing manifold pressure. The greater pressure difference between the manifold and the cylinders increases intake air flow, and therefore fuel flow, to increase power and accelerate the car.

Driving down a level road, you can cruise along comfortably and maintain a desired speed with a relatively small throttle opening. When you come to a hill, it is necessary to press farther down on the accelerator to maintain the same speed, even though engine rpm is unchanged. The hill has demanded more work from the engine—created a higher load—and the engine has demanded more air and fuel to match that load.

Regardless of engine speed, the air flow and fuel delivery demands of the engine depend on the load being placed upon it. That load, and the resulting throttle opening, directly affect manifold pressure. Manifold pressure in turn affects air flow and thus fuel requirements.

2.4 Fuel Pressure

Both carburetors and fuel-injection systems rely on pressure or pressure differential to dispense fuel into the intake air stream. The atomized fuel vaporizes and mixes with the air to produce a combustible mixture.

In a carburetor system, the fuel system supplies fuel to the carburetor float bowl. The bowl is vented, and the fuel in the bowl is at atmospheric pressure. Intake air passing through the carburetor's venturi creates low pressure in the venturi—lower than atmospheric pressure. This pressure differential—between atmospheric pressure in the carburetor bowl and reduced pressure in the venturi chamber—causes fuel to flow from the bowl through the discharge nozzle, and into the intake air stream.

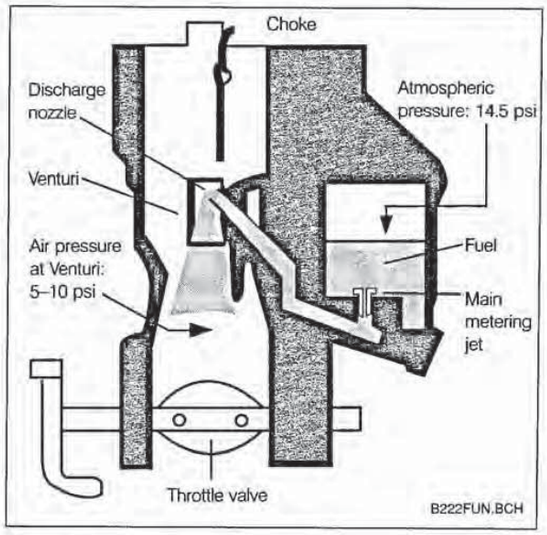


Fig. 2-11. The fuel-metering part of a carburetor operates with small differences in pressure: fuel in the bowl at atmospheric pressure vs. reduced pressure at the discharge nozzle in the venturi.

The pressure differential in the fuel-metering system of a carburetor is usually pretty small—only a few pounds-per-square-inch (psi). In contrast, fuel-injection systems introduce the fuel at higher pressures, anywhere from 30 to 90 psi depending on the system and specific operating conditions. Fuel delivery at these higher pressures ensures that the fuel is better atomized, and it is vaporized more completely in the airstream. Higher fuel pressure also makes possible more precise control of fuel delivery.

2.5 Pressure Measurement

As I get into the specific functional details of each of the various fuel-injection systems, you'll see that many functions and relationships are defined in terms of pressure. They may be fuel pressure values in the fuel system, manifold pressure in the air intake system, or atmospheric pressure. I may be talking about a differential pressure—the difference between two opposing pressure values somewhere in the system.

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In any case, pressure values are always expressed in one or more of the following units or terms. All are correct. With the appropriate conversion factors, all are interchangeable. Fortunately, the math required to convert between the different units is simple.

- **Pounds-per-Square Inch (psi).** The English system unit of pressure defined as force (pounds) divided by area (square inches). Atmospheric pressure at sea level is approximately 14.5 psi.
- **Bar.** A metric term derived from barometer or barometric pressure—atmospheric pressure. One bar is approximately equal to standard atmospheric pressure at sea level, so 1 bar = 14.5 psi. Typical fuel pressure in a pulsed-injection system might be 2.5 bar, or about 36 psi. European manufacturers' specifications and pressure gauges usually refer to pressures in bar.
- **kiloPascal (kPa).** The proper metric unit for pressure. 1 bar = 100 kPa, so atmospheric pressure at sea level is 100kPa. Used mainly in the U.S.
- **Inches of Mercury (in. Hg).** Originally refers to measurement of pressure using a mercury manometer. (Hg is the chemical symbol for mercury). This is a term used to specify manifold vacuum; 29.92 in. Hg is the difference between standard atmospheric pressure at sea level and absolute vacuum.

Table a lists the various units of pressure and appropriate conversion factors.

Table a. Units of Pressure Conversion

Unit	Atmospheric pressure (sea level)	to convert to:			
		psi	bar	kPa	in.Hg
		multiply by:			
psi	14.5	—	0.069	6.9	2.06
bar	1	14.5	—	100	29.92
kPa	100	0.145	0.01	—	0.299
in.Hg	29.92	0.485	0.033	3.34	—

If you watch the local TV weatherperson, you'll see how barometric pressure readings (in. Hg) are used to describe atmospheric pressure changes. Listen to the references to "highs" and "lows". Changing atmospheric pressure changes the density of the air. Denser intake air can slightly alter the air-fuel ratio and may affect how your engine operates. Some Bosch fuel-injection and engine-management systems have features which allow the system to compensate for variations in air density.

Gauge Pressure vs. Absolute Pressure vs. Vacuum

I've described engine intake air flow and load in terms of manifold pressure, and I've discussed the units of measure used to describe pressure. Now it is important that you understand exactly what you are measuring.

For many years, people have traditionally thought about engine air flow and load in terms of vacuum—the "vacuum" created in the intake manifold by the pistons' intake strokes. Using atmospheric pressure as a baseline, as zero, the lower manifold pressure is expressed as a negative value—vacuum.

By the 1980s, the automotive industry had moved away from thinking in terms of vacuum. Widespread use of fuel injection began to demand more accurate measurement of manifold "vacuum", and turbocharging—where manifold pressure may exceed atmospheric pressure—began to blur the distinction between vacuum and pressure. A simpler and more useful approach is to think in terms of manifold absolute pressure (MAP). MAP refers to the pressure in the intake manifold which is positive compared to zero absolute pressure, rather than negative compared to atmospheric pressure.

If that seems hard to understand, think of atmospheric pressure at sea level. We tend to think of this as zero pressure and, in fact, an open fuel-pressure gauge will read 0 at sea level. But remember, atmospheric pressure at sea level is actually 1 bar (14.5 psi). Almost all pressure gauges use atmospheric pressure as their reference. Any measurement made with the gauge reads pressure only with respect to atmospheric pressure. As indicated by Fig. 2-12, a gauge which reads 0 pressure at sea level (atmospheric pressure) is actually measuring 1 bar on the absolute pressure scale.

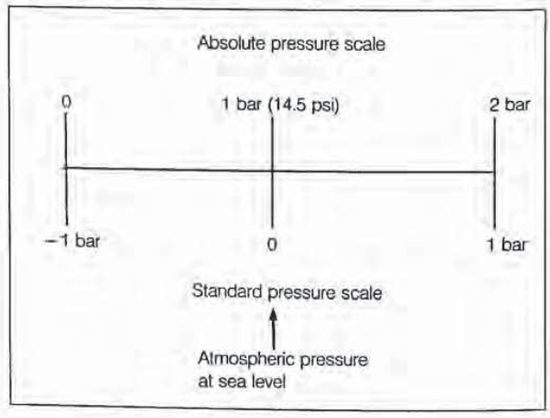


Fig. 2-12. Calibration of pressure gauge influences how you interpret pressure readings.

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Using absolute pressure as the reference point, the piston on its intake stroke is creating a very low pressure in the cylinder—approaching zero absolute pressure. The pressure in the intake manifold—manifold absolute pressure (MAP)—is higher and always a positive number. Higher still is atmospheric pressure outside the engine, its influence on manifold pressure controlled by the throttle. Boost from a turbocharger or supercharger is pressure above atmospheric pressure. Many European boost gauges read MAP. They are calibrated from zero absolute pressure so, with the engine off, the gauge reads 1 bar—normal atmospheric pressure.

I've been driving with a "vacuum" gauge connected to the intake manifold of each of my last 9 cars. The gauge comes calibrated in terms of vacuum, so at wide open throttle (WOT) it reads close to zero. I have also marked my gauges to read MAP, positive manifold pressure relative to absolute pressure at or near sea level. That means that at WOT (near zero vacuum), my gauge reads about 9 on the homemade MAP scale, as shown in Fig. 2-13. I can read it two ways: multiply by 10 to read pressure in kPa (90 kPa), or divide by 10 to read pressure in bar (0.9 bar). The important point is that the numbers increase as the load and power increase. Fig. 2-14 shows approximate range of gauge values for various driving conditions and throttle positions. By coincidence, 65 mph cruise reads about 65 kPa or 0.65 bar.

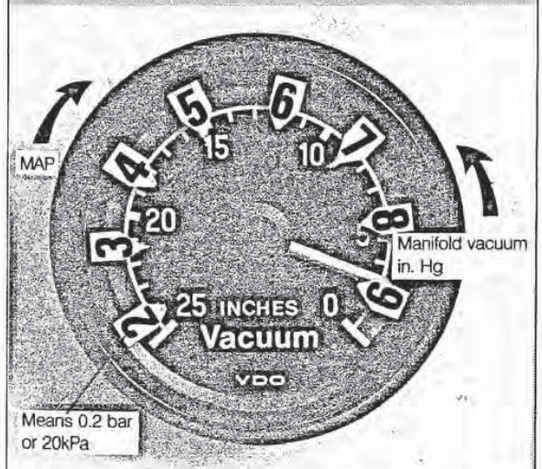


Fig. 2-13. Manifold vacuum gauge calibrated to read vacuum (in. Hg) can also be calibrated to read manifold absolute pressure (MAP). With fuel-injection or forced-induction systems, MAP makes it easier to relate engine load and throttle opening to manifold pressure.

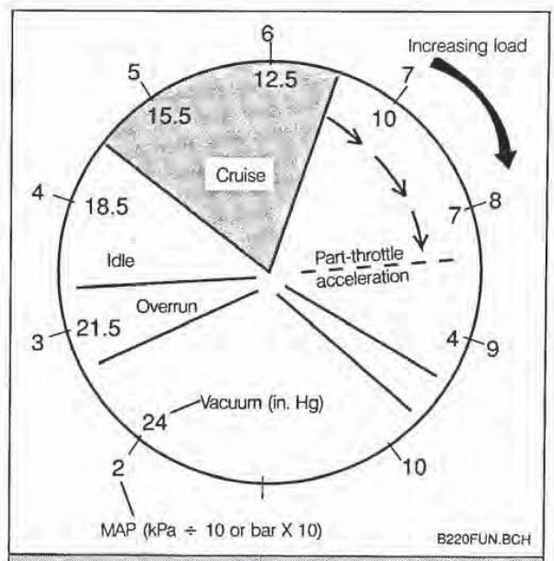


Fig. 2-14. Gauge schematic shows how vacuum and MAP indications relate to throttle opening.

On a turbocharged car, boost will read above 10 (100 kPa) on the MAP scale. MAP changes continuously from about 20kPa during overrun (coasting with closed throttle) to perhaps 160kPa at maximum boost. When we discuss the importance of manifold pressure to fuel injection, you will find it an advantage to think in terms of the positive MAP values (from absolute zero) rather than vacuum.

3. Operating Conditions and Driveability

If I were talking about the requirements of a stationary industrial engine, I'd expect it to operate under basically fixed conditions: constant rpm, constant load, nearly constant temperature, limited stops and starts, no acceleration, and no heavy-footed driver. Such an engine would operate quite nicely at a fixed air-fuel ratio. It could be easily tuned to maximize fuel economy, and would require only the simplest of fuel systems.

Cars, however, are a different story. We expect them to perform under the widest possible variety of operating conditions. And we have given "performance" a new definition it is not only impressive horsepower and torque, but also maximum fuel economy, and controlled exhaust emissions. As if these performance demands were not enough, we also expect the car to meet these demands effortlessly, at any time, under any conditions, and at the turn of a key. We expect what has come to be called "driveability"—the ability of the car to provide smooth, trouble-free performance under virtually any conditions while delivering power, fuel economy, and controlled emissions.

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10 ENGINE MANAGEMENT FUNDAMENTALS

Driveability is a term which evolved out of the early days of strict emission control and the '70s energy-crisis concerns over fuel economy. The less-developed technology of the time dictated an approach to both problems which often resulted in the engine running too lean. Running too lean robbed power and contributed to rough idle, poor throttle response, stumbling and stalling, and overall poor running. Fuel injection and more complex engine-management systems offer the precise control and flexibility necessary to meet modern performance requirements.

To meet these demands under different operating conditions, the engine has different air-fuel requirements. I'll discuss these operating conditions, the effect they have on basic air-fuel requirements, and how the capabilities of fuel-injection and engine-management systems are used to meet these requirements. I'm describing what these systems in general can do, not necessarily what a basic Jetronic fuel-injection system will do, particularly those systems on cars manufactured before 1982.

3.1 Normal (Warm) Cruise

Normal cruising at light load with the engine fully warmed up is the baseline operating condition. The basic fuel system is designed to meet the engine's need for the proper air-fuel ratio under these simple cruising conditions. The design must be flexible enough to handle fuel delivery at different speeds and loads, but this basic fuel metering is the fuel system's simplest task. Though the driver may add power on a hill or to pass another car, or cut back power to slow down, fuel management is still relatively simple. All other parts of the fuel system which compensate for different operating conditions do so by making adjustments to this main fuel-metering function.

When you are cruising down the interstate, if the road is level the engine is operating under relatively constant normal conditions. The fuel quality may vary from one tank fill to the next; weather and outside temperature may change; it may be dry or it may be damp. The ideal air-fuel ratio will be different for each of these conditions. A fuel-injection system can adjust to these changing conditions with little challenge, maintaining air-fuel delivery near the ideal (stoichiometric) ratio of 14.7:1 to satisfy the most important considerations of fuel economy and low exhaust emissions.

3.2 Starting

As an owner, you expect the engine to start instantly; whether it's at sub-zero temperatures or parked in the desert, too hot to touch; whether it's been sitting for five minutes at the store or for five weeks in the garage.

As far as fuel system requirements are concerned, starting makes different demands depending on temperature. I'll discuss cold start, warm start, and hot start.

Cold Start

This means the engine is cold; that is, it probably hasn't run for at least 12 hours. In most cases, the temperature needle is at the low end of the gauge. The engine might be as cold as −20°F (−30°C), sometimes called cold-cold; or as hot as 115°F (45°C), sometimes called warm-cold. In either case, the engine is still cold compared to its normal operating temperature of about 195°F (90°C).

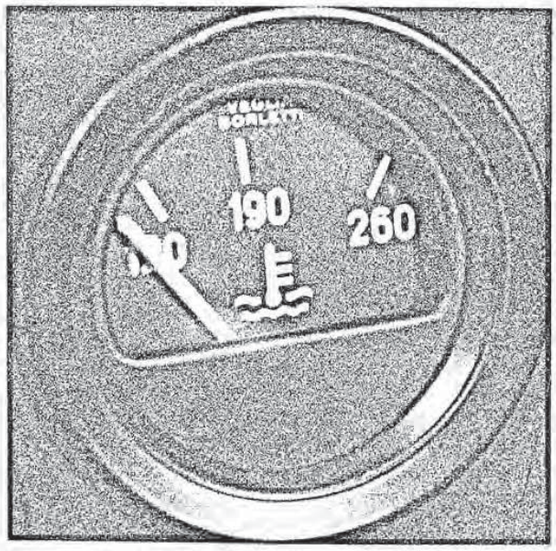


Fig. 3-1. Engine-cold temperature varies according to outside temperature. Cold start means the engine has not run for several hours.

