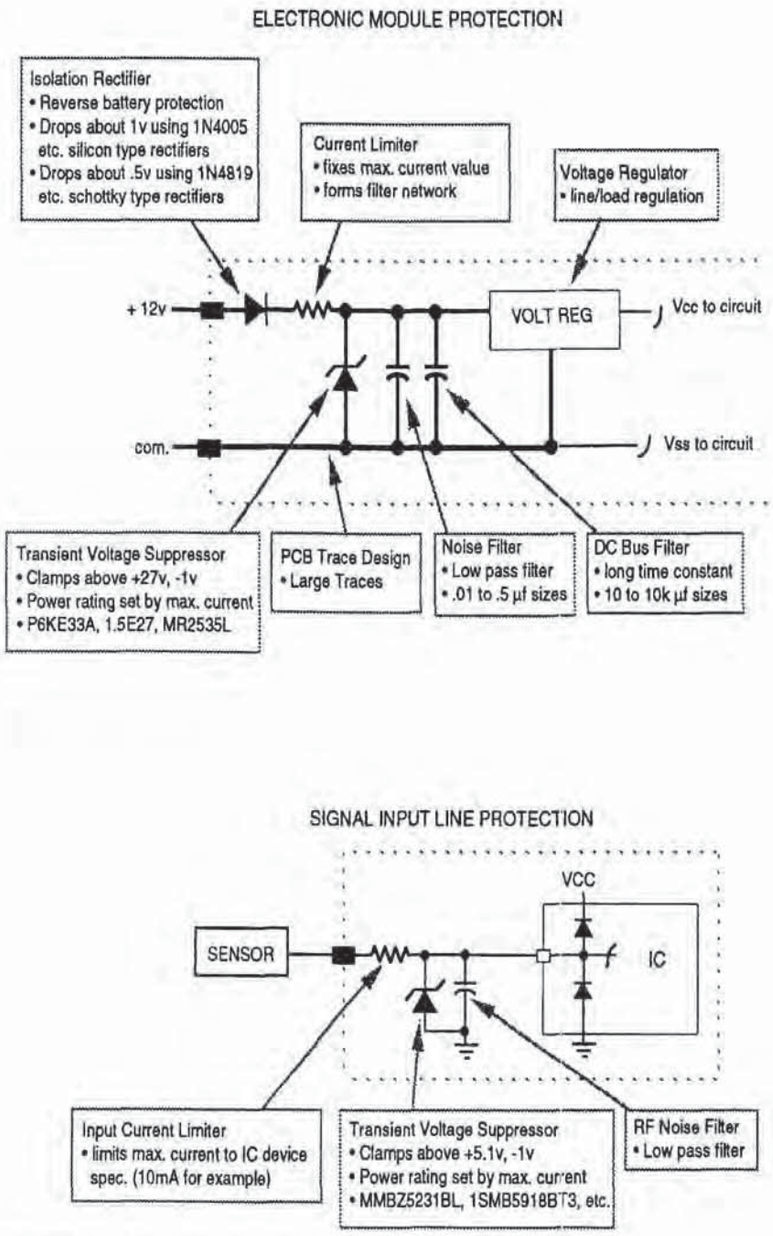


FIGURE 19.15 Voltage clamping networks.

membership called "comfortable," whereas 20 °C might be 0 percent and 30 °C might be 0 percent. Memberships could include "icycold," "cold," "cool," "comf.," "warm," and "hot." This thinking process fuzzifies the input temperature analog signal into numerical values that are attached to each membership. The user setpoint temperature is also divided into membership functions. The user setpoint temperature input is also fuzzified. Figure 19.16 shows the ambient and user setpoint memberships graphically. Other inputs, such as outside temperature, humidity, solar radiation, etc., could also be incorporated to produce a high-performance HVAC system. Once the input signals have been fuzzified, the first of three parts of a fuzzy design has been completed.

A second part of the fuzzy design is to assign membership functions as shown in Fig. 19.17 to the output control signals. In this example, only the heater side is shown. The output mem-

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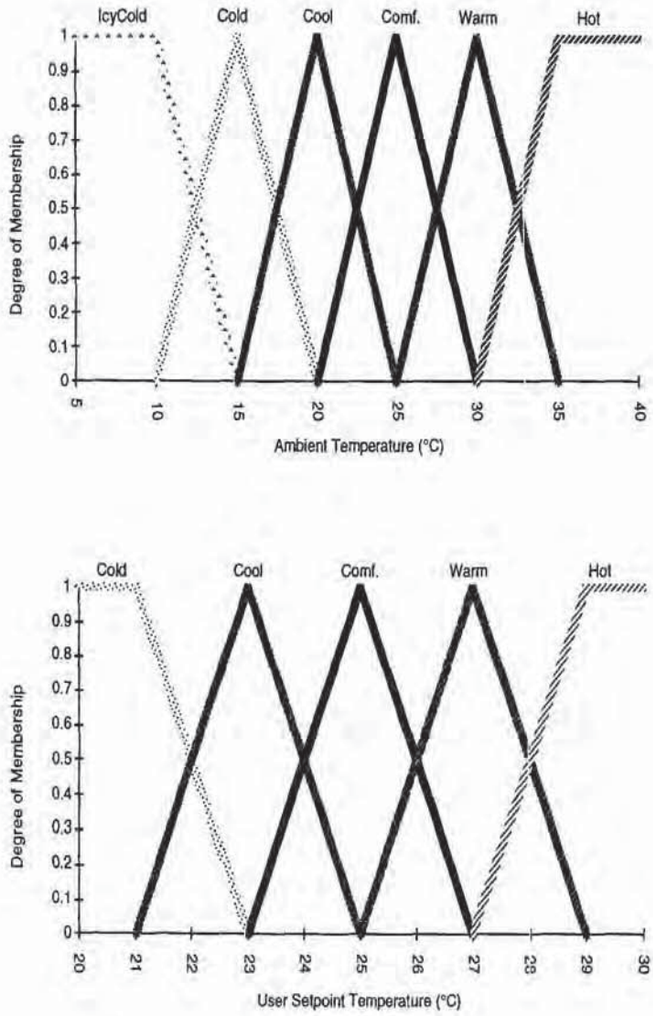


FIGURE 19.16 Fuzzy input memberships.

bership functions are classified as singletons, which only gives one value per membership. This approach trades precision for memory size.

The third part of a fuzzy design uses the min-max inference method to establish rules. A matrix representation of the input and output memberships and rules is helpful as shown in Fig. 19.18. The matrix size is determined by the input membership quantity, which is 5 for the user setpoint and 6 for the ambient temperature. This means a total of 30 rules are possible ($5 \times 6 = 30$). The designer selects which output membership function occurs for each input membership function.