To understand the distinctions I've made in cold-start temperature, consider the Environmental Protection Agency (EPA) definition of cold start. For EPA testing, cold is room temperature, about 68°F (20°C); all cars are tested on dynamometers inside the lab. The engine must cold-soak at 68°F in the lab next to the dynamometer for 12 hours before the test. Cars are pushed onto the dynamometer for the cold-start test. As it happens, 68°F is close to actual cold start temperatures in Southern California and much of southern U.S. Engine temperature affects the driveability of your engine, which may be much colder than an EPA cold engine. For scientific comparison testing, and for the regulatory aspects of EPA testing for emissions and fuel economy, uniformity is the most important factor.

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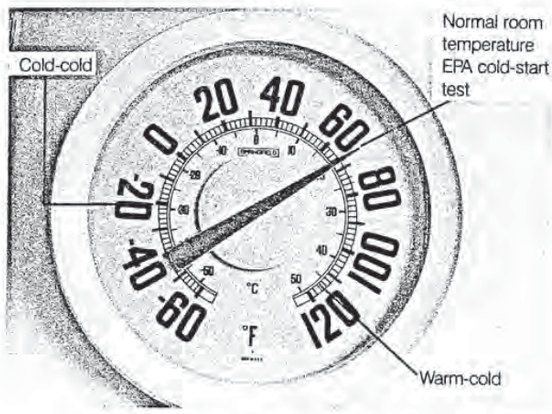


Fig. 3-2. Fuel requirement for engine starting varies according to outside air temperature: cold-cold or warm-cold. These temperatures are both cold compared to normal engine operating temperatures.

In most parts of the country, you will at times be faced with cold-cold starting conditions; the most challenging of all. Gasoline is less likely to vaporize when it is cold. Even if it is adequately vaporized, some fuel condenses on the cold parts of the engine before it can be burned. The engine requires extra fuel for starting so that, in spite of vaporization and condensation problems, the engine still receives a combustible air-fuel mixture.

What constitutes a combustible mixture depends on air temperature, the volatility of the gasoline, altitude, barometric pressure and humidity. While a carburetor relies on a relatively crude choke mechanism to increase fuel delivery for cold starting, fuel injection compensates for many of these factors. Temperature is the most important.

Cold-start enrichment quickly becomes a problem if the engine does not start right away; due to a marginal battery, ignition components in poor condition, or whatever. Enrichment during cranking must be cut back in a matter of seconds; if it goes on too long, the air-fuel mixture will be too rich to ignite. The spark plugs may become fuel-fouled, particularly when they are cold, and the engine will not start.

Cold starting also needs help in terms of intake air flow. A closed throttle and slow cranking speeds do not allow enough air for starting. Drivers of carbureted cars develop intricate starting procedures: depress the accelerator to the floor, release, then hold the throttle about ⅓ open (for example). The first depression is necessary to set the carburetor choke and fast-idle cams; the second is to open the throttle and make sure the engine is getting enough air. Fuel-injection systems can control the air by bypassing the closed throttle, admitting more air when cold without any effort or attention from the driver.

Warm Start

Warm starting is very much like warm running. The air-fuel demands are simple. A warm engine helps promote fuel vaporization, and fuel is much less likely to condense out of the air stream onto warm engine parts

Depending on the temperature, the engine may benefit from some small portion of the usual cold-start compensations. A carbureted car may benefit from a light push on the throttle, using the accelerator pump to deliver a little extra fuel. A fuel-injection system sensing temperature only a little below normal may just slightly enrich the mixture and slightly increase intake air to improve warm starting.

Hot Start

This means the engine is hot; perhaps after being driven for some time on a hot day, and then allowed to sit for a short time, unable to significantly cool. Under these conditions, sometimes called "hot soak" under-hood temperatures may exceed 250°F (120°C).

The most important aspect of hot soak and subsequent hot starting is the possibility of overheating the fuel. For a carbureted engine this may mean boiling the fuel in the fuel bowl and losing it as fuel vapor into the atmosphere. Hot starting becomes more difficult, since it takes time for the fuel system to refill the bowl so that fuel can reach the discharge nozzle.

In any engine, the excess heat may raise fuel temperatures and cause "vapor lock"—vaporized fuel in the lines. Unlike fuel, the resulting vapor in the lines is compressible, so the fuel pump cannot necessarily overcome the problem and deliver fresh fuel. In fuel-injection systems, the number of fuel lines to individual injectors and the routing of lines near the engine makes heat-soak a more acute problem. To ensure quick hot restart, the system must maintain pressure in the fuel lines and the injectors while the engine cools to prevent vapor lock.

Some fuel-injection systems combat the fuel vaporization problem by adding small doses of extra fuel, similar to cold start enrichment. The extra fuel while cranking slowly helps the engine start; then the increased air flow and fuel demands of the running engine can overcome the vapor lock.

Ignition Timing and Starting

For the more sophisticated engine-management systems, adjusting the ignition timing can help start a cold engine. If the engine is turning over a little slowly because of thick, cold oil in the crankcase, or reduced battery voltage at low temperatures, the best ignition timing is near Top Dead Center (TDC). More advanced timing, even as little as 10 degrees before TDC, allows the slow-turning engine to fire while the piston is still rising; the reverse torque may damage the starter.

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On a warm day, ignition timing of a cold engine can be advanced because the engine spins a little faster. But if the temperature were high (hot start), retarded ignition timing can prevent reverse torque and starter damage caused by igniting the air-fuel mixture before the piston reaches TDC. Also, the engine may knock during starting if intake air temperature is too high. In short, it is desirable to retard ignition timing for conditions of low cranking speed, and on the basis of high intake-air temperature. More advanced ignition timing is permissible under less challenging, warm starting conditions.

3.3 Post-Start and Warm-Up

Post-start refers to the period immediately after the engine fires. The engine requires less enrichment than for starting, but it is still cold. Some enrichment is required to compensate for poor fuel vaporization and for condensation; and to improve torque and throttle response, even though acceleration at this point might not be good driving practice. Engine torque must be sufficient to carry the load of a cold automatic transmission shifted from Neutral to Drive; many cold engines have a tendency to stall when so shifted.

The amount of post-start enrichment required depends on temperature and time; a colder engine requires more enrichment for a longer period of time. On the other hand, exhaust emission control demands that enrichment be cut back properly. An engine can fail its EPA emission test in the first thirty seconds after "cold" start if the post-start enrichment causes excessive exhaust emissions.

Post-start ignition timing can be advanced to improve the engine running and incidentally to reduce the requirement for enrichment during this period. Post-start can end in a few seconds or may last as long as fifteen or twenty seconds if the temperature is extremely cold. But, strangely, ignition retard can be used to heat the exhaust, and therefore the lambda sensor and catalytic converter, which work as intended only at high temperatures. That means emission control can be effective quickly after a start.

Warm-up refers to that period when the engine is in transition from its cold, post-start temperature, to its normal operating temperature. As the engine begins to warm up, it begins to require less and less enrichment. Since warm-up is a smooth, gradual process, the reduction of enrichment needs to be gradual too. If the engine is really cold, warm-up can last for several minutes. Since the car is probably being driven during the warm-up period, enrichment which is appropriate for the conditions at any given time is essential to ensure driveability.

On a carbureted engine, the choke mechanism is sensitive to temperature. As the engine warms the choke warms, gradually reducing warm-up enrichment. Fuel-injection and engine-management systems also use temperature as the main input for control of warm-up enrichment. Engine coolant temperature is the most common input. Some systems also respond to changes in intake air temperature.

For systems that have the capability to control ignition timing, advancing the timing during warm-up under part-throttle load can aid driveability. Retarding timing during warm-up under closed-throttle deceleration will reduce hydrocarbon (HC) emissions which risk being excessive anyway due to the warm-up enrichment.

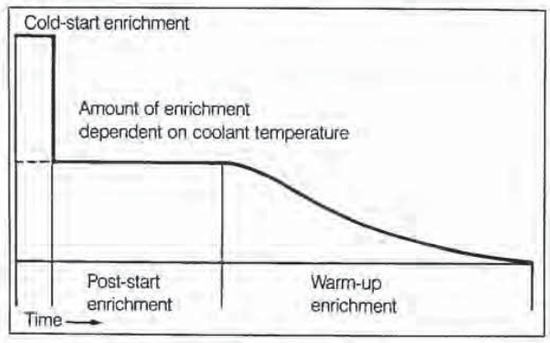


Fig. 3-3. Until the engine is fully warm, various degrees of enrichment are required. Starting requires maximum enrichment, depending on engine temperature. Post-start enrichment keeps the engine running for the first 30 seconds or so. Warm-up enrichment slowly drops off as the engine warms to normal operating temperature.

3.4 Idle

Our cars spend a lot of time idling, so a smooth idle and good off-idle throttle response are important aspects of driveability. First, there are some unique requirements for idle control during post-start and warm-up. Once the engine is warm, there are other factors which influence idle speed, and fuel injection's capabilities make possible improved idle characteristics.

Cold and Warm-up Idle

As I've already suggested under **3.2 Starting**, a cold engine has different air-fuel requirements than a warm engine. At idle, more air and more fuel are needed just to overcome the higher running friction of a cold-engine. A slightly higher idle speed is necessary to keep the cold engine from stalling, and to support good off-idle throttle response.

Fuel-injection systems, using both temperature inputs and direct rpm input, can precisely control idle speed by controlling intake air flow. With this precise control, cold idle is higher, but driveability is maintained. One of the joys of driving cars with fuel-injected engines is the freedom from a too-fast idle that can jar the car when an automatic transmission is shifted into Drive or Reverse.

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Warm Idle

The main requirements of a warm engine running at idle speed are smoothness, and smooth response once the throttle is opened. Some engines require a richer mixture at idle for smooth running, and to ensure good off-idle response. With ignition timing control capability, it is also possible to operate with a leaner mixture and achieve a smooth idle by changing ignition timing.

In general, the engine should idle at the lowest speed at which the engine will still run smoothly enough to satisfy the driver. Reducing idle speed to a minimum reduces noise and fuel consumption.

The biggest obstacle to low idle speeds is the variation in load on the engine at idle. At idle, small changes have big consequences. Friction loads change with temperature; the power required to operate the charging system varies with electrical load (headlights, for example); air conditioning compressors switch on and off; on cars with automatic transmissions, shifting into Drive or Reverse at idle increases the load.

Fuel injection's capabilities include idle stabilization (also called idle-speed control). By monitoring and constantly correcting idle speed, it is not necessary to maintain a higher-than-minimum idle to handle variations in engine performance, changing of loads, and similar causes of stalling from idle.

Advanced idle-speed stabilization systems satisfy some sophisticated requirements, particularly on cars with air conditioning (A/C) and automatic transmission:

1. In Neutral, A/C off: maintains the minimum idle speed that is required for engine smoothness

2. In Neutral, A/C on:
   - for small compressors, increases idle speed to run the compressor faster (increase A/C performance)
   - for large compressors, maintains idle speed by compensating for added compressor load
   - through A/C relay, delays compressor-clutch engagement for ½ second to prevent temporary rpm drop

3. In Drive:
   - for smooth-idling engines, reduces idle speed to minimize stoplight creep
   - for rough-idling engines, increases idle speed to minimize idle/load-induced vibration

4. In Drive, when A/C switches on: controls idle speed increase to avoid inadvertent surge when driver does not expect it

3.5 Acceleration

Any time you press the accelerator, opening the throttle increases manifold pressure which in turn increases intake air flow. The fuel system, responding to this increase in air flow, meters additional fuel to maintain the correct air-fuel mixture.

Accelerating—opening the throttle very quickly—places additional demands on the system. The sudden transition from closed throttle to open throttle produces sudden spikes in manifold pressure. The fuel system responds quickly to these changes, but not instantly. Some additional fuel delivery capability is required to compensate for these changes in manifold pressure—to prevent stalling and produce the quick throttle response we have come to expect and demand.

For quick, smooth throttle response under acceleration, the basic system of air flow sensing and fuel metering is too slow. The fuel system must be able to instantly compensate for rapid increases in manifold pressure with additional fuel. In many carburetors, additional fuel is supplied by the accelerator pump. It mechanically squirts additional fuel into the intake air stream whenever the throttle is opened suddenly. As you will see in later chapters, fuel-injection systems employ various methods of acceleration enrichment.

In **2. Basic Factors** I explained that fuel injection systems are designed to maintain the air-fuel ratio in the narrow range around stoichiometric, but that maximum power output is achieved with an air-fuel ratio that is slightly richer. In addition, the engine may need a richer mixture to reduce the tendency to knock. Many fuel-injection systems recognize full-throttle acceleration as a special case, and provide additional acceleration enrichment keyed to the full-open throttle position.

During acceleration, systems which can control ignition timing can deliver the best balance between advanced timing for maximum torque, and retarded timing for knock control.

3.6 Deceleration and Coasting

In the quest for minimum fuel consumption, engineers are quick to take advantage of opportunities to reduce fuel waste. One such opportunity is coasting cut-off, also known as overrun or deceleration cut-off.

The basic idea of deceleration fuel cut-off is this: the engine takes in some air and the fuel system delivers some fuel even when the throttle is completely closed (at idle, for example). On the road, when the car is decelerating or coasting with the throttle closed, this fuel is wasted. It is passing through the engine and being expended, but doing no useful work. Cutting off fuel during these conditions can save fuel, even in city driving. It also reduces exhaust emissions. To prevent stalling, fuel flow must be re-established at some programmed engine speed (above idle).

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Fuel cut-off behavior may be less satisfactory when the engine is cold, so normally the rpm limits for cut-off and for re-establishing fuel injection are higher for a cold engine. Coasting cut-off must also be restricted so it will not operate during shifting of manual transmissions, and so it will not interfere with cruise control.

Engine-management systems which can control ignition timing can retard the timing during the transition to smooth the response to the cut-off and resumption of fuel injection.

Deceleration fuel cut-off was a feature of the early D-Jetronic systems supplied on some Volkswagens, but the air-cooled engine cooled irregularly during the cut-off so emissions were actually increased; the feature was discontinued.

Water-cooled engines equipped with Jetronic systems have greater temperature stability, and can use deceleration cut-off successfully to save fuel and reduce emissions. Fuel cut-off is less successful in carbureted engines and those with throttle-body injection because the fuel is delivered so far from the cylinders. As fuel flow is resumed, the lag between restoring fuel delivery and resuming combustion spoils driveability with jerky response.

3.7 Altitude

At altitudes above sea level, the air is less dense; for a given volume of air, there is less oxygen to support combustion of fuel. In carburetors, and in fuel-injection systems which measure intake air by volume, less dense air changes the effective air-fuel ratio; at higher altitude, the mixture is richer.

Some fuel-injection systems can measure and respond to changes in air density, changing the air-fuel ratio as required to maintain the ideal (stoichiometric) ratio.

3.8 Engine Shut-Off

Engine shut-off is another chance to prevent wasting fuel. Carburetors dispense fuel into the intake air stream as long as the engine is turning over, whether or not the ignition is on. In contrast, turning off the ignition of a fuel-injected car also cuts power to the electric fuel pump. Fuel flow is immediately cut-off to prevent dieseling, or run-on.

3.9 RPM Limitation

Precise control of fuel delivery allows the fuel system to be used to limit engine rpm and prevent damage from over-revving. Before the days of catalytic converters, rpm was limited by simply cutting out the ignition when the rpm got too high. Cutting the ignition, however, still allows unburned fuel into the catalytic converter and causes it to overheat; sometimes dangerously. Since the mid-1970s and the advent of catalytic converters, rpm limitation has been accomplished by the fuel-injection system cutting back on fuel delivery. The goal is to keep the engine running at its limitation without dumping unburned fuel into the catalytic converter.

3.10 Ignition Timing

For some of the specific operating conditions described above, I've described how ignition timing adjustments can be used to enhance performance and satisfy driveability requirements.

In terms of all four major aspects of performance—power, fuel economy, emission control, and driveability—ignition timing is a significant factor; perhaps as significant as air-fuel mixture. Combustion in the cylinders takes a certain amount of time. In terms of how we usually think about time, combustion is very rapid, but it is not instantaneous.

As the piston is compressing the mixture on the compression stroke, the exact point at which the spark plug fires to ignite the mixture—ignition timing—has profound effects on the quality of combustion and the amount of power that is produced. Because of its influence on the combustion process, ignition timing also affects combustion temperature which can also significantly affect exhaust emissions.

Modern fuel-injection systems have evolved into engine-management systems—systems which manage much more than fuel delivery. Chief among the extra capabilities of an engine-management system is simultaneous control of ignition timing and fuel delivery. Controlling both factors opens up new possibilities for power and driveability improvements while maintaining tight control of exhaust emissions and fuel economy.

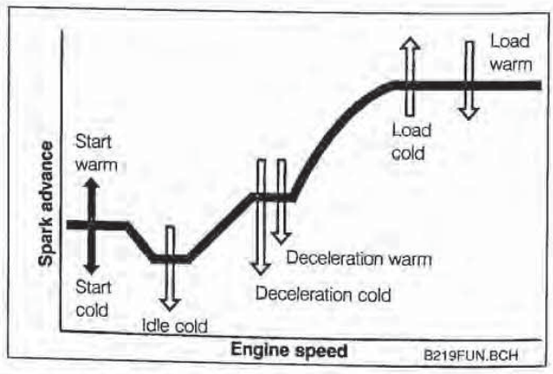


Fig. 3-4. Typical ignition timing advance curve can be modified for best performance, from starting to acceleration.

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4. Emission Control

It is practically impossible to separate the development of today's fuel-injection and engine-management systems from the increasing demand for control of harmful exhaust emissions. Exhaust emission control could not have been accomplished as successfully without fuel injection and, likewise, fuel injection may not have been so successful and widely used were it not for the challenges of meeting emission control regulations.

With changing legislation and tougher regulatory standards, fuel-injection systems have undergone significant changes so that engines can meet the emission standards while providing the driveability demanded by owners. The superiority of these systems is also demonstrated by the fact that, even as U.S. fuel economy standards have tightened, fuel injection has added both economy and power to smaller engines.

It is interesting to note that many fuel-injected cars are able to eliminate some types of emission control that interfere with driveability on carbureted cars, including exhaust gas recirculation (EGR) and air pumps. If you know something about emissions and the limits placed on them by legislation, you'll understand more about how fuel-injection and engine-management systems work.

> Until a few years ago, because of less stringent emission regulations in Europe, many European cars were built with fuel injection for delivery in the U.S., but had carburetors for delivery in Europe. When I spoke with a chief engineer of one of Europe's largest manufacturers, he expressed reluctance to change his engines from carburetors to the more expensive fuel injection, and suggested that we in the U.S. were a little paranoid about clean air. Time has passed, and Europeans are recognizing the importance of clean air too. Fuel-injection systems are spreading to more cars sold in Europe. In fact, many late-model German cars are sold in both the U.S. and Germany with the same fuel-injected engines using the same catalyst emission controls, and requiring the same lead-free fuel.

4.1 Combustion By-Products

Combustion of the air-fuel mixture in the engine cylinders creates gaseous by-products which make up the exhaust. Some of these are harmless, and some are known to be harmful. Three gases: hydrocarbons (HC); carbon monoxide (CO); and oxides of nitrogen (NO_x) are the most harmful ones. Emission of these gases in vehicle exhaust is regulated by the Federal Clean Air Act. The same gases are often subjected to tighter limits by state regulation in California.

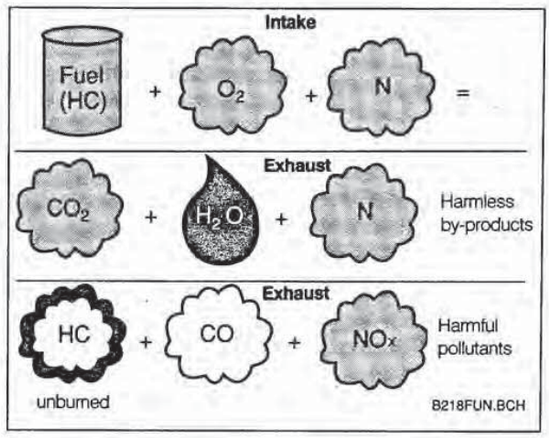


Fig. 4-1. The emission equation: Engine takes in fuel, oxygen, and nitrogen (top). Combustion produces harmless by-products: carbon dioxide, water, and nitrogen (middle); and harmful pollutants: unburned hydrocarbons, carbon monoxide, and oxides of nitrogen (bottom).

Hydrocarbons (HC). Gasoline is a compound composed of hydrogen and carbon; in the combustion process, these elements combine with oxygen to form the by-products water (H_2O) and carbon dioxide (CO_2); HC in the exhaust is unburned gasoline, the result of incomplete combustion.

Carbon Monoxide (CO). CO, a poisonous gas, is another result of incomplete combustion; when gasoline burns completely, the result is CO_2.

Oxides of Nitrogen (NO_x). (NO_x) refers to several kinds of nitrogen oxide which result from nitrogen and oxygen during combustion. Nitrogen and oxygen are normal parts of air, but they exist in air as separate elements. And, as long as the combustion temperature stays below about 2000°F (1100°C), the nitrogen and oxygen do not combine. The nitrogen passes out the exhaust pipe just as it came in, separate and harmless. Combustion temperatures only slightly higher, however, cause these two elements to combine chemically into various forms of nitrogen oxide (NO_x), a key element of smog.

Remember, these exhaust gases are normally colorless and invisible. A clear tailpipe is not the sure sign of a clean-burning engine; it may be pumping out invisible pollutants.

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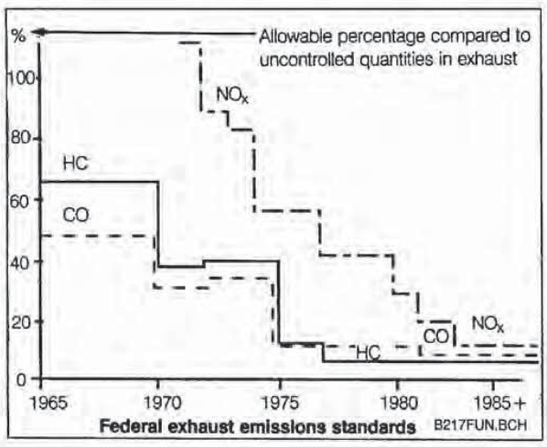


Fig. 4-2. Evolution of U.S. government-mandated emission control standards. Jetronic fuel injection came in to meet the early exhaust emission standards. As limits tightened after 1980, virtually all European cars sold in the U.S. were equipped with Bosch fuel injection.

4.2 Effects of Air-Fuel Ratios on Pollutants

Although exhaust pollutants are not normally visible, some visual clues are a tip-off to poor air-fuel mixture control. Black smoke coming from the exhaust pipe is usually a sign of unburned gasoline; a rich mixture. But look around you on the street; black smoke is something rarely seen on fuel-injected cars.

Just as variations in the air-fuel ratio affect power output and fuel consumption, they also affect exhaust emissions. As I described in **2. Basic Factors**, the air-fuel ratio is a key to complete combustion of the fuel. It also affects combustion temperature which in turn affects the formation of pollutants. Too rich (too little air), and the fuel will not be completely burned. The unburned fuel will enter the atmosphere as CO and HC. Too lean (too much air), and elevated combustion temperature increases NO_x. Fig. 4-3 shows how relative levels of each of the three major pollutants in the engine exhaust are affected by variations in the air-fuel ratio.

While Fig. 4-3 illustrates the effects of air-fuel ratio on the formation of harmful emissions, it also illustrates the fundamental problem in the control of these three pollutants: adjusting air-fuel ratio to ensure complete combustion and minimize the production of HC and CO has the undesirable side-effect of increasing NO_x. Likewise, richening the mixture to minimize combustion temperature and the formation of NO_x brings unacceptable increases in HC and CO.

It becomes clear then that manipulation of the air-fuel ratio is simply not enough to adequately control all three of the most harmful pollutants, especially in the face of increasingly tough emission control regulations. Control of air-fuel ratio to optimize emissions is a first step, to be followed by treatment of the exhaust after it leaves the engine. Maintaining precise control of the air-fuel ratio by electronic control of fuel metering is important not only to the composition of the combustion by-products but also, as you'll see, to the operation of three-way catalytic converters.

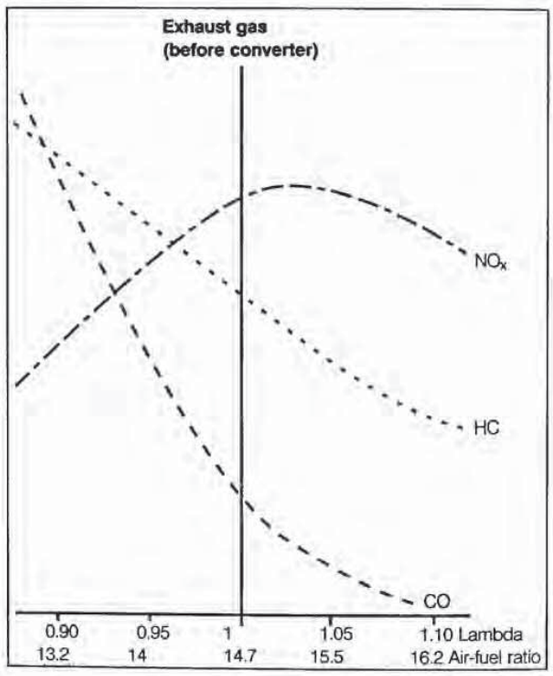


Fig. 4-3. Pollutant levels in engine exhaust change drastically as air-fuel ratio changes. Notice the trade-off between control of HC and CO, and control of NO_x.

When I flew piston-engine aircraft, I adjusted for a rich air-fuel mixture during high-power climbs to keep the engine cool. Then, during cruise, I leaned the mixture. If the needle on the temperature gauge started to rise above the green arc, I knew I had leaned the mixture too much. If you install an exhaust gas temperature (EGT) gauge on your car engine, you can make similar observations (though the mixture is not cockpit-adjustable). I added an EGT gauge when I installed an aftermarket turbocharger.

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4.3 Exhaust Gas Recirculation (EGR)

Exhaust Gas Recirculation (EGR) is a technique for reducing the formation of oxides of nitrogen (NO_x). A small amount of exhaust gas is rerouted back into the combustion chambers, diluting the combustible mixture and lowering combustion temperature. You'll remember that excessive combustion temperature is the cause of NO_x formation.

EGR is necessary to properly control emissions in almost all carbureted engines; fuel-injected engines can often do away with EGR by maintaining proper control of the air-fuel ratio and treating the exhaust with a three-way catalyst.

4.4 Exhaust Gas Aftertreatment

As I discussed above under **3.2 Effects of Air-Fuel Ratios on Pollutants**, precise control of the air-fuel ratio alone is not enough to provide adequate reduction and control of engine exhaust pollutants. While this precise control is essential, the necessary reductions require additional treatment of the exhaust after it leaves the engine—aftertreatment.

A variety of methods of exhaust gas aftertreatment have been employed as the allowable levels of pollutants have been forced lower. All rely to some degree on particular exhaust characteristics to function properly, so the success of all depends on precise control of the air-fuel ratio.

Thermal Afterburning

One of the first methods of exhaust gas aftertreatment to be widely used in production cars was thermal afterburning. Using a device in the exhaust system called a thermal reactor, the basic premise is to delay the exhaust flow and use the residual heat of combustion in the exhaust to promote additional chemical reactions which reduce pollutants.

The disadvantages of thermal reactors are that they must be rather large in order to adequately delay the exhaust flow, and they produce a lot of heat. They were used for only a short time in production before other methods of exhuast gas aftertreatment became more popular.

Catalytic Converters

Catalytic converters are installed as part of the exhaust system, located between the exhaust manifold and the tailpipe. The interior surfaces of a catalytic converter are coated with special materials—catalysts—that promote additional chemical reactions with the pollutants in the exhaust gas and convert them into less harmful substances.

Oxidation catalysts make use of excess air supplied by an air pump to oxidize CO and HC—add oxygen—and convert them to CO_2 and H_2O. Reduction catalysts work without the addition of excess air to reduce NO_x. The combination of an oxidation catalyst and a reduction catalyst in one housing—a dual-bed catalyst—produces a complex series of chemical reactions which reduce all three pollutants. A disadvantage of dual-bed catalysts is that they rely on a slightly rich air-fuel ratio which increases fuel consumption.

To work most efficiently, the converter must be as hot as possible. For this reason, the best placement is in the exhaust system as near to the engine as possible. In addition to operating at high temperature, the reactions themselves produce heat. Most catalytic converters require heat shields to prevent combustion of something under the car. Even so, drivers are cautioned to avoid parking a hot car near anything combustible, such as tall grass or dry leaves.

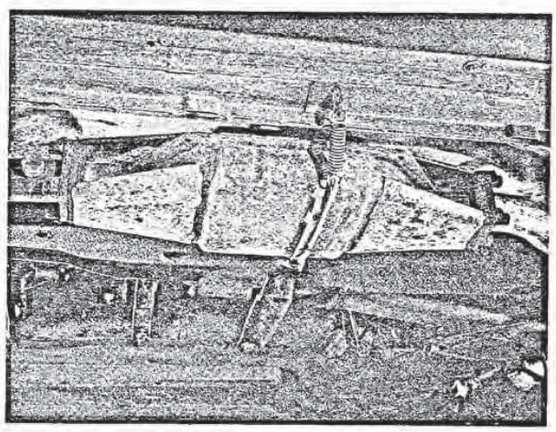


Fig. 4-4. Catalytic converter treatment of exhaust generates heat, so converter has heat shield to protect car and anything combustible under the car.

Three-way Catalytic Converters

The most advanced—and by now the most widely used—catalyst is the three-way catalyst, so-called because its chemical reactions operate to lower all three controlled pollutants to levels which could not be achieved previously.

Remember that, in complete combustion, $HC + O_2 + N = CO_2 + H_2O_2 + N$; incomplete combustion produces CO instead of CO_2; and high temperature combustion, as from a lean mixture, combines $N + O_2$ to form NO_x.

In the three-way catalytic converter, we want to (1) add oxygen to oxidize the HC and CO to make H_2O and CO_2 and, (2) take away oxygen to reduce NO_x, separate it into N and O_2.

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You might think it's as simple as taking the oxygen away from the NO_x and giving it to the CO. Stated simply, that is what happens in some three-way catalytic converters.