Fuzzy logic development tools are available that can simulate the fuzzy design. These programming design tools simplify testing the program's performance before production. A 3-D interactive graphic display allows the designer to visually examine the input to output relationships. Irregularities can be traced back and corrected before the first prototype is built. The availability of integrated fuzzy design software for personal computers allows the system engineer to evaluate the fuzzy design approach.

In summary, the fuzzy design method requires: the input data to be applied to the input membership functions or fuzzified, invoking the rule set to the fuzzified data, and, finally, generating an output or defuzzification based upon the rules and output function type. The fuzzy

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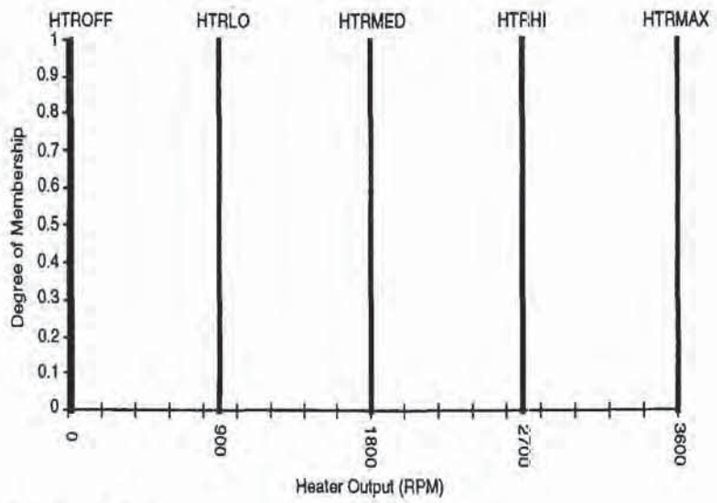


FIGURE 19.17 Fuzzy output memberships.

design can be modified with common-sense rules and rule strengths, whereas the conventional algorithm design method may require modifications at the most basic assembly code levels.

19.4 MISCELLANEOUS LOAD CONTROL REFERENCE

19.4.1 Current-Sensing Power FETs

Internal current-sensing power FETs can be used for current sensing, but their implementation may require some additional considerations. The current-sensing power FET device is a

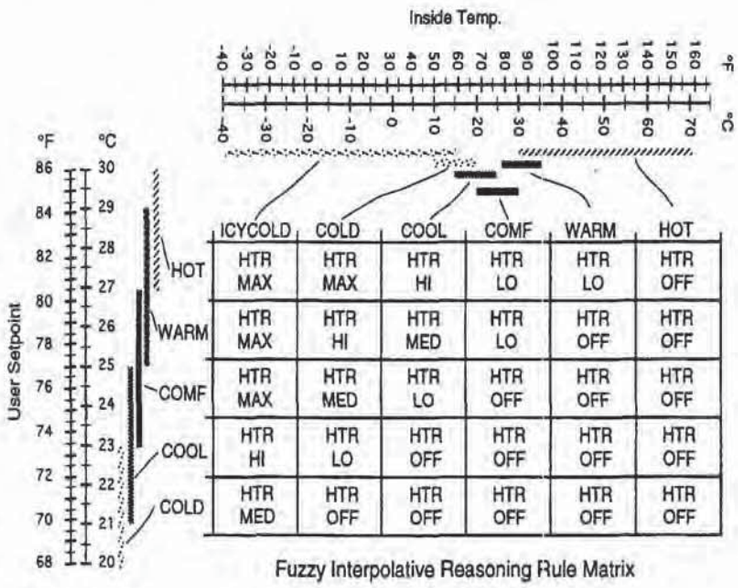


FIGURE 19.18 Fuzzy rules.

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normal power FET transistor with a very small portion of its active die area set aside for a current mirror. To use its current-sensing ability, an external resistor is connected between the current mirror output and the Kelvin output. The voltage drop across this resistor will be directly proportional to the device's current level when the device is operated in the active region. Choosing the correct value of the sense resistor is important to maintain an accurate drain current-to-sense voltage ratio over wide temperature ranges and when the unit is operated in the full ON or ohmic region.

When operating in the full ON region, the current mirror network changes from a constant current mode to a voltage source mode. This mode change occurs because the forward transconductance of the current mirror FET cells is decreasing due to the lower drain-to-source voltage. The result lowers the mirror current level to the sense resistor during full ON conditions when the load is connected between the drain and Vcc.

By selecting a sense resistance value that is less than 10 percent of the ohmic or rM(ON) value, the current mirror accuracy can be maintained. For example, if the current-sensing power FET device's rDS(ON) is 0.16 ohm and the current mirror ratio is 1800, the rM(ON) will be about 288 ohms ($0.16 \times 1800 = 288$). Therefore, a sense resistor value of less than 28 ohms is required. If a lower rDS(ON) current-sensing power FET device is used, for example, 0.026 ohm, and the current mirror ratio is 950, a sense resistor of less than 2.5 ohms should be used.

The use of an amplifier stage is still required to boost the current mirror's output signal level, which is similar to a traditional current-sensing network that uses very low resistance values (0.005 to 0.1 ohm). A low-cost operational amplifier (op-amp), LM324A, for example, will give fair performance over wide temperature ranges. The input offset voltage range of the op-amp will be a determining factor in the overall accuracy of the current-sensing power FET circuit design because of the low-millivolt current mirror signals. Instrument-grade op-amps can be used when higher accuracy is required. The op-amp circuit layout should be connected in close proximity to the current-sensing power FET's Kelvin and mirror output pins to minimize external noise pickup.

19.4.2 Overvoltage, "Load Dump," Reverse Battery

A hazard to any automotive electronics is reversed power supply connections. The power FET's internal rectifier will become forward-biased and will turn on the motor or lamp load. The FET's power dissipation will increase about 5 times normal since its voltage drop is now about 1 volt instead of the nominal 0.2 V. A standard bipolar transistor does not have the internal collector-to-emitter rectifier, but it still will suffer from a reversed power supply condition. The emitter-base junction avalanches at around 6 to 8 V, and the base-collector forms a rectifier. Therefore, the typical bipolar transistor is cooking itself into oblivion with about an 8-V drop while conducting about 1 A of lamp current. Most auto manufacturers specify that any electronic or electrical device must be able to withstand a reverse battery connection. The exact magnitude of the reverse voltage requirement varies per manufacturer, but the worst case seems to be –24 V for 10 min. This requirement is especially troublesome when the load requires an inductive kickback clamp rectifier, and either a power FET or bipolar transistor is used as the load driver. The power transistor's intrinsic rectifier and the load rectifier become forward-biased as shown in Fig. 19.19. The result? The clamp rectifier fails by shorting, the transistor shorts, and then the fuse may blow unless the rectifier or power transistor blows open first. A simple reverse battery isolator relay can be used to guard against incorrect battery polarity connections. This simple relay has been incorporated in the power supply line, which will open the line in the event of a power supply voltage reversal or if the power supply should exceed 32 V.

There are several other hazards for 12-V vehicular electronics that have to be considered. These can be divided into two groups: minimum/maximum operational voltages and voltage transients.

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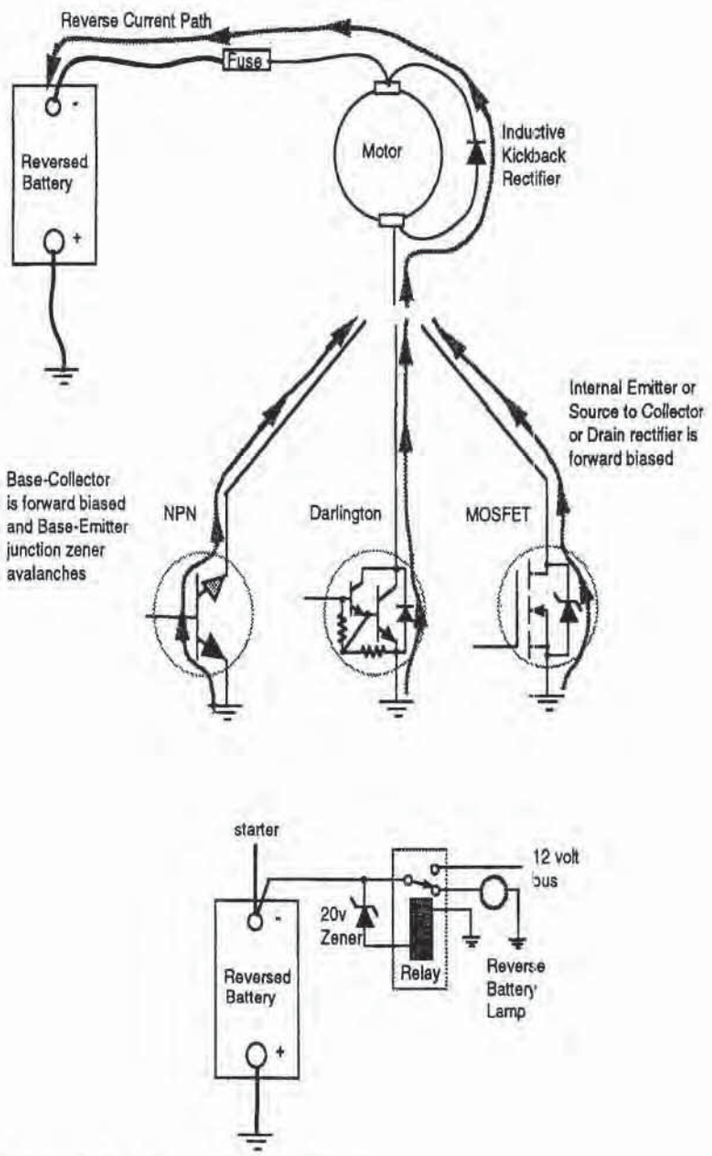


FIGURE 19.19 Reverse battery rectifier path.

The typical power supply voltage operating range for nonengine functions is 8 to 16 V. Most nonengine vehicular loads are either lamps or motors, and these types of loads will function in some proportion all the way down to near zero voltage when controlled by simple switches. When electronic control circuits are used with these loads, a power supply voltage threshold level occurs, and the load abruptly stops functioning. This threshold level normally takes place between 3 to 8 V and is dependent upon the control circuit's biasing networks and internal transistor technologies. The important criterion is that the electronic control should behave in a stable fashion when the power supply voltage varies between nominal levels and zero. A smooth transition during power supply on/off conditions in the electronic designs can be implemented with some form of hysteresis element for the analog portions and a low-voltage interrupt/reset for MCU/digital circuits.

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Voltage transients tend to be either high-energy, up to 125-V levels, or low-energy, high-voltage spikes. The alternator "load dump" voltage spike ranges from about 85 to 125 V for a duration of approximately ½ second. This voltage spike is of a high-energy nature because of the alternator's low source impedance. By using Zener-type rectifiers in the alternator in place of the alternator's normal rectifiers, the load dump voltage can be clamped to under 40 V.

High-voltage transients are generated by the fast turnoff of high-current inductive loads, such as air-conditioning compressor clutches. The polarity of high-voltage inductive kickback spikes depends upon the control switch configuration. Adding a rectifier across the inductive load to clamp the turnoff voltage spike will affect the mechanical performance of some solenoids, actuators, or relays. The mechanical turnoff will slow down. As the solenoid's magnetic field collapses, a countervoltage is generated that, in turn, causes the magnetic field to reverse, which speeds up the solenoid's turnoff action. The insertion of a back-emf rectifier clamps or shunts the counter voltage, and therefore minimizes any significant reversal of the magnetic field. Using back-to-back Zener rectifiers across the inductive load that are selected will allow satisfactory mechanical turnoff action, and yet will protect the power electronics.

Another form of electrical stress that the motor control system has to sustain is ESD or electrostatic discharge. The ESD is normally encountered in the manufacturing cycle, but can occur in the application. To minimize ESD, the control shafts, switch handles, user faceplate, etc., should be designed to dissipate ESD through a ground path away from the electronic module.

19.4.3 Microcomputer I/O Line Protection

Voltage transients on MCU input or output (I/O) lines can cause the MCU to fail. Figure 19.20 shows three different methods to contain excessive MCU input or output line voltage spikes.

Single input line protection is accomplished by a 5.1-V Zener clamp to contain positive-going transients and a Schottky rectifier for the negative-going transients. The Schottky rectifier does have temperature problems at both ends. At 125 °C, its leakage current may reach 50 μA when the input line is at a 5-V level. Therefore, the input signal may lose 50 μA of current to the Schottky which may reduce its voltage level too much for the MCU input port to respond properly. Another problem occurs at cold temperatures. At –40 °C, the forward voltage rises to about 0.47 V, which is getting close to the –0.50-V maximum level specification for most HCMOS-type microcomputer chips. A simple RF low pass filter network is also a good idea to incorporate on each input line. The RC network will minimize problems from high-energy RF fields and will limit excessive current levels from flowing through the MCU's internal substrate.

Multiple input line protection uses two Schottky rectifiers per line for clamping positive- and negative-going voltage transients. A single 4.7-V Zener is used as a common clamp to all input lines.

MCU output line protection uses a resistor, capacitor, Zener, and Schottky rectifiers. The resistor is connected in series to the load, and will therefore have to be sized to drop about 5 to 10 percent of the nominal load voltage. The resistor's main function is to limit reverse current into the MCU in case the output line is raised above Vdd or below Vss, and no other protective devices are used. Adding a small value capacitor at the load output will help minimize RFI, at the expense of reducing switching time from the MCU. Adding a Schottky and Zener rectifier to the MCU output line will protect against both negative- and positive-going transients.