The catalytic material in the converter helps these chemical reactions take place. In order for reduction (taking away oxygen from NO_x) to match oxidation (adding oxygen to CO and HC), the proportion of the gases in the engine exhaust must be controlled very closely; that means the intake air-fuel ratio must always be in the narrow range near stoichiometric—lambda (λ) = 1, or an air-fuel ratio of 14.7 parts of air to one part of fuel. In some three-way converters, oxygen is pumped in after the reduction to further enhance oxidation.

Fig. 4-5 illustrates the degree of emission control afforded by a three-way catalyst on an engine running very near the stoichiometric ratio. You can see that if the air-fuel strays from λ = 1, the proportion of exhaust gases (HC, CO, & NO_x) exiting the converter changes. As the air-fuel ratio becomes leaner, hotter combustion temperature causes increased production of NO_x. A rich mixture will produce an excess of HC and CO.

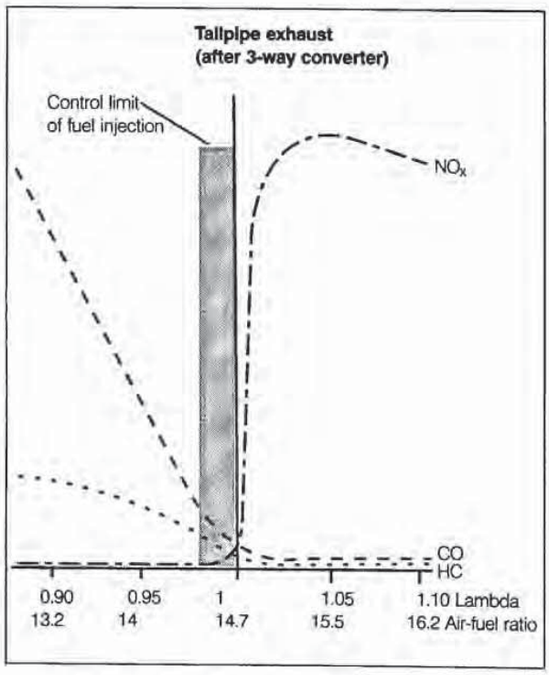


Fig. 4-5. Three-way catalytic converter treats three exhaust gases. HC and CO are oxidized, NO_x is reduced so tailpipe gases meet emission limits. Engine can be tuned to stoichiometric air-fuel ratio for better driveability and economy. Compare with untreated exhaust (Fig. 4-3 above).

When the air-fuel ratio is maintained at λ = 1, the ideal air-fuel ratio, the emission of all three pollutants is reduced to very low levels. Precise control, however, is very important to the successful operation of three-way converters. Any significant deviation from λ = 1 upsets the balance of the chemical reactions in the converter and the level of one or more pollutants increases dramatically. Development of three-way catalytic converters has been accompanied by development of more sophisticated systems for the fine control of air-fuel ratio.

5. CONTROL SYSTEMS

By now, you are aware that control plays an overwhelmingly important part in maintaining the acceptable balance of power, fuel economy, emission control, and driveability. The modern fuel-injection system, by responding to measured inputs and precisely metering the appropriate amount of fuel for the conditions, offers unparalleled control.

Fuel injection's basic control systems are one-way or "open-loop" controls. They take the information about operating conditions received from various sensors, and then use that information to determine—either by mechanical means or using pre-programmed electronics—exactly how much fuel it should dispense to achieve the desired air-fuel mixture. Accuracy of the fuel metering and the resultant air-fuel mixture depends entirely on how well the system—whatever type it may be—can predict the engine's needs based on its "knowledge" of operating conditions.

A major advance in fuel-injection control systems has been the advent of "closed-loop" controls—systems which not only try to predict the engine's needs based on operating conditions, but also measure the results of their fuel metering, using that information as an input to achieve ever more precise control.

5.1 Closed-loop Control Systems

In a closed-loop or feedback control system, information about whatever is being controlled is continuously fed back to the system as an input. The operation of a thermostat in an automatic heating system is an example of closed-loop control. As the temperature falls, the thermostat senses lower temperature and signals the furnace to add heat. As soon as the temperature rises above the setting, the thermostat senses the results of its own control action—heat produced by the furnace—and signals the furnace to cut back the heat.

An open-loop system may, for example, sense low temperature and simply turn on the heat for a predetermined amount of time; however, the closed-loop control is automatic, temperature stays relatively constant, and energy consumption is probably reduced. All in all, the result is better, more precise control.

Lambda Sensor

As you saw above in Fig. 4-5, the three-way catalytic converter operates best when the air-fuel ratio is near stoichiometric, when lambda (the excess air factor) is within a very narrow range around λ = 1. Fuel-injection systems, while very good at controlling the air-fuel ratio, cannot hold the air-fuel mixture within the required range. The necessary precision requires the additional feedback available from a closed-loop control system.

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The source of this feedback is a lambda sensor (also called an exhaust-gas sensor, or oxygen sensor), installed in the exhaust system. The sensor generates a low-voltage signal; the signal's strength is based on the amount of unused oxygen remaining in the exhaust stream—an indirect measurement of the air-fuel ratio. The lambda sensor signal provides feedback to the fuel-injection ECU, indicating by actual results whether the air-fuel ratio needs to be corrected. The system can then adjust its fuel metering so that $\lambda = 1$, and the exhaust remains as clean as possible.

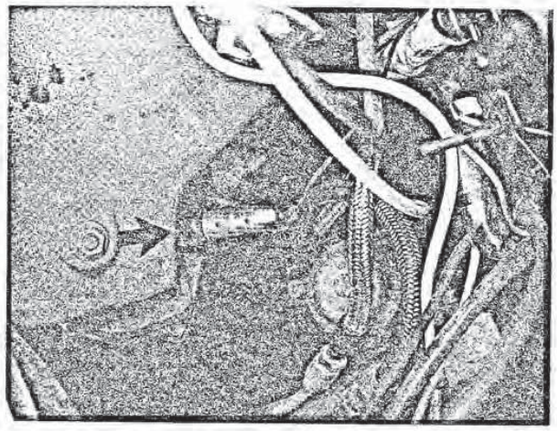


Fig. 5-1. Lambda sensor, usually installed in exhaust manifold, is about the size of a spark plug. Mounting location near engine is required to maintain proper sensor temperature.

Because of tightening exhaust emissions regulations and the need for three-way catalysts, you'll find a lambda sensor on virtually every car made since 1981, domestic or import, fuel-injected or carbureted. For more information on the lambda sensor and its closed-loop control, see chapter 3.

Changing Engine Conditions

You can see that closed-loop lambda sensor system provides automatic control of air-fuel ratio, continuously adjusting the amount of fuel injected in response to the amount of oxygen in the exhaust. The lambda sensor system can also adjust fuel metering to compensate for changing engine conditions over time. If general wear or a leaking valve causes a change in combustion, the feedback system can compensate within its limits and still provide the best possible air-fuel mixture. It has been described as the equivalent of having a skilled technician riding under the hood, continually tuning the mixture for the best operation under the current conditions.

The ability to finely adjust fuel metering to match conditions is what makes lambda control so important, but lambda-sensor closed-loop control is limited to small adjustments within its range of operation. It is often referred to as fine-tuning; in fact, as you'll see in chapters 4 and 6, one of the measures of properly set mixture control is consistent output of CO—the same whether the lambda sensor is working closed-loop, or whether its circuit is disconnected and running open-loop. This means that the basic mixture adjustment is correct and the lambda sensor is operating in the center of its range of adjustment, giving it maximum possible correction range.

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Chapter 3

Pulsed Injection—Theory

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1. General Description

You'll find a number of different Bosch fuel-injection systems which are all based on electronically-timed, pulsed injection. See **Table a** on the next page. These systems are sometimes referred to by the term EFI (Electronic Fuel Injection), or AFC (Air-Flow Controlled) injection. The pulsed systems I'll discuss in this chapter include:

- L-Jetronic
- LU-Jetronic
- LH-Jetronic
- Motronic
- LH-Motronic
- D-Jetronic
- Digifant II

I use the term "pulsed" instead of "electronic" to describe this branch of the Bosch family tree because, since 1980 the other branch, the continuous injection systems, also use some electronic controls to adjust fuel metering.

This chapter begins with a general description of the main components and operating principles of all Bosch pulsed injection systems. It then describes pulsed systems in detail, starting with L-Jetronic. For more basic information on fuel injection, see chapter 1 and chapter 2. To determine what system is installed on your car, see **1.2 Applications**, and the detailed applications table at the end of chapter 1.

1.1 Pulsed Injection Systems

All of the systems in this chapter are pulsed injection systems. They meter fuel to the engine by electronically controlling the amount of time that the fuel injectors are open. In contrast to the continuous systems where the injectors are open and flow fuel from the moment the engine starts, pulsed injectors open and close in time with the engine to deliver the fuel. The main components of pulsed systems are the air-flow meter, the electronic control unit, and the fuel injectors. See Fig. 1-1.

In pulsed injection, all air entering the engine first flows through an air-flow meter. The air-flow meter measures this air, which indicates engine load, and converts that measurement into an electrical signal to the control unit. The control unit uses the air flow and engine rpm inputs to compute the amount of fuel necessary to give a good air-fuel mixture, and then electrically opens the injectors at each cylinder intake port to inject the appropriate amount of fuel into the intake air stream. The control unit times the injections to the rotation of the crankshaft. The main fuel pump supplies fuel under pressure to the injectors.

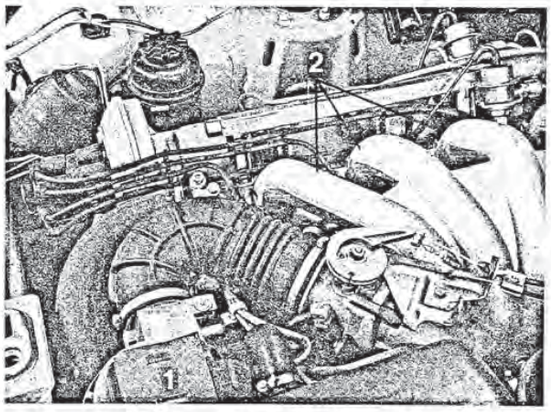


Fig. 1-2. Motronic pulsed injection system on Porsche 944. Note air-flow sensor (**1**) and fuel injectors (**2**). Components may differ depending on system.

Bosch pulsed systems also use many additional sensors that monitor engine operating conditions. The control unit monitors the signals from these sensors and increases or decreases injector opening time – increasing or decreasing the amount of fuel delivered – to give the best air-fuel mixture for the various conditions.

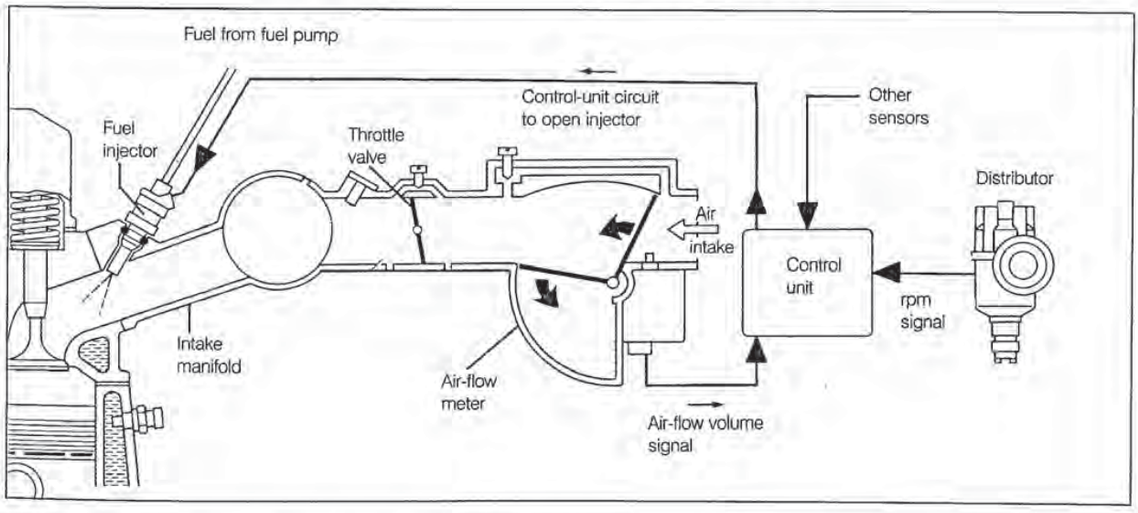


Fig. 1-1. Schematic of pulsed injection operation. Air-flow meter measures air entering engine. Control unit computes proportional amount of fuel required and opens injectors.

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Table a. Bosch Pulsed Fuel Injection Systems

Name	First used	Measure load	Fuel pressure	Computer /no. of pins	Lambda
D-Jet	1967 VW 311	manifold pressure	pressure 2.0 bar (29 psi)	analog/25	no
L 1-Jet	1974 Porsche 914	air flow	2.5–3.0 bar (36–43.5 psi)	analog/35	some
LH 1-Jet	1982 Volvo	air mass	2.5–3.0 bar (36–43.5 psi)	digital/35	all
Motr.ML.1	1982 BMW 528e	air flow	2.5–3.0 bar (36–43.5 psi)	digital/35	all
LU-Jet	1982 BMW 318i	air flow	2.5–3.0 bar (36–43.5 psi)	analog/25	all
LH 2-Jet	1984 Volvo	air mass	2.5–3.0 bar (36–43.5 psi)	digital/25	all
Motr.ML.3	1984 BMW/Porsche	air flow or air mass	2.5–3.0 bar (36–43.5 psi)	digital/35	all
LH-Motr.	1988 BMW	air mass	2.5–3.0 bar (36–43.5 psi)	digital/35	all

1.2 Applications

Bosch L-Jetronic systems are installed in many makes of cars sold in the U.S., beginning in 1974. Considering licensed versions, L-Jetronic has the largest world-wide installed base of any port-type injection system. The Bosch pulsed systems are developments of L-Jetronic, except D-Jetronic. That leads to an interesting name confusion. To contrast with the original D-Jetronic, a pressure-controlled system, L-Jetronic was described as AFC for Air Flow Control. As it turns out, all Jetronic systems that followed D-Jetronic are air-flow or air-mass controlled, including the continuous systems.

The term "Motronic" originally (in 1979) meant a single control unit controlling L-Jetronic fuel injection and ignition timing. Nowadays, there is more than one type of Bosch Motronic system controlling fuel injection and ignition timing (LH-Motronic, KE-Motronic), so following Bosch nomenclature, I'll use Motronic to mean the original definition: L-Jetronic fuel injection and ignition-timing control. Why do I tell you all this? To help steer you through the various names that auto manufacturers and service people have attached to Bosch systems for 20+ years.

2. L-JETRONIC

In the broad terms I've discussed, L-Jetronic is a fuel-injection system, not an engine-management system. While most L-Jetronic cars have electronic ignition, they do not have electronic management of ignition timing. In most cases, the control unit will affect only the injection pulse-time. Ignition timing will be controlled traditionally—advanced or retarded by fly weights and vacuum diaphragms at the distributor.

Identifying Features

A quick way to recognize L-Jetronic systems is by the curved housing of the air-flow sensor as shown in Fig. 2-1. Note that's also found on most Motronic systems.

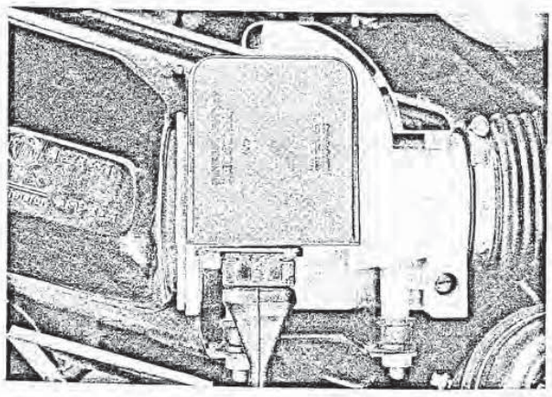


Fig. 2-1. Curved housing of air-flow sensor identifies L-Jetronic, also most Motronic.

Depending on its mounting in the engine compartment, you may also see the waffle grid of the curved housing. That design saves weight while maintaining a rigid flat surface inside for vane contact.

L-Jetronic systems seem to require more parts than the familiar carbureted fuel systems, yet several of these are also required by modern feedback-carburetor systems. See Fig. 2-3 for a diagram of the system components.

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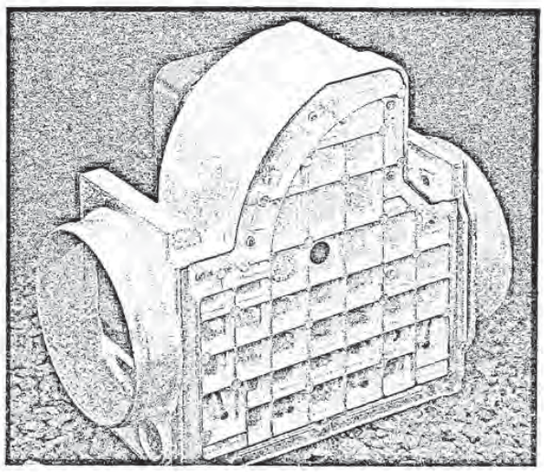


Fig. 2-2. Waffle grid of air-flow sensor maintains a rigid inside surface.

Pulsed systems are completely electronically controlled. Sensors supply information to the central control unit which then operates the port injectors. In the simplest terms, the air-flow system measures the air intake; the fuel system delivers clean, pressurized fuel to the injectors; the control system adjusts the amount of fuel needed for the various operating conditions and electrically opens the fuel injectors to deliver the fuel corresponding to air intake. In addition, somewhat separate from the control system, is the electrical system. Beginning about 1980 (earlier in California), Lambda control was added to the system. To see how they work together, I'll look at how these parts and systems meet the engine needs discussed in chapters 1 and 2.

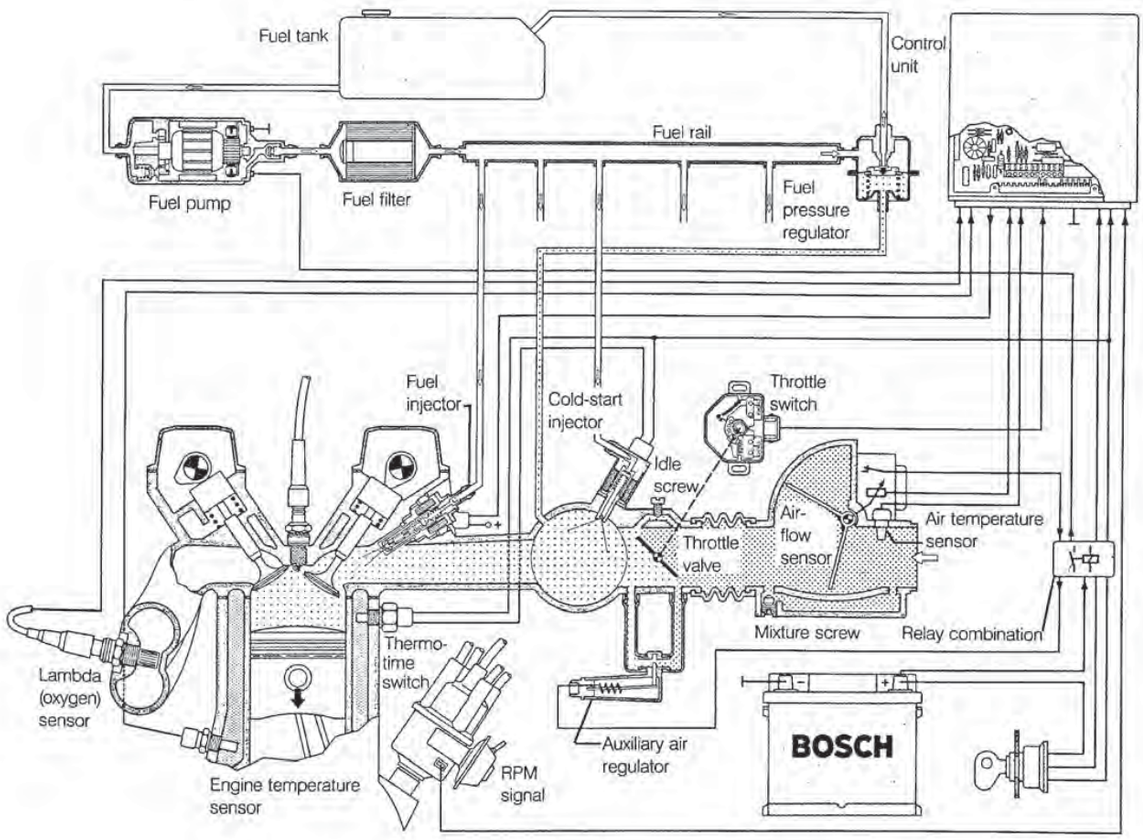


Fig. 2-3. L-Jetronic system diagram. LH-Jetronic is similar, except it has air-mass sensor instead of air-flow sensor.

L-Jetronic

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Basic Flow Rate

The design of pulsed fuel injection is based on achieving the ideal air-fuel ratio for normal cruise at part throttle, with a warm engine. The pulse time of the injectors that satisfies the fuel requirements for this condition is known as the Basic Flow Rate. Two engine conditions determine the basic flow rate: load and speed. In measuring the volume of the air passing through the intake manifold into the engine, the air-flow sensor provides a measure of engine load. Engine speed is measured as in a tachometer, by counting the ignition pulses in the primary circuit. From the basic flow rate, compensation times can be added or subtracted for other operating conditions.

2.1 Air-Flow System

The air-flow system measures the amount of air being drawn into the engine (engine load), and sends a voltage signal to the control unit based on that measurement. The air-flow system also regulates idle speed and idle mixture.

Air-Flow Sensor

The L-Jetronic air-flow sensor is a vane-type, so called because its internal vane deflects, or moves, as air is drawn into the engine. The sensor measures the air flow controlled by the regular throttle valve; the sensor does not regulate the air flow. The air vane (also called an air flap) is lightly spring-loaded, and pivots by the force of the air flow as the throttle opens to admit more air. See Fig. 2-4.

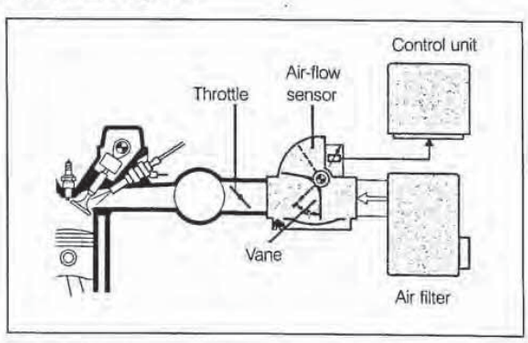


Fig. 2-4. Air-flow sensor air flap measures intake air; throttle controls intake air.

Air-Flow Sensor Design and Operation

If you could remove the waffle-grid cover of the air-flow sensor, you would see the air vane and the damper flap. See Fig. 2-5. The air vane is pushed by the incoming air. In the curved portion of the housing, and mounted on the same shaft as the air vane, the damper flap operates to dampen, or cushion the movement of the air vane by pressing against the air in the chamber. It reduces flutter caused by manifold pressure variations from the opening and closing of the intake valves.

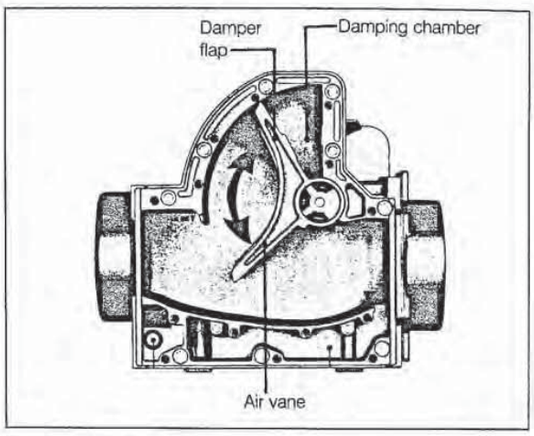


Fig. 2-5. Backfires and pulsations cancel out as opposite forces on the air vane.

Notice the damper flap is the same area as the air-flow vane, and is at right angles to it. This is a clever design: any pulse of increased pressure that rotates the air vane also rotates the damper flap the other way, cancelling the effect of the pressure change. During sudden throttle openings, the air-vane assembly will rotate clockwise rapidly, but its final movement will be cushioned by the damper flap as it squeezes the air in the damping chamber. Bosch tests show the air pressure drop at the sensor is only 0.12 kPa (0.017 psi). That's a fraction of a percent of the atmospheric pressure that forces air into the air system.

The shape of the housing surface opposite the end of the air vane is calculated so the relation between the air passing through and the angle of the flap is logarithmic. That is, a doubling of the air vane angle indicates that air flow has increased 10 times. That means that the most sensitive measurements are at low air flows; at low speeds, measurements are more critical. Maximum air flow is 30 times the minimum.

A moving electrical contact called a wiper is mounted on the same shaft as the air vane. As the vane rotates, the wiper also rotates, crossing a series of resistors and conductor straps on a ceramic base, increasing resistance. See Fig. 2-6. On L-Jetronic air-flow sensors, the resistors oppose current flow from a fixed-voltage input from the control unit. As a result, the more air passing through, the less the voltage signal to the control unit. The control unit is designed to interpret such inverse signals, so the more air there is, the longer the injection pulses are.

In addition to the measured air signalled by the air vane, additional unmeasured air is admitted through a bypass channel to change the idle air-fuel ratio (mixture), as shown in Fig. 2-7. When you turn the bypass screw clockwise, that decreases the amount of unmeasured air. Because the amount of fuel injected is unchanged, decreased air passing into the manifold (for a given vane position) enriches the mixture. Turn the screw counterclockwise to lean the mixture.

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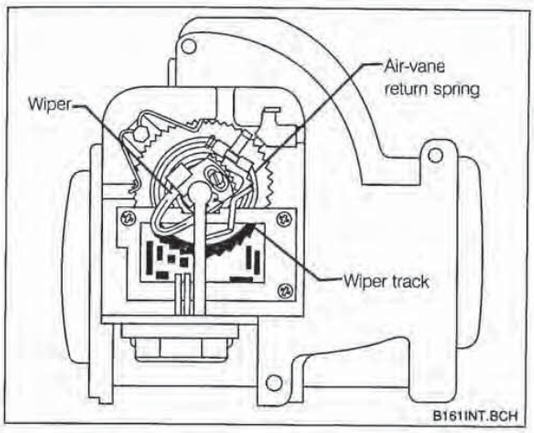


Fig. 2-6. Under the air-flow sensor cover, you can see how the wiper is rotated on the wiper track.

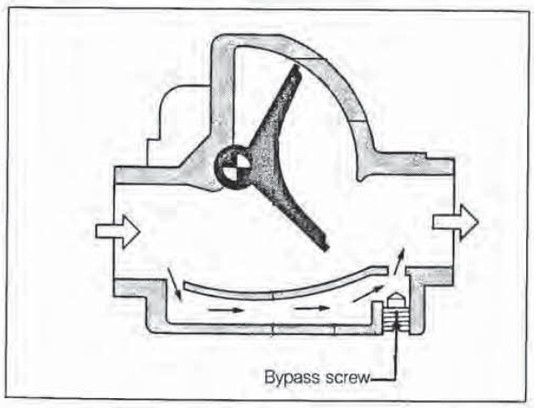


Fig. 2-7. Idle-mixture (bypass) adjusting screw changes bypass of unmeasured air.

Advantages of Sensor Design

What are the advantages of such an air-flow sensor? It provides a direct measurement of the air intake by the engine. By measuring air flow, it tends to compensate for changes to the engine during its service life, such as changes caused by wear, combustion chamber deposits, or valve settings. It permits Exhaust Gas Recirculation (EGR) for emission control without disturbing the measurement of fresh air and the related fuel to be burned with it. In addition, aging of components and varying temperatures have no effect on accuracy because of the resistors in the measurement circuit.

Limitations of Sensor Design

What are its limitations? First, vacuum leaks can be caused by any loose clamp or gasket, or by any slit in the flexible intake boot or vacuum hoses. The air-flow sensor is usually mounted some distance from the intake valves rather than directly on the engine manifold. Any air that enters the intake system between the sensor and the valves is unmeasured air, so-called "false air". Therefore the engine gets no fuel to match that air. The result can be lean mixtures that can cause hard starting, rough idle, low CO, and stumbling; it adds up to poor driveability. Later, in chapter 4, you'll see how to check Jetronics for false air.

Second, the sensor vane measures volume of air intake, but the engine burns weight, or mass of air. Colder air is heavier and requires more fuel than the same volume of warm air. The air temperature sensor corrects for this problem to some degree, as you'll see in **2.3 Control Unit.**

Third, in most cars (those without an anti-backfire valve in the air vane) the vane can be damaged by backfires. The best advice to help prevent this damage when starting the engine is to keep your foot off the accelerator.

Fourth, the air-flow sensor costs more than the pressure sensor, also widely used, particularly in U.S. fuel injection as a measure of engine load. Bosch discarded the pressure sensor in 1974. For more information see **5. D-Jetronic.**

2.2 Fuel System

The fuel system, shown in Fig. 2-8, delivers clean, pressurized fuel to the injectors—usually about one gallon every 2 minutes. As in most newer cars, it is a re-circulating system; the electric pump delivers more fuel than is needed even at maximum consumption, so most of the fuel is returned to the tank. The fuel tank itself is usually pressurized at 7–14 kPa (1–2 psi), controlled by a relief valve in the filler cap. Vapor lock is virtually eliminated because:

- the fuel is cooled by constant recirculation
- the fuel is pressurized, usually at about 2.5 bar (36 psi)

Fuel Pump

The fuel pump, shown in Fig. 2-9, is electrically-driven. Fuel enters at tank pressure through the inlet and is pressurized by the roller cells as shown in Fig. 2-10. The pressure limiter opens and directs fuel back to the tank if fuel pressure in the lines goes over a limit. High-pressure fuel is delivered through a check valve, which closes when the fuel pump stops to hold pressure in the lines. Constantly-pressured fuel lines ensure quicker restarts, and also help prevent vapor lock.

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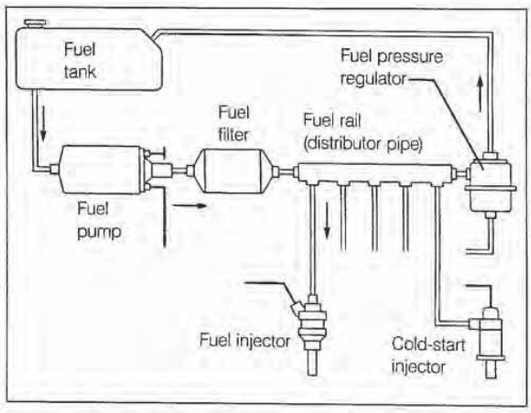


Fig. 2-8. Fuel circulates as pressure regulator at end of fuel rail returns unused fuel to tank.