Adding program traps in the MCU software will help to restart the MCU in the advent of a software crash. Experiments have shown MCU-based electronic modules that fail (program crashes, and MCU locks up until hardware restarts it) due to high bursts EMI or RFI, will still perform, but at reduced throughput, when software traps are used. One method uses a trap consisting of three NOP instructions followed by a JMP to RESET instruction. These traps

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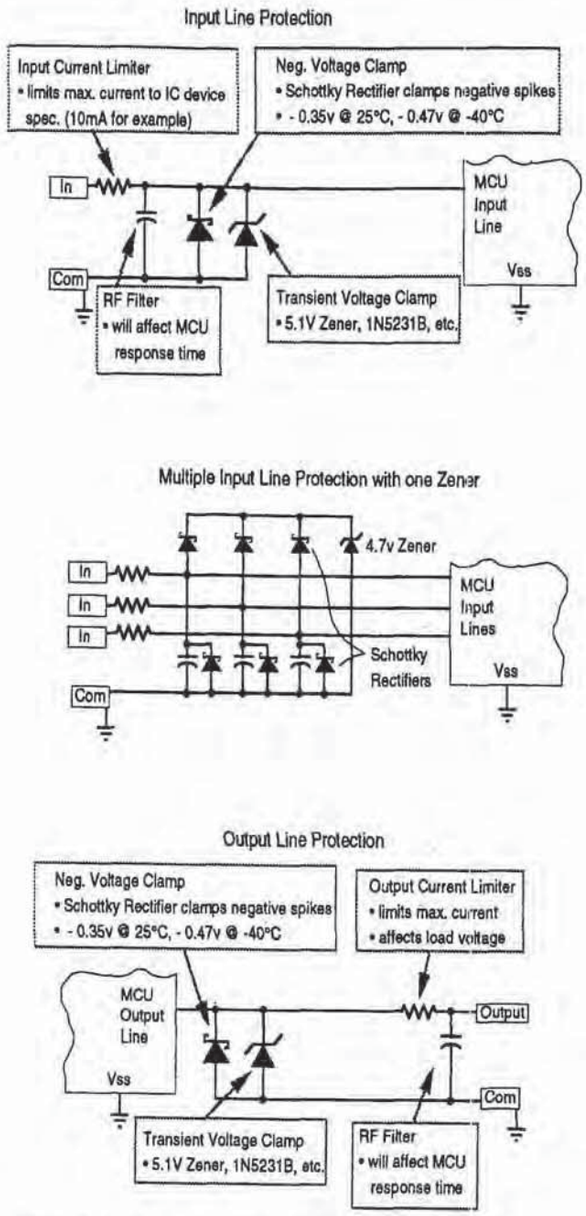


FIGURE 19.20 MCU I/O voltage spike clamping.

are used after loops or subroutines. These software traps, in addition to a watchdog timer if the MCU has this feature, will help in catching an out-of-control program.

The location of the watchdog timer reset instruction code is also important. If the watchdog timer is reset from within an interrupt routine, there is a possibility that the program could still be out of control, but that the interrupt vectors could still be working, and will therefore not reset. A good place to locate the watchdog update code is in a main program path rather than in an interrupt routine.

The PCB or thick-film design layout affects the MPU's reliability in terms of overvoltage transients. The clamping networks should be located physically close to the input socket pins

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and common. The MPU common traces should not be in the path of any voltage-clamping networks. It may also be a good idea to place an inexpensive metal shield around the MPU PCB area to protect against RFI and ESD problems.

19.4.4 Wire Size Reference

Most wire tables only give basic weight, dimensions, and dc resistance. A more complete version would include straight-line inductance as shown in Table 19.2. Unlike resistance which adds in a linear proportion to its length, inductance adds up on a logarithmic scale.

19.5 FUTURE LOAD CONTROL CONCEPTS

Higher integrated or more complex semiconductor power devices are available for specific load controls that can justify the extra cost of these smarter power types. The tradeoff is that the extra internal circuitry in the device usually limits its application to specific loads.

TABLE 19.2 Wire Gage Resistance and Inductance

Wire #	Dia., mm	Dia., in	Ohms per 305 mm (ft)	L of 25 mm (1 in), μH	L of 305 mm (1 ft), μH	L of 914 mm (1 yd), μH
1000 MCM	29.261	1.1520	0.000008	.003	.182	.746
500 MCM	20.650	0.8130	0.000016	.004	.203	.810
250 MCM	14.605	0.5750	0.000031	.006	.224	.873
0000	11.684	0.4600	0.000049	.007	.238	.914
000	10.404	0.4096	0.000062	.008	.245	.935
00	09.266	0.3648	0.000078	.008	.252	.956
0	08.252	0.3249	0.000098	.009	.259	.977
1	07.348	0.2893	0.000124	.010	.266	.999
2	06.553	0.2580	0.000156	.010	.273	1.019
4	05.189	0.2043	0.000248	.011	.287	1.062
6	04.115	0.1620	0.000395	.012	.301	1.105
8	03.264	0.1285	0.000628	.014	.315	1.147
10	02.588	0.1019	0.000999	.015	.329	1.189
12	02.052	0.0808	0.001589	.016	.344	1.232
14	01.628	0.0641	0.002526	.017	.358	1.274
16	01.291	0.0508	0.004016	.018	.372	1.317
18	01.024	0.0403	0.006386	.020	.386	1.359
20	00.812	0.0320	0.010154	.021	.400	1.401
22	00.644	0.0254	0.016139	.022	.414	1.444
24	00.511	0.0201	0.025671	.023	.428	1.486
26	00.405	0.0159	0.040818	.024	.443	1.529
28	00.321	0.0126	0.064914	.025	.457	1.571
30	00.255	0.0100	0.103093	.027	.471	1.613
32	00.202	0.0080	0.164095	.028	.485	1.656
34	00.160	0.0063	0.260891	.029	.499	1.698
36	00.127	0.0050	0.414849	.030	.513	1.741
38	00.101	0.0040	0.659695	.031	.527	1.783
40	00.080	0.0031	1.048548	.033	.542	1.825

$R_{ohm} = 4\,Lp/\pi D^2$. L = length in meters, D = length in mm, p = resistivity .017241Ω per μΩm (= Ω mm²/m). (Ref: *Automotive Handbook*, 2d ed, Bosch, 1986, pp. 176–177.)

$L\mu H = (0.0002\,L)*[(IN(2*L/(D/2)) - 0.75)]$. L = length in mm, IN = nat. log., D = dia. in mm. (Ref: *ARRL Handbook*, 1988, pp. 2–18.)

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Some form of more intelligent brake indicator system may help minimize the classic chain vehicle crashes that occur in poor driving conditions. One possible method using electronic switched stop lamps would involve a rate of closure detector system to determine if the vehicle's speed is safe for objects ahead of it. If the closure rate is unsafe, the stop lights could be activated to alert trailing (or tailgating) drivers to a pending accident.

19.5.1 Fully Integrated Power Devices

The concept of putting the MCU and power drivers on one piece of silicon is viable at limited power levels and breakdown voltages. The MC68HC05V8 MCU is but one of several semiconductor industry examples of this technology.

GLOSSARY

Charge pump A circuit that usually consists of an oscillator driving logic gates that yield out-of-phase signals that are applied to a rectifier voltage doubler network. The charge pump circuit can be integrated into MCUs and other power analog integrated circuits.

Current mirror A design that generates a signal whose level is directly proportional to another current level. The current mirror concept is used in current-sensing power MOSFETs.

Electromagnetic interference (EMI) Unwanted magnetically coupled voltages that affect the normal operation of electronic systems. EMI is a problem when high-energy circuits are in close proximity to high-impedance sensors, or any low-energy electronic control circuit. EMI also occurs in a wiring harness. One wire conducting a high-energy pulse in this harness will couple the pulse into the other harness wires. Twisted wire pairs are often used to minimize EMI susceptibility.

Freewheeling rectifier A rectifier that is connected across an inductive load or transistor switching device to suppress the voltage spike generated when the load is turned off.

H-bridge A design utilizing four power devices that are connected to reverse the voltage across both terminals of a load. H-bridges are used for bidirectional motor controls.

Half H-bridge A design using two power devices that are connected in series from the positive power supply bus to common, and a load terminal connected to the transistor's middle-connection. Two half H-bridges can make a full H-bridge. Three half H-bridges are commonly used in three-phase motor controls.

Intrinsic rectifier A rectifier that is inherently part of a semiconductor design. Most power MOSFET transistors have a drain-to-source rectifier that is formed by the nature of the MOSFET design structure. In battery-powered designs, the intrinsic rectifier is a concern during reversed battery hookups.

Load dump The effect of disconnecting the load from an alternator running at full power. In automotive equipment this condition can be caused by intermittent battery connections when the alternator is applying maximum current to the battery. When the load is abruptly disconnected, the alternator control circuitry shuts off the field current, but this current takes up to ¼ s to decay, and allows the alternator to produce a voltage much higher than its nominal value, up to 125 V in some cases. This abnormal voltage tracks the field current decay.

Pulse-width modulation A common control signal modulation method used in dc speed controls. The signal's frequency is fixed at a rate of 100 Hz to 20 kHz, but its pulse width is var-

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ied from 0 to 100 percent. The variable pulse width, in effect, acts like a variable voltage source when driving most automotive type loads.

P-channel MOSFET Usually a power transistor that requires a negative gate-to-source control voltage of 3 to 10 V. P-channel MOSFETs are normally connected between power supply positive bus and the load, and can operate from a positive voltage bus.

N-channel MOSFET Usually a power transistor that requires a positive gate-to-source control voltage of 3 to 10 V. N-channel MOSFETs are normally connected between common and the load, and operate from a positive voltage bus. The gate input characteristics are capacitive with gate power loss occurring during the switching edge transition period.

Radio frequency interference (RFI) High-frequency signals of sufficient magnitude to influence the normal operation of electronic systems. RFI sources from automotive equipment include spark plug arcing, dc motor brush arcing, electrical contact switching, and fast transitional voltage pulses from power electronic circuits.

Saturation A power transistor's forward ON region normally defined as when an increase in drive input voltage or current has little effect upon further reducing the transistors forward ON voltage. Saturation regions vary from less than 0.1 to over 3 V depending on the transistor technology and design.

Zener rectifier A semiconductor rectifier device that is designed to operate in a reverse bias mode. When the reverse voltage reaches the Zener voltage, the device abruptly starts conducting current. Zener rectifiers are used for shunt voltage regulators, overvoltage protection, and voltage level detectors. Zener rectifiers are also designed specifically for high-power voltage transient suppression. These devices are constructed to handle very high momentary current levels.

Note

Based in part on the article by Richard Valentine, "Don't underestimate transistor-based lamp driver design," *EDN*, June 7, 1990, pp. 119–124.

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ABOUT THE AUTHOR

Richard J. Valentine is a principal staff engineer at Motorola SPS in Phoenix, Ariz. His present assignments include engineering evaluation of advanced semiconductor products for emerging automotive systems. He holds two patents and has published 29 technical articles during his 24 years at Motorola.

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DISPLAYS AND INFORMATION SYSTEMS

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CHAPTER 20
INSTRUMENT PANEL DISPLAYS

Ronald K. Jurgen, Editor

20.1 THE EVOLUTION TO ELECTRONIC DISPLAYS

In the early automobile years, cars had analog displays that contained minimal information, usually just car speed and oil pressure. As the use of electronics increased in cars dramatically from the late 1970s on, however, the traditional mechanical or electromechanical analog displays with a circular dial face and a pointer began to be challenged by newer technologies. The major ones included gas discharge or plasma displays, vacuum fluorescent displays (VFDs), liquid crystal displays (LCDs), cathode-ray tubes (CRTs), and more recently, head-up displays (HUDs). These newer technologies made it possible for car makers to give drivers a broad spectrum of information, including sophisticated graphics.

In 1978, the first production electronic digital display, a gas plasma device, was used in the Cadillac Seville; in 1984, the first standard equipment production LCD cluster was used in the Chevrolet Corvette; and in 1985, the first full-color CRT was used in a production vehicle, the Toyota Soarer.[1]

The initial rush by car makers to use electronic displays has now abated somewhat. Drivers, in many instances, did not take kindly to overkill with electronic displays—any more than they did to electronically generated voice messages—and today's use of displays tends to be more conservative. In fact, one approach fast gaining popularity is electronic analog displays rather than strictly digital ones.

This chapter will describe typical electronic displays used in cars. It is not intended to be all-inclusive. That would be beyond the scope of this handbook. But the display examples given are representative of what can be found in cars today.

20.2 VACUUM FLUORESCENT DISPLAYS

One of the most widely used electronic displays is the vacuum fluorescent display. It was first used in automotive clocks and has since been applied in other ways including audio systems, air conditioning/heating, message centers, and head-up displays. Its popularity stems from features that include availability of a variety of colors, high luminance, low voltage operation, reliability, and long life.

The basic structure of a modern VFD, Fig. 20.1, consists of a cathode, grid, and anode.[2] The tungsten-wire cathode emits thermal electrons that are accelerated when a positive voltage is applied to the anode and grid. The phosphor-coated anode emits a blue-green light when

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struck by the emitted electrons. Other colors such as yellow-green, green-yellow, yellow-orange, orange, and red-orange colors, obtained through the use of optical filters, can be used independently within the same display. Thick- or thin-film screens are used to shape the phosphor pattern in any desired manner. VFDs produce maximum perceived brightness at low input power.