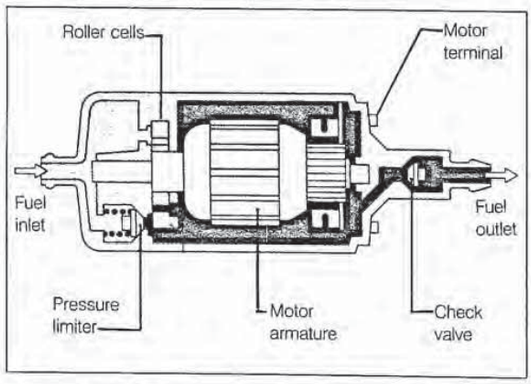


Fig. 2-9. Fuel pump and its electric motor operate surrounded by fuel that cools motor.

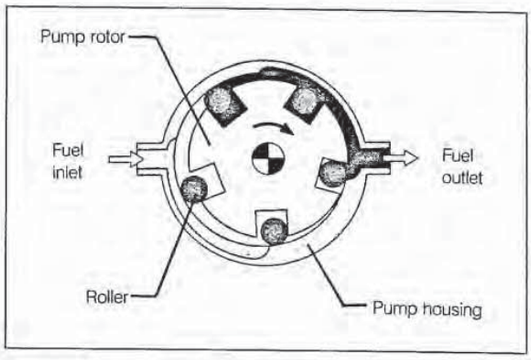


Fig. 2-10. Operation of roller-cell pump. Rotor disc is mounted eccentrically in pump housing. When rotor turns, the rollers are pressed outwards by centrifugal force, and act as a circulating seal. Fuel pressure builds as rollers and disc move fuel through narrowing passages to outlet.

The electric motor actually operates in the fuel in the pump housing. The thought of an electric motor running in gasoline may seem dangerous, but it is safe because the housing never contains an ignitable mixture. There are those who, fearing a burnable mixture, say "never run out of gas with a fuel-injected car," but thirty years of electric pump experience shows they just don't catch fire that way. On the contrary, the gasoline is important – it cools the pump. So if you do run out of gas, just don't crank a long time or you may ruin the pump.

Bosch systems locate the fuel pump next to the fuel tank. This pressurizes the maximum length of the fuel lines to reduce vapor lock. Some cars place the pump inside the tank, or provide a low-pressure electric supply pump in the tank to deliver pressurized fuel to the main electric pump. Electric fuel pumps require relays and safety circuits to ensure that the pumps stop when the engine stops. For more information see **2.4 Electrical Circuits**.

Fuel Filter

In most fuel-injected cars, the fuel filter is located next to the fuel pump. It is much larger than the usual carburetor fuel filter because clean fuel is so important to fuel-injection systems. It is also finer. The paper filter, shown in Fig. 2-11, has a medium pore size of 10 micrometers. It is backed by a strainer that catches any loose particles, and is supported by a plate. The filter is replaced as a complete unit, not as an insert. Vehicle specifications usually call for 30,000–80,000 km (20,000–50,000 mi). When you replace it, observe the direction-of-flow arrows on the filter housing. Some late-model cars use fuel filters that need no replacement unless contaminated.

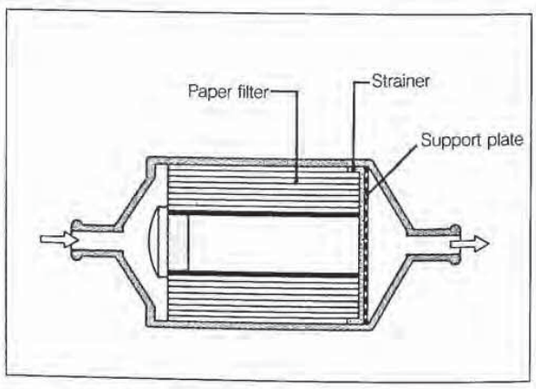


Fig. 2-11. Cut-away of typical fuel filter. Filter is large and fine pore size of 10 micrometers.

Fuel Rail

The fuel rail (also known as the distributor pipe) serves two purposes. The first is to deliver fuel to the injectors. The second is to stabilize fuel pressure at the injectors. You can imagine

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how the pressures change rapidly in the fuel rail as the injectors pop open and closed. This can affect the amount of fuel injected. But the larger the pipe, the more fuel it stores and the steadier the pressure at the injectors.

On later engines, the fuel rail is larger, a square box, as shown in Fig. 2-12. In the large rail, fuel pressure is more stable at the injectors. On earlier engines, the distributor pipe looks like a typical fuel line, a round pipe leading to all the injectors. In the smaller pipes, with small volume, pressure tends to fluctuate each time the injectors open.

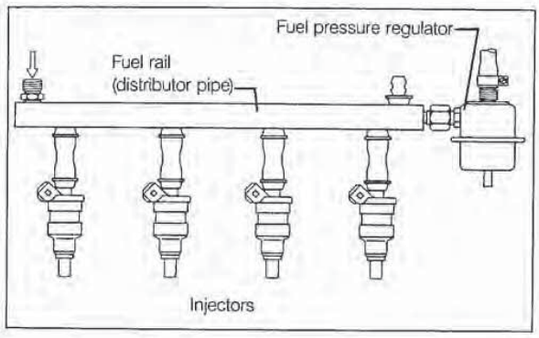


Fig. 2-12. Large fuel rail reduces pulsations as injectors open and close.

Pressure Regulator

Relative fuel pressure in the fuel system is held constant by the pressure regulator, usually mounted on the fuel rail. As shown in Fig. 2-13, spring pressure normally keeps the regulator valve closed. When the fuel pump turns on, fuel pressure presses on the diaphragm to compress the spring and open the valve, returning excess fuel to the tank. The higher the pressure, the more the diaphragm moves away from the return pipe, increasing the volume of the chamber, maintaining the desired pressure. Most systems operate on 2.5 bar (36 psi) gauge pressure, but some higher-powered engines use 3 bar (44 psi) for greater fuel delivery per millisecond.

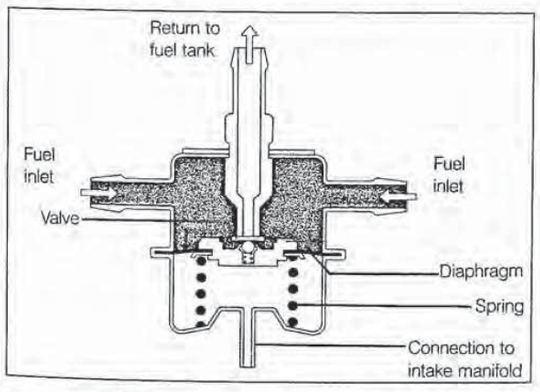


Fig. 2-13. Pressure regulator controls system pressure, usually 2.5 bar (36 psi) above manifold pressure.

Relative Fuel Pressure and Fuel Delivery

For each millisecond of injector pulse time, the amount of fuel delivered through the injector tip depends on the size of the injector opening; that's a fixed factor. But fuel delivery also depends on the relative pressure—the difference between fuel pressure pushing the fuel out into the manifold, and manifold absolute pressure pushing back, as shown in Fig. 2-14.

As you know, manifold pressure changes with throttle opening. If the fuel pressure were constant for all manifold pressures, then at low engine loads, with the throttle partly closed, reduced manifold absolute pressure would increase fuel delivery. To keep that relative pressure constant as the throttle is opened and closed, the fuel-pressure regulator is connected to the intake manifold by a vacuum hose. Manifold pressure acts on the diaphragm to hold the relative pressure constant.

When thinking about fuel pressure, remember that the ordinary fuel-pressure gauge measures relative pressure—the amount that fuel pressure is greater than barometric pressure (14.5 psi). But barometric pressure is measured from an absolute zero pressure, so 2.5 bar (36 psi) gauge pressure actually means 2.5 bar greater than 1 bar of barometric pressure, or 3.5 bar (51 psi) absolute, measured from an absolute zero. When the gauge is not connected, it reads zero: zero here means the difference between the open connection and barometric pressure.

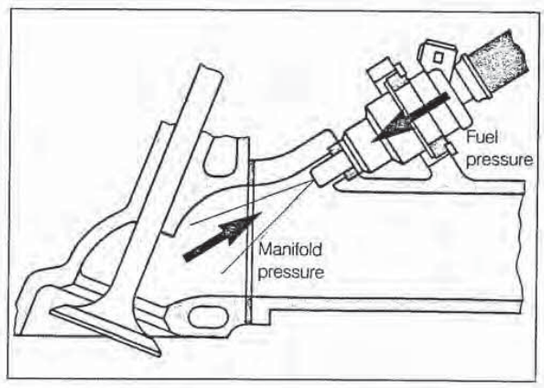


Fig. 2-14. Pressure regulator changes injection pressure.

For example, with the engine off, manifold pressure is the same as barometric pressure. If you measure fuel pressure with the pump running and the engine off, the regulator controls fuel pressure balancing the forces: fuel pressure on one side of the diaphragm balanced against spring force plus the force of barometric pressure in the manifold. The gauge then reads 2.5 bar, 2.5 bar (36 psi) more than atmospheric. At wide-open throttle (WOT), manifold pressure is close to barometric, so again, the fuel-pressure gauge reads about 2.5 bar.

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At idle, absolute pressure in the manifold is about 0.3 bar (0.7 bar less than barometric)—old-timers would say "20 inches vacuum". Now the manifold absolute-pressure pushing the pressure-regulator diaphragm is only 0.3 bar instead of 1 bar. The reduced manifold pressure on the diaphragm allows it to move away from the opening, returning more fuel to the tank, and dropping the gauge fuel pressure in the distributor pipe to about 1.8 bar (2.8 absolute). The relative pressure at the injector tip is still 2.5 bar (2.8 minus 0.3 absolute). That's why fuel delivery per injection is not affected by changes in the manifold absolute pressure. When you understand this principle of fuel delivery, you'll understand the checking of fuel pressures. You'll also understand how greater delivery for off-road and performance operation may be increased by increasing fuel pressures.

Fuel Injectors

The port injectors (located at the intake ports next to the intake valve) are solenoid valves. Each injector is opened by an electrical signal from the control unit, and closed by spring force when that signal stops. See Fig. 2-15. When current is sent through the connection to the winding, electromagnetic force lifts the solenoid, and fuel is delivered. The lift is about 0.15 mm (0.006 in), and takes about 1 millisecond. When the needle valve is closed by the spring, no fuel flows. The pintle on the tip of the needle valve helps to atomize and distribute the fuel.

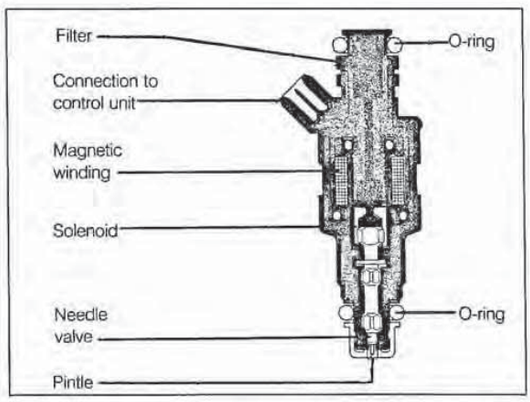


Fig. 2-15. Injectors seal to fuel rail and to manifold by O-rings.

Interestingly, the injectors are electrically-hot all the time the key is ON and the relay combination is closed. For fuel delivery, they are grounded in the final stage of the control unit. In early L-Jetronics (until about 1978) each injector circuit includes a resistor to limit the current flow. In these circuits, the initial current-flow must be great enough to rapidly open the solenoid/needle valve, and then flatten out when only a holding current is needed. Since about 1979, L-Jetronics regulate the current in the control-unit final stage, and so do not need separate series resistors. The resistance is built into the injector itself, using a solenoid winding of brass (higher resistance than the previously-used copper winding). This also requires less power than the series-resistor type.

The injectors are held in the intake manifold with O-rings that tend to insulate the injectors from engine heat and vibration. If the O-rings crack, false air enters, leans the mixture and increases idle rpm. In most engines, the injectors are connected directly to the fuel rail with safety clips. In other engines, they are connected to the rail with fuel lines.

Fuel Metering and Pulse Time

In pulsed injection, the metering of fuel takes place at the tip of the injector as the fuel flows past the pintle. The lift of the needle valve from its seat is always the same distance, so assuming that fuel pressure is regulated as described above, the amount of fuel injected into the engine depends solely on the amount of time the control unit applies voltage to open the injector.

This injector opening time is known as the Pulse Time, and it can vary anywhere from 2 milliseconds to as much as 15 milliseconds or more. The injector takes about 1 millisecond to open, which is counted in the injection time. The closing time is not counted, but it averages out; pulse time is the effective injector open/delivery time.

If, when the control unit grounds the circuit, you measured voltage at the injectors on an oscilloscope, it would look something like Fig. 2-16. Remember that the injectors are always hot, and are grounded in the control unit. Note that when reading pulse time on a scope, it can be referred to as pulse width—the actual width of the pulse-time voltage on the screen.

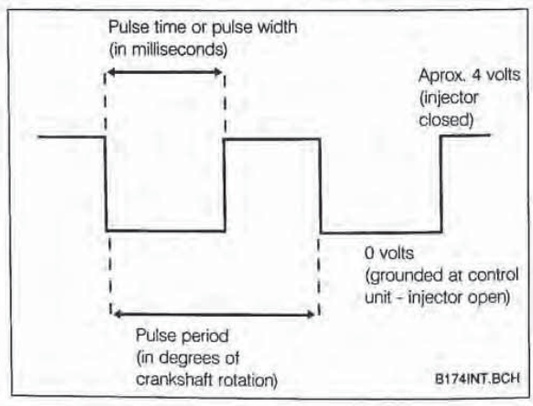


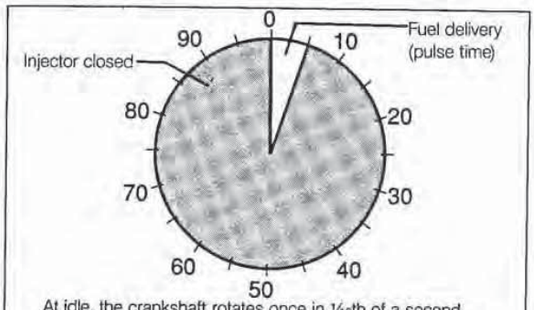
Fig. 2-16. Fuel-injector voltage over time, showing difference between pulse time and pulse period. Voltage supply at injectors is always approximately 4 volts. Oscilloscope shows change in circuit as it is grounded in control unit.

Various operating factors determine pulse time as you'll see below, but there is one other basic factor—called Pulse Period. This is the total time from one opening of an injector to the next opening of the same injector. Normal pulse period for the pulsed systems covered by this book is twice per 4-stroke cycle, or once per crankshaft revolution. Half of the total amount of fuel needed for one firing of a cylinder is injected in each injection. If the pulse period were once per 4-stroke cycle,

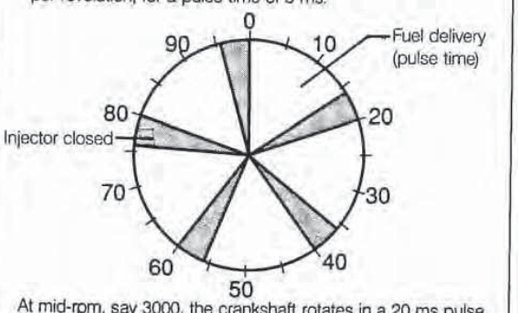
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then pulse time would increase so that all of the fuel was injected at once.