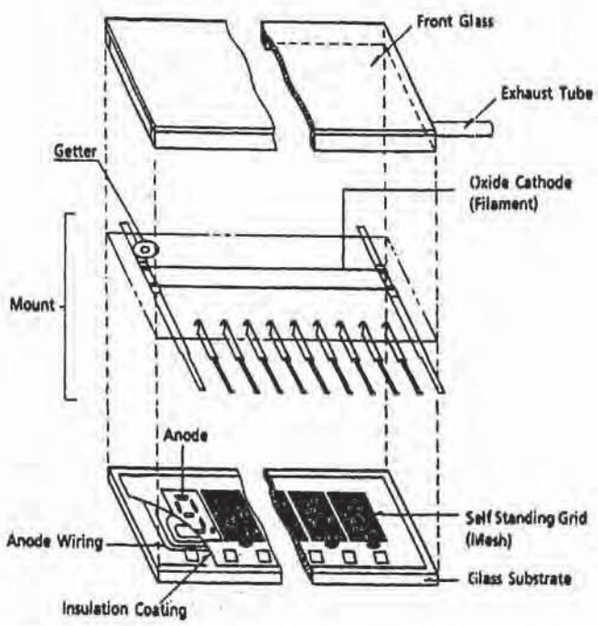


FIGURE 20.1 The basic structure of a vacuum fluorescent display. *(Reprinted with permission from SAE SP-858 ©1991 Society of Automotive Engineers, Inc.)*

Initial VFDs were single-digit displays. Multiple-digit displays followed and now single large-scale VFDs contain multiple functions such as speedometer, fuel and temperature gages, trip odometer, turn indicators, and warning signals.

A typical application of VFDs was in the electronic instrument panel on the 1985 Chrysler LeBaron.[3] The VFDs are controlled (Fig. 20.2) by a Motorola MC6805R3 8-bit, HMOS, single-chip microprocessor with internal analog-to-digital converters. Another microprocessor, a 4-bit device, is used to generate a high switching rate for the center display in the instrument panel.

20.3 LIQUID CRYSTAL DISPLAYS

LCDs are fluids consisting of organic compounds whose molecular orientation rotates polarized light by 90 degrees as light passes through the material.[4] When an electric field is applied to the fluid, its molecular orientation is altered as is its polarizing ability. The change is visible in reflected or transmitted light and can be used to form predetermined patterns or characters.

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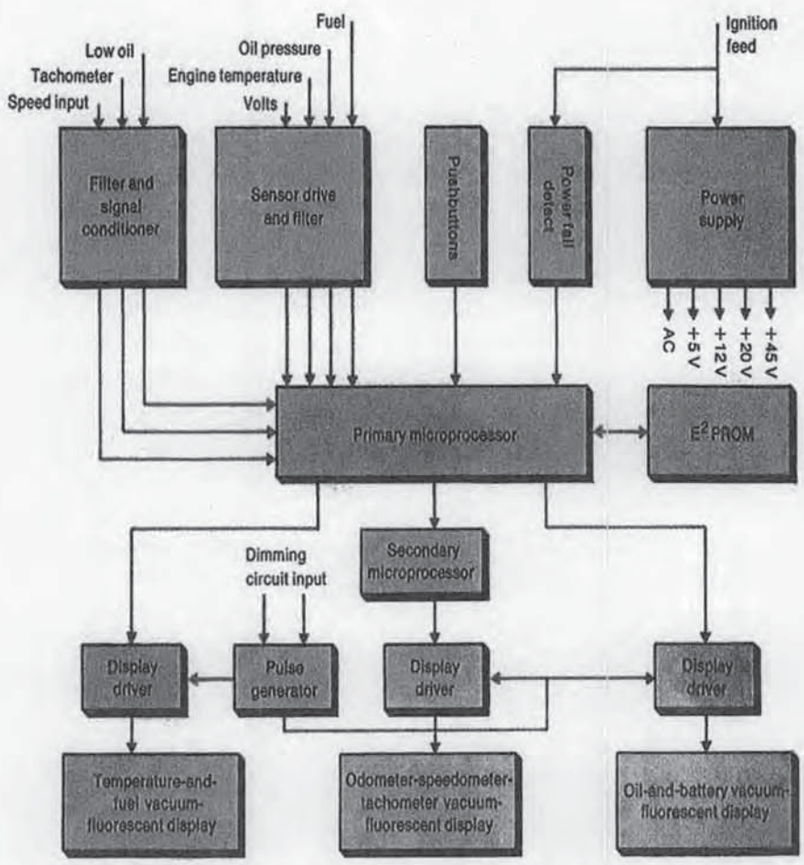


FIGURE 20.2 Vacuum fluorescent displays and their driving circuits as used in the 1985 Chrysler LeBaron. *(©1984 IEEE)*

There are three general classes of liquid crystals called *nematic, smectic,* and *cholesteric.*[5] In nematic liquid crystals, the molecules are lined up in one dimension but have random order in the other two directions. In smectic liquid crystals the ordering of the molecules is similar except that it is much higher. In cholesteric liquid crystals, the molecules stack in layers that have a twist and tilt that gives the molecules a spiral configuration.

Certain chemical substances applied on top of the two electrodes of a liquid crystal display orient the long axes of the molecules so that they line up parallel to the surface of the glass plate. The display cell is assembled so that the long axes of the molecules on the top plate are oriented at 90 degrees to the direction of the molecules on the bottom plate. The molecules between the plates assume a spiral configuration.

A polarizer is placed on top of the display cell. When light enters the liquid crystal region of the display, the direction of polarization is rotated as the light travels along the spiral configuration. A second polarizer behind the bottom plate is oriented to allow the light with its altered polarization to pass through. The display then appears bright to the observer. An electric field applied across the display cell, the molecules realign with their long axes parallel to the direction of the field. The polarized light entering the cell is no longer twisted and the second polarizer cuts off the light passing through the liquid crystal. The observer sees a dark screen.

In what is called a dichroic LCD, no polarizers are used, but a dichroic dye is combined with the liquid crystal material.[4] The dye molecules combine with the liquid crystal molecules

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to produce unique spectral absorption characteristics. With no voltage applied, the dye absorbs certain wavelengths of the incident ambient light and the observer sees a colored background. When the display is activated, the observer sees colorless display elements against the colored background.

In simple liquid crystal displays containing only a few seven-segment characters, each numeral is addressed by activating the appropriate segments to form a specific numeral. But for more complex displays, consisting of many picture elements (pixels) that are twisted nematic cells, this type of addressing is too cumbersome and matrix addressing is used instead. The pixels are turned on by applying voltage to both their row and their column electrodes rather than directly to the individual pixels.