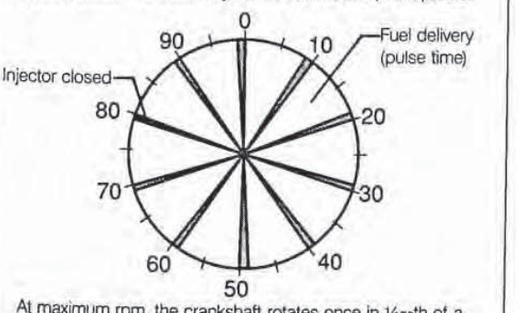
To see the relationship between pulse period and pulse time, let's take a typical engine that idles at 600 rpm and has a maximum rpm limit of 6000 rpm. Dividing each of those revs/minute by 60 seconds, we can say the engine idles at 10 revs/second, and runs max at 100 revs/second. Fig. 2-17 shows pulse period and pulse time for this engine. Each circle represents 100 milliseconds (ms) of time.



At idle, the crankshaft rotates once in 1/10th of a second, or 100 ms. That's the pulse period. The injectors open once per revolution, for a pulse time of 5 ms.



At mid-rpm, say 3000, the crankshaft rotates in a 20 ms pulse period. Full-load delivery for maximum torque at wide-open throttle requires longer injection times than at maximum rpm since at mid-rpm the engine takes in more air per stroke. But a pulse time of 15 ms easily fits into the 20 ms pulse period.



At maximum rpm, the crankshaft rotates once in 1/100th of a second. Pulse period is now 10 ms; in 100 ms the crankshaft rotates 10 times, and the injectors open ten times. If the pulse time is 8 ms, the injectors barely have time to close before they open again.

Fig. 2-17. Relation between pulse period and pulse time.

It's important to remember the inputs that control the basic injection pulse time: air-flow volume and rpm. Fig. 2-18 shows that full-throttle injection time varies from about 6 milliseconds to 9 milliseconds, and that injection time follows the torque curve.

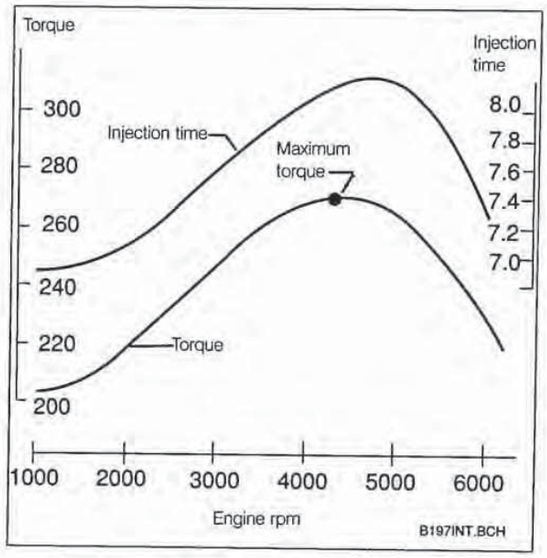


Fig. 2-18. Typical pulse time in milliseconds for full-load matches torque curve.

2.3 Control Unit

The control unit is sometimes called the "brain" of the control system. It receives input of signals from various sensors, processes those signals, computes the pulse-time for the injectors, and completes the circuits in a series of pulses to deliver the required fuel.

The control unit is a complicated piece of electronic equipment. If you open it—and that is not recommended—you'll find it full of transistors, integrated circuits, and printed circuit boards, as shown in Fig. 2-19. The heart of the control unit is a microprocessor chip, about the size of a thumbnail as shown in Fig. 2-20.

In most cases, the control unit is sensitive to heat and vibration, so it is usually located in the passenger compartment away from the engine. A common location is the kick panel to the right of the passenger's feet. You may also find it behind the glove box, under the passenger seat, or in the fresh air compartment under the hood.

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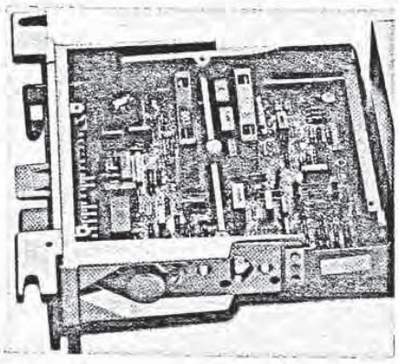


Fig. 2-19. Control unit does the data processing for fuel-injection management.

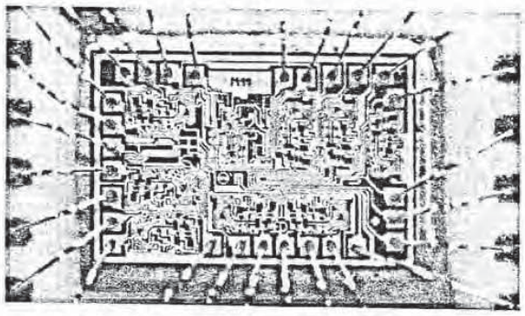


Fig. 2-20. The chip is the heart of the control unit. This integrated circuit is about the size of a thumbnail.

Modern control units are protected from EMI (Electro-Magnetic Interference)—stray radio frequency signals that can scramble the control-unit brain. I've heard a story about early pulsed systems, before proper shielding was provided: A driver in a Volkswagen Beetle, running on the freeway beside an 18-wheeler, called the truck on his CB radio. When the 18-wheeler answered, using CB power boosted way over the legal limits, the CB signal shut down the VW engine. Story, remember.



Fig. 2-21. Jetronic car is tested under transmitter antenna to check EMI shielding.

L-Jetronic

Control Unit Inputs and Outputs

Fig. 2-22 is a block diagram showing the basic processing functions of the control unit for the inputs it receives. The rpm signal from the ignition circuit enters the control unit through a shaper and a divider. As shown in Fig. 2-23, from each ignition pulse, the pulse shaper generates a rectangular pulse (voltage on/voltage off), 4 per each 4-stroke cycle. This is divided by two to provide one injection pulse per crankshaft revolution; for a 6-cylinder engine, it is divided by 3.

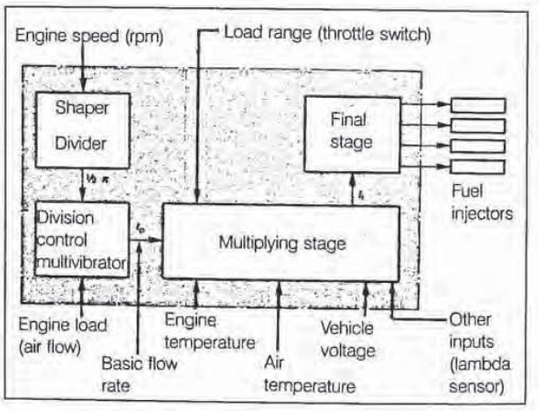


Fig. 2-22. In control unit, basic pulse time is compensated for variables including engine temperature, air temperature, vehicle voltage.

In the division-control multivibrator, the output of the shaper (rpm divided by two) is combined with the load-signal input from the air-flow sensor, resulting in a basic-pulse time. This corresponds to the basic-flow rate, the quantity of fuel to be injected for each injector opening.

The multiplying stage processes the compensation inputs, such as those from the two temperature sensors, engine temperature and air temperature; from the throttle-switch, closed or full-open signals. In later cars, generally those since 1980, it also processes inputs from the lambda sensor. The control unit calculates compensation factors, applying them to the basic pulse-time. In most cases, this will enrich the mixture: when the engine is cold, the injection pulse-time may be two to three times the basic-pulse time.

Compensation for battery voltage is also necessary. This is because battery voltage may vary from 14 volts while the alternator is charging, to 10 volts or less during cold cranking. The lower the battery voltage, the less power to the injector solenoids, and the less fuel injected, perhaps during a cold start when the engine needs it most.

In a 4-cylinder system, the final stage grounds 4 injectors at the same time. Control units for 6-cylinder engines may have two final stages, but they operate together, firing all injectors simultaneously. With two injections per four-stroke cycle, each delivery is half of the total required.

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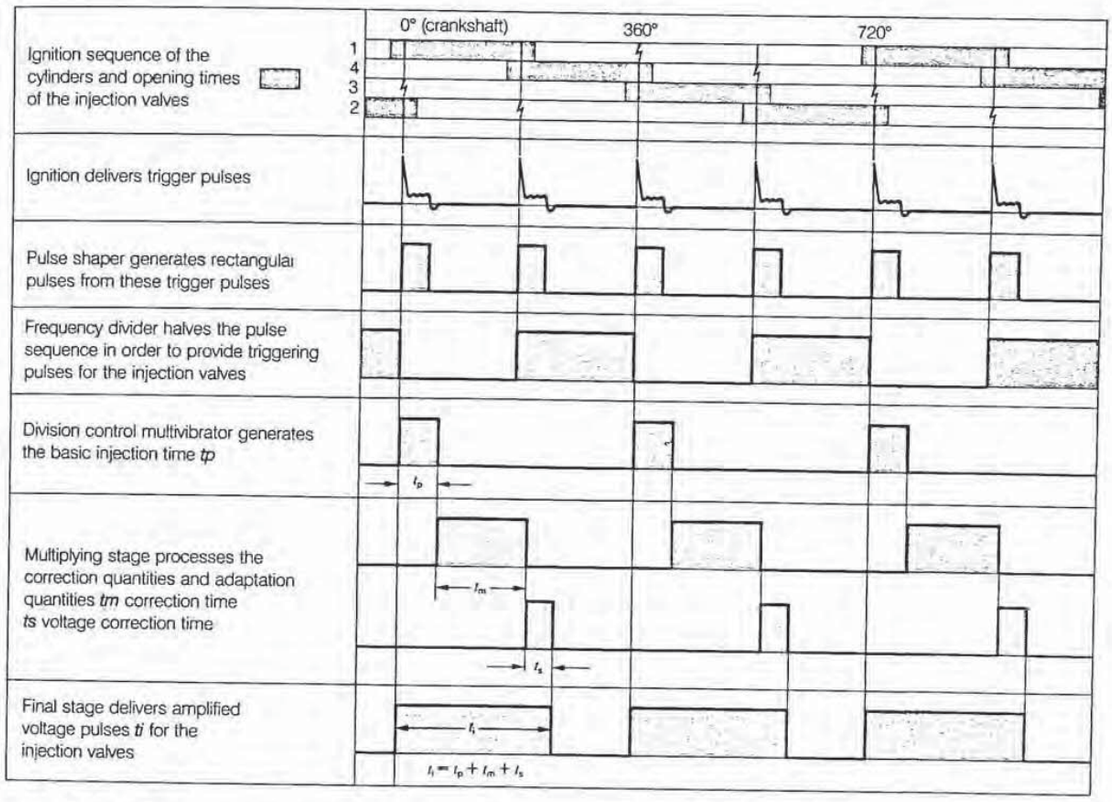


Fig. 2-23. Each basic injection pulse-time is compensated and corrected.

Although it may seem as if the control unit passively receives inputs from the sensors, in some cases its role is an active one, as shown in Fig. 2-24. For example: voltage output from the control unit (terminal 5) is fed to the engine temperature sensor. The sensor reduces the flow of current back to the control unit (terminal 13) which the control unit measures. The colder the engine, the more resistance, and the less current back to the control unit. In the same manner, a voltage signal is sent to the air-flow wiper track, and the return signal is measured. Note that the cold-start injector, thermo-time switch, and auxiliary-air device operate independently of the control unit.

RPM Signal. Engine rpm, to help determine the basic flow rate, is one of the most important inputs to the control unit. Bosch pulsed systems are synchronized, that is, injector pulses are synchronized with crankshaft rotation. All L-Jetronic injectors fire twice per 4-stroke cycle, or once per crankshaft revolution. As you saw earlier, the total amount of fuel delivered depends on how many injections there are per minute, and how long the injectors are open for each injection.

In the control unit, air measurements alone could determine the amount of fuel required for the ideal air-fuel ratio. But, as you'll see, injector opening-times are computed for many conditions and air-fuel ratios, some of which depend on engine rpm. So engine rpm is one factor in determining the basic flow rate.

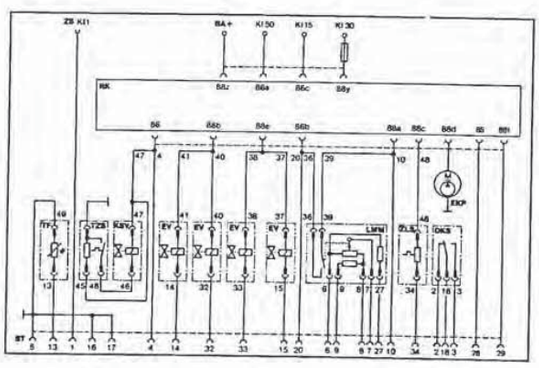


Fig. 2-24. Example of control-unit connections for L-Jetronic system with regulated final stage and no resistors. For component identification, see **Table b** below.

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The L-Jetronic rpm signal comes from the primary ignition pulse, the current that turns the coil on and off. For most cars, that is a signal from the negative terminal of the ignition coil.

The ignition circuit sends four signals for each 720° of crankshaft revolution (each 4-stroke cycle). In a 4-cylinder engine, this means that the ignition circuit closes every 180° of crankshaft revolution (once for each distributor revolution). If you look at Fig. 2-23, above, you'll see the ignition pulses for the firing order at the top of the diagram, and the opening time of the intake valves.

Analog/Digital

Early control units were analog-type; later are digital. You are bound to run into these terms when troubleshooting, so it's important to know the difference. Analog measures continuously; an analog display changes in direct proportion to the input, such as an ordinary odometer. If you've gone two-thirds of a mile since it measured an even mile, the tenths digit will read about two-thirds. On the other hand, digital measures in steps. The digital clock shows exact steps, nothing in between as shown in fig. 2-25. Each step can be extremely accurate, and does not change with wear or aging factors.

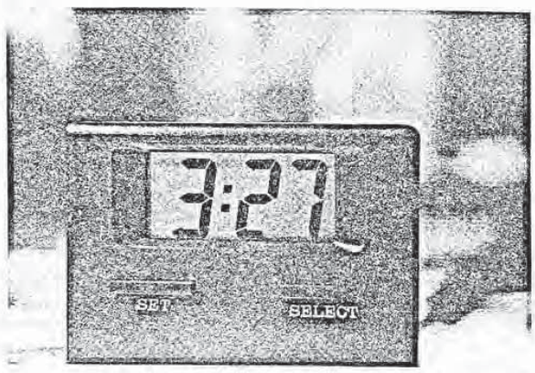


Fig. 2-25. Analog measures continuously; digital measures in steps, and each step is exact.

The important point is: steps versus continuous change. See Fig. 2-26. Analog accuracy is limited, as indicated by the curved line measuring the signal of the straight line. But analog measurement can be more accurate than digital measurement that uses large steps. By increasing the number of steps, digital accuracy is usually greater than analog.

Some inputs are analog; for example, consider the changing current flow from the resistor of the engine-temperature sensor. That analog signal must be changed in the control unit by an analog-to-digital (A/D) converter. Some inputs are digital, for example the rpm pulses from the ignition primary.

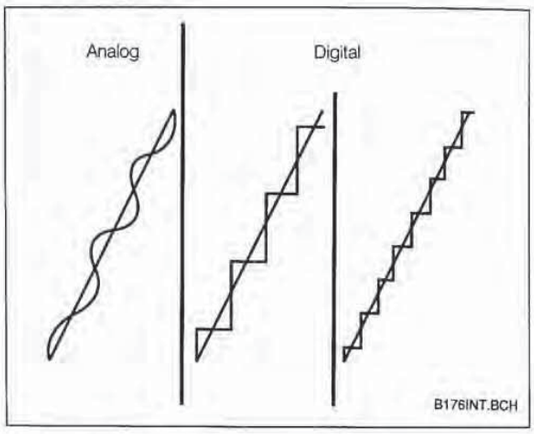


Fig. 2-26. Analog accuracy is limited by many variables; digital limited by number of steps.

Some outputs are digital, as you'll see later. These are a series of pulses sometimes described as percent dwell. Analog outputs from digital control units are handled by digital-to-analog (D/A) converters.

Control-Unit Connectors

Inputs and outputs of the control unit are generally handled by a multiple-connector plug, as shown in Fig. 2-27. Some control units provide 35 pins for the connectors, while others, with simplified circuitry, operate with 25-pin connectors. When reading circuit diagrams or making tests at the control-unit connector you'll need to understand the German abbreviations that often identify the connector terminals. **Table b** lists the common abbreviations and their English equivalents.

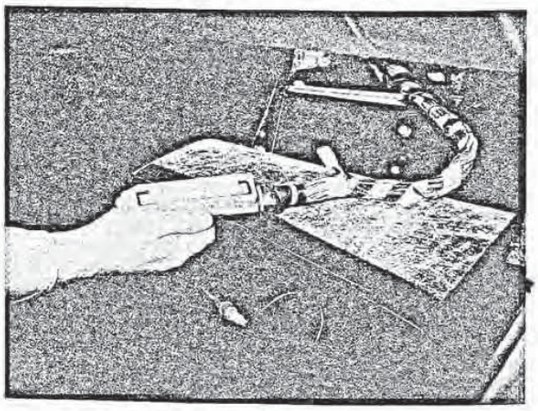


Fig. 2-27. Multiple-pin connector handles all inputs and outputs to control unit pins.

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Table b. Fuel-Injection Wiring Harness Terminal Identification

Abbr.	German Word	English Equivalent
TF	TEMPERATURFUHLER	Engine-temperature sensor, NTC II
TZS	THERMOZEITSCHALTER	Thermotime switch
KSV	KALTSTARTVENTIL	Start valve
EV	EINSPRITZVENTIL	Injector
LMM	LUFTMENGENMESSER	Air-flow sensor
ZLS	ZUZATZLUFTSCHREIBER	Auxiliary-air device
DKS	DROSSELKLAPPENSCHALTER	Throttle-valve switch
EKP	ELECTRISCHE KRAFTSTOFFPUMPE	Electric fuel pump
RK	RELAISKOMBINATION	Relay combination
ZS	ZUNDUNG, SPULEN	Ignition coil
BA	BATTERIE	Battery
ST	MEHRFACH-STECKER	Multiple-plug to control unit

2.4 Electrical Circuits

In addition to the electronics of the control system, L-Jetronic requires simple electrical circuits to power the control unit, fuel pump, and other components.

Control Relay

When the ignition is turned on, battery power flows through the ignition switch to a relay, or a combination-relay. This relay then closes to provide current to the control unit; it also feeds the cold-start injector, and the auxiliary-air valve. Thus, do not replace a control unit to "fix" these parts. See Fig. 2-28.

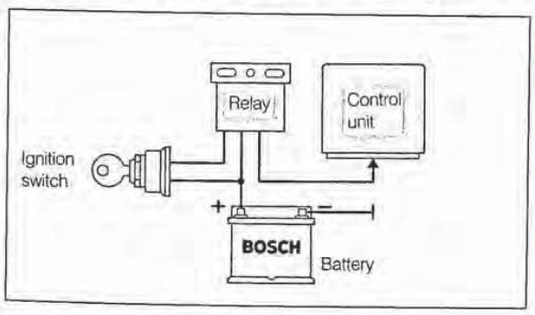


Fig. 2-28. System power flows through relay powered by ignition switch.

Fuel-Pump Safety Circuit

The relay also controls the fuel-pump safety circuit. The START position of the key starts the fuel pump during cranking. But the pump will stop running in 1–2 seconds unless it receives a signal that the engine is turning. This helps prevent flooding, or a fire in the event of an accident. See Fig. 2-29. In most L-Jetronics, the relay receives the rpm signal from the ignition circuit and shuts down the pump if the engine is not turning fast enough: 4-cylinder engines, faster than 225 rpm; 6-cylinder engines, faster than 150 rpm. Early L-Jetronics (before 1978) do not use the rpm signal; instead, a safety switch in the air-flow sensor closes when the air vane begins to open.

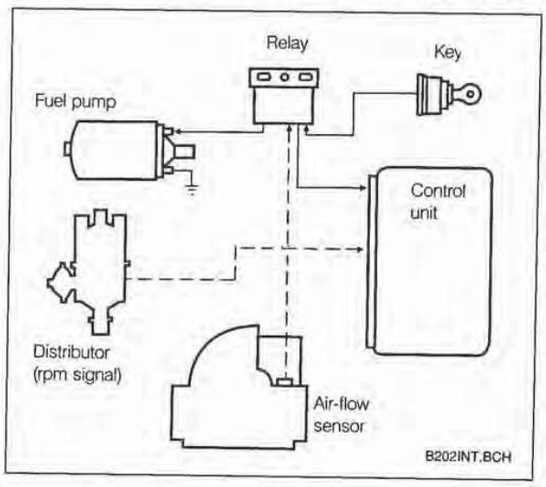


Fig. 2-29. Pump safety circuit is usually controlled by rpm signal from primary ignition circuit; in early L-Jetronics, control is by air-flow sensor switch.

Service technicians can bypass the safety circuit to run the fuel pump without running the engine: on early cars by reaching in to move the air vane with the ignition on; on later cars by jumping the rpm safety circuit either at the relay set or at the air-flow sensor. For more information see chapter 5.

2.5 Operating Conditions

For all of the conditions under which the engine operates, the control system computes the following:

- Main variables: engine load and speed for the basic flow rate. Each basic flow rate can be modified, or compensated based on inputs from sensors that signal changes in operating conditions.
- Compensation variables: such as starting, cold operation, and special load conditions, and
- Precision compensation: tweaking the other compensations for overrun or coasting, and mixture (lambda) control for emission-reduction.

All compensations are added to, or subtracted from the basic flow rate. So let's look at each of the conditions and see what sensors and signals affect L-Jetronic through the control unit. We'll also see some auxiliaries that operate independently of the control unit.

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Starting

As we've seen, depending on the temperatures, the engine may need additional fuel, and also additional bypass air around the closed throttle. How does L-Jetronic compensate for all the different starting conditions? How does the system operate without any setup by the driver; how can you simply turn the key to start it?

These systems have no choke or fast idle cam to set. As the car sits, the engine changes temperature due to changing weather, or cooling after running. Its sensors signal the control unit about engine temperature and other conditions that could affect starting. Other components inject additional fuel or allow additional air.

Engine Temperature Sensor. The most important sensor is the engine temperature sensor, shown in Fig. 2-30. It is a semi-conductor resistor, also known as a thermistor. You may find service instructions referring to it as NTC II. NTC stands for Negative Temperature Coefficient, meaning the sensor's resistance goes down as the temperature goes up. This is the opposite of most resistors; hence the term "negative." See Fig. 2-31.

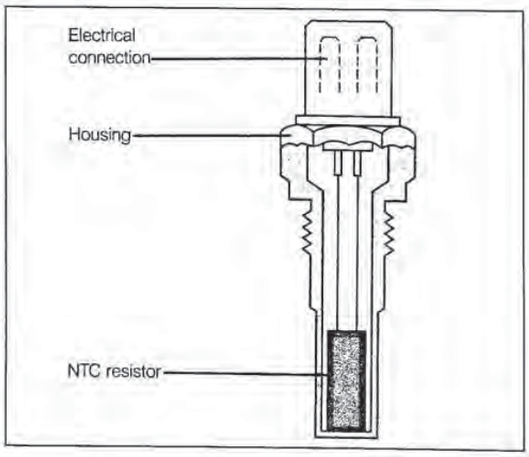


Fig. 2-30. Engine temperature sensor is a solid-state resistor, sometimes called a thermistor. NTC means Negative Temperature Coefficient.

Suppose the engine is in the shop and has not run recently, say for several hours. In round numbers, the resistance at ordinary indoor temperatures is about 3Kohms (3,000 ohms). If the engine has run recently, long enough to fully warm up, resistance is only about 400 ohms. If the control unit applies a fixed voltage to the NTC resistor, it will receive a smaller signal back as input from a cold resistor with higher resistance than from a warm one. From a cold input signal, the control unit will compensate by adding to the basic pulse time as shown in Fig. 2-32.

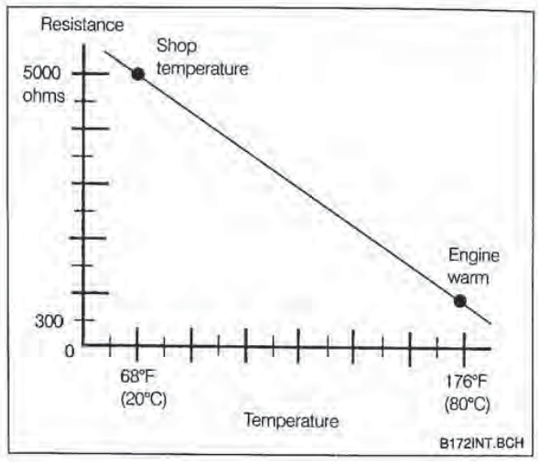


Fig. 2-31. NTC resistance is lower when engine is warm.

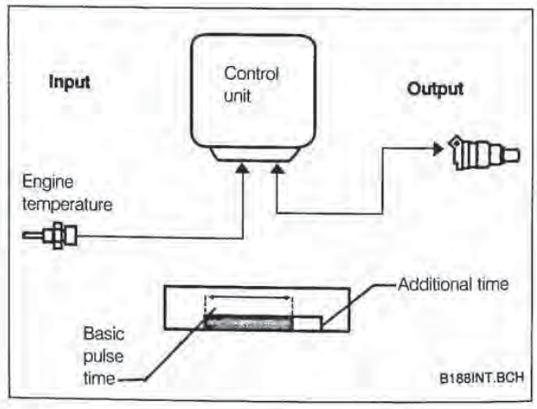


Fig. 2-32. Cold engine temperature sensor causes increased pulse time.

On water-cooled engines, look for the engine temperature sensor, sometimes called NTC II, to be mounted in the cooling system, usually in a fitting near the block, or in the thermostat housing. See Fig. 2-33. Be careful not to confuse the engine temperature sensor with the thermo-time switch or the coolant temperature sender for the instrument-panel temperature gauge.

The NTC sensor is quite simple: an electrical connector on a housing, enclosing the thermistor. The first L-Jetronic came on an air-cooled engine, so on those, you'll find NTC II in a cylinder barrel or a head.

Air Temperature Sensor. With the air cleaner removed, you can see the Intake Air Temperature Sensor in the air-flow sensor as shown in Fig. 2-34. Known as NTC I, this sensor also has a negative-temperature coefficient. Remember, the control unit sends a signal which is changed by the air temperature sensor.Cold air, weighing more, needs more fuel, so a cold-air

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signal also adds fuel to the basic-pulse time. The air-fuel ratio relates weight of air to weight of fuel. The combination input signals of volume (from the air-flow sensor), corrected for temperature, are the same as inputs of weight or mass of air passing into the engine.



Fig. 2-33. Engine temperature sensor (also called Temp II or NTC II) is often mounted in thermostat housing. In this BMW, temperature sensor (**2**) is mounted with thermo-time switch (**1**) and engine temperature sender (**3**).

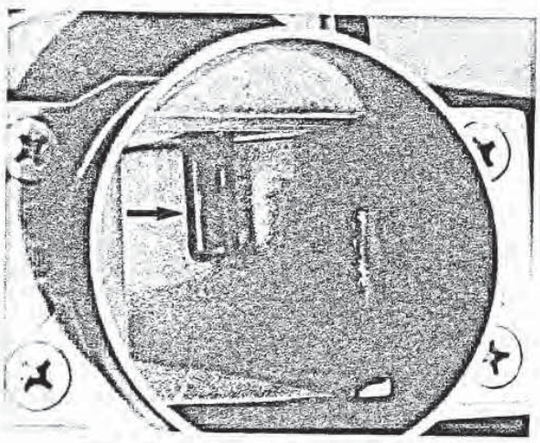


Fig. 2-34. This air-temperature sensor (**arrow**) (also called Temp I or NTC I) signals intake air temperature.

Cold Starting Enrichment. There are two ways that additional fuel can get to the engine during cold starting. The first is an auxiliary or cold-start injector which is controlled by the thermo-time switch. The second method is the Start Control System in the control unit which adjusts the pulse time of the fuel injectors as needed. Most L-Jetronics use the cold-start injector. Some combine that with start control; and a few use only start control.

> One system missing from most fuel-injection engines is the Intake Air Heater, or Heated Air Cleaner. For emission control and driveability, carbureted and throttle-body-injected engines heat the intake air to about 100°F (40°C). Warmed air tends to prevent condensation of the air-fuel mixture on the intake walls, which causes stumbling and increased emissions from the lean mixture. Because L-Jetronic delivers fuel at the intake ports, it can compensate fuel flow as necessary, enriching for cooler air without wall wetting. Without the Intake Air Heater, L-Jetronic delivers cool air, with greater density, producing more power in cold conditions.

The cold-start injector (also called the cold-start valve) is energized during cold starting. When the key is turned to start, a relay delivers power to the start injector. A thermo-time switch grounds that circuit, causing fuel delivery based on switch temperature. This auxiliary injector does not operate through the control unit, and is not usually affected by the engine temperature sensor.

If installed the cold-start injector is easy to find, mounted on the intake manifold downstream of the throttle, as shown in Fig. 2-35. It has an electrical connector and a fuel line. Whenever the system is pressurized, the start injector is pressurized; that means it is under pressure whenever the engine is running, and for some time afterward. Why is that important? If this injector leaks, the engine runs rich.

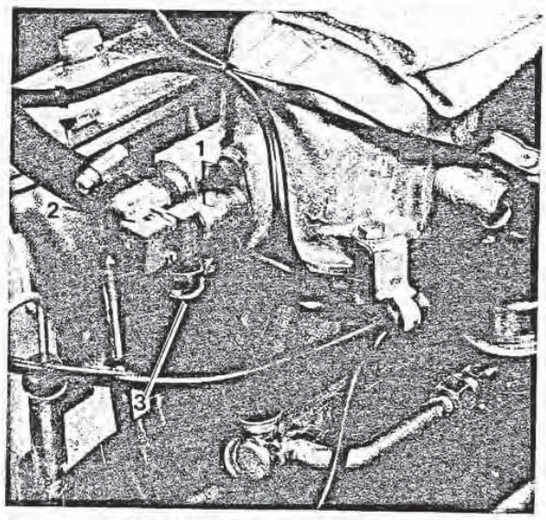


Fig. 2-35. Cold-start injector (**1**) delivers fuel into intake manifold to enrich mixture for all cylinders. Electrical connection is at **2**, fuel connection at **3**.

The cold-start injector is solenoid-operated, something like the port injectors, but it holds open for seconds rather than milliseconds. At system pressure, fuel enters through the fuel

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