20.4 CATHODE-RAY TUBE DISPLAYS

Although the cathode-ray tube (CRT) has found wide success in a variety of applications including television receivers, instruments, and radar and medical equipment, it has been far less successful in the automotive field. Some of the reasons for its lack of impact are the amount of space needed behind dashboards to house the CRT, possible washed-out images in sunlight, lack of instant-on capability, and possible safety hazards from x-ray exposure, implosion, and high voltages.[6]

Despite the difficulties that CRTs present to car makers, there have been limited applications in cars over the years in several General Motors cars and in some Ford Motor Company models. In 1986, for example, the General Motors Corp. introduced a CRT-based display called a Graphic Control Center in 1986-model Buick Rivieras.[7] The center combined diagnostic with control functions in an integrated information system and handled inputs from 7 to 10 microprocessors with the actual number dependent on the number of options on the car. The center could be used to call up information on the CRT in the basic areas of climate, radio, trip monitor, and gages, in addition to diagnostics information. The display for each area would appear as a "page" of information. In some cases, there would be more than one page, starting with the general and proceeding to the more specific.

When the ignition key was turned on, a summary page would appear displaying key information from all the basic areas. To access more detailed information, the driver simply touched an appropriate spot on the screen. A Mylar switch panel positioned over the screen used ultrathin wires encoded by rows and columns to send signals to the control circuits.

Although General Motors had CRT systems in the Riviera and subsequently the Buick Reatta and a somewhat similar system in the Oldsmobile Toronado and Trofeo, they were eventually dropped. One of the main drawbacks was that the driver had to take his or her eyes off the road in order, for example, to tune the radio. The Oldsmobile system improved on the Buick version in this regard by careful placement of some of the more commonly used controls so that the driver could activate them while still looking at the road. But car buyers, by and large, never became convinced that the CRT system was necessary or desirable.

A possible comeback for the CRT may be in the offing when automobile navigation systems take hold (see Chap. 29). Many of those systems use CRTs to provide the driver with useful trip information.

20.5 HEAD-UP DISPLAYS

A head-up display (HUD) is aptly named since it allows viewing of data superimposed on the driver's visual field with his or her head up. HUDs have been used in the military aircraft

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industry for over 20 years and more recently have had limited application in automobiles. A main advantage of a HUD in a car is that the driver need not constantly refocus his or her eyes as when switching them from the road to conventional dashboards and back again. The first applications in production automobiles were in the 1988 Nissan Silvia model and in special editions of the 1988 Oldsmobile Cutlass Supreme.

One of the first HUDs to appear in cars was in 1988 when the Oldsmobile Cutlass Supreme Indianapolis 500 Pace Car and its 54 replicas were equipped with the systems.[7] This was followed by offering the HUD as an option on the 1989 Oldsmobile Cutlass Supreme and on the Pontiac Grand Prix. Those systems were developed jointly by General Motors engineers from the Hughes Aircraft Corp., Delco Electronics Corp., and C-P-C Engineering. HUDs continue to be offered today by General Motors on some models.

The heart of the original GM system was an image source—a custom-designed, high-intensity, blue-green vacuum fluorescent tube made by Futaba Corp. of America. High brightness was made possible by keeping the cathode energized at all times and the electrodes at higher voltages than would be used in vacuum fluorescent tubes for conventional purposes.

The system works as follows. Speed and other sensor inputs are processed by an electronic module which then sends signals to the vacuum-fluorescent tube to activate segments of seven-segment numbers or graphic symbols in the tube. Optical elements then project the light from those energized segments onto the windshield of the car. The driver sees virtual images that seemingly float in space near the front end of the car (Fig. 20.3).

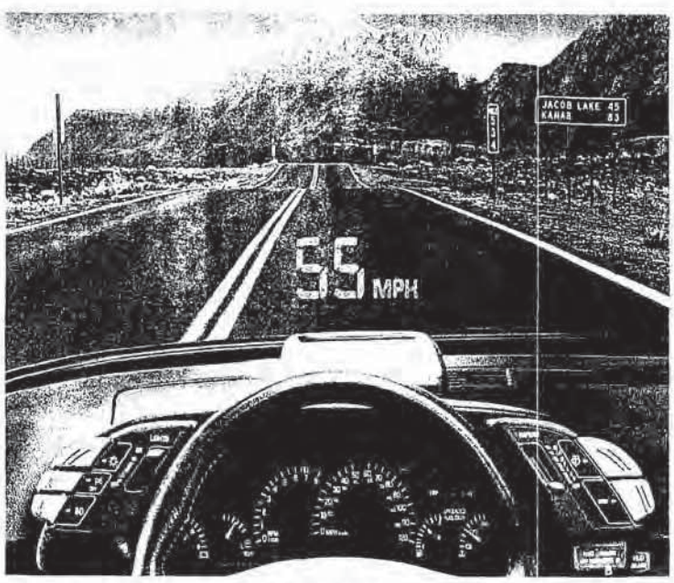


FIGURE 20.3 This head-up display, showing a virtual image of car speed, was standard on General Motors' Pontiac Division's 1993 Bonneville SSEi and is available as an option on the Bonneville SSE and on all Grand Prix models. Information that is projected onto the windshield includes vehicle speed, turn signal indicator, high-beam lights, check gages warning, and low-fuel alert.

The images can display car speed in either mi/h or km/h, left and right arrows for turn signal indications, a headlight symbol for high-beam indicator, and a gas pump for low-fuel warning.

As shown in Fig. 20.4, the image is projected from the image source onto the car's windshield by mirrors. A proprietary optical design keeps the image in the correct aspect ratio. The driver can adjust both the brightness and the vertical location of the image but the horizontal

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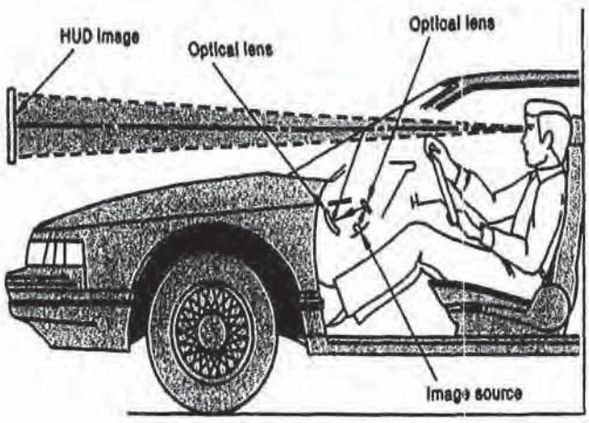


FIGURE 20.4 General Motors' head-up display uses an image projected onto the windshield of the car but the driver sees a virtual image of the projected information positioned at the front of the car. *(©1988 IEEE)*

location is fixed. Making it variable would require expensive variable-magnification changes in the system optics.

20.6 ELECTRONIC ANALOG DISPLAYS

Despite the proliferation of electronic digital displays in cars, many drivers still prefer analog displays. To satisfy this need while at the same time taking advantage of advances in electronics, many car makers have introduced electronic analog displays. These displays, despite their dependence on electronic circuits, present the driver with essentially the same type of display as in the electromechanical speedometer, for example.

Some car makers have seized the opportunity to offer their customers unique analog displays. One notable example is the high-precision electronic analog display in the Toyota Lexus LS 400.[8] Called a combination meter, Fig. 20.5, it uses a smoked-filter glass to cover the

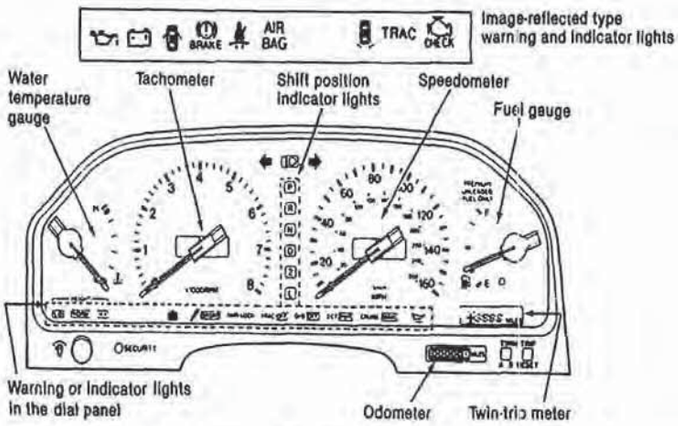


FIGURE 20.5 Toyota's Lexus LS 400 has a so-called combination meter that presents analog displays that are electronically activated. *(©1989 IEEE)*

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entire display area that is blacked out when the ignition switch is turned off. Cold-cathode tubes containing mercury gas light the light-transmitting dial panel. When powered, the tubes emit a white light to illuminate the dials when the ignition switch is turned on.

The speedometer, tachometer, fuel gage, and water temperature gage all have self-light-emitting needles consisting of cold-cathode tubes with a sealed-in mixture of neon and xenon gases that emit white light when energized. A cableless speedometer driven by a moving coil indicates speed based on pulse signals from the transmission speed sensor.

20.7 RECONFIGURABLE DISPLAYS

What may be a future trend in displays was presented at the Society of Automotive Engineers annual meeting in Detroit, Mich., in 1993. A reconfigurable automotive display system was described that displays multifunctional information on a dot matrix fluorescent indicator panel.[9] An advanced 8-bit microcontroller with real-time processing capabilities is used in the system to perform display refreshing, keypad scanning, and serial communications.

The dot matrix display in the system is a vacuum fluorescent type composed of an 80 by 16 matrix of pixels in a 9.85-mm-high by 50.5-mm-long graphics area. Two lines of 13 characters each can be displayed using a 5 by 7 font. The system can display text messages of different sizes, locations, and font types as well as graphics symbols. The advantage is that several fixed segment display systems can be replaced with a single dot matrix display system to cut costs and packaging space.

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CHAPTER 21
TRIP COMPUTERS

Ronald K. Jurgen, Editor

21.1 TRIP COMPUTER BASICS

Trip computers have evolved over the years from simple systems that estimate only the distance that can be traveled with the remaining fuel to sophisticated systems that also offer such features as instantaneous and average fuel economies, amount of fuel used, average speed, amount of fuel remaining, estimated time of arrival, oil life indicator, and diagnostic capabilities.

21.1.1 Basic System Configurations

A simple distance-to-empty system such as that shown in Fig. 21.1[1] has transducers that convert distance and fuel quantity into time-varying voltages or currents. Electronic signal pro-

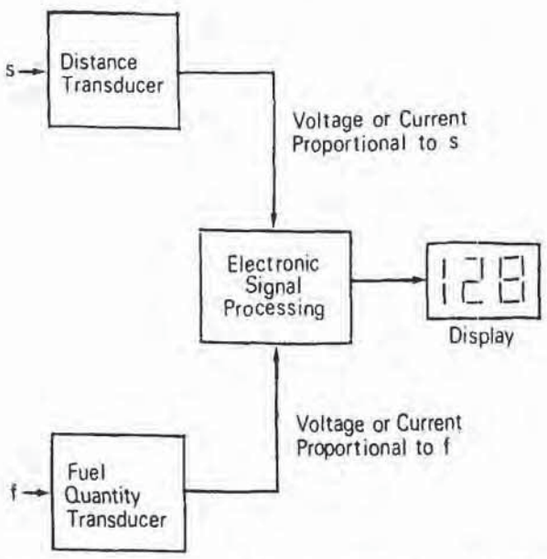


FIGURE 21.1 Elements of a basic distance-to-empty system. *(Reprinted with permission from SAE Technical Paper 800240 ©1980 Society of Automotive Engineers, Inc.)*

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cessing operates on those voltages or currents to produce a distance-to-empty estimate that is formatted for transmission to a display device.

A basic trip computer, shown in Fig. 21.2,[2] in addition to distance-to-empty, computes instantaneous fuel consumption, average fuel consumption, and average cruising speed. Through use of a sequential selector button, the driver causes the readouts to appear in order on the display.

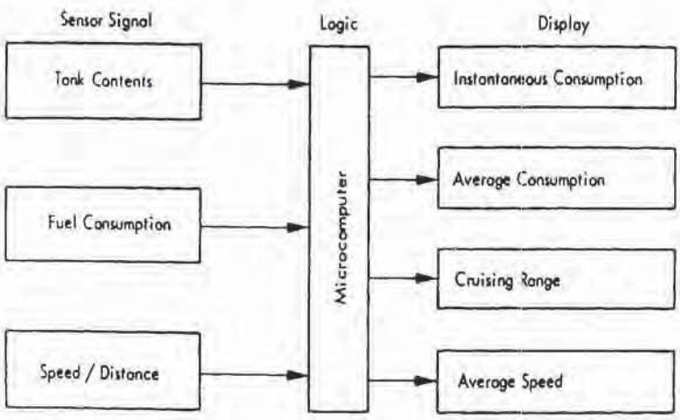


FIGURE 21.2 A simple version of a basic trip computer. *(Reprinted with permission from SAE Technical Paper 810302 ©1981 Society of Automotive Engineers, Inc.)*

21.1.2 A Full-Function Trip Computer

A full-function trip computer, shown in Fig. 21.3,[2] incorporates many more functions. The driver can feed information into the computer at the beginning of a trip—distance to destination, for example. During the trip, the driver can request specific information.

21.2 SPECIFIC TRIP COMPUTER DESIGNS

Different car makers have taken various approaches to trip computers for their car models over the years. Two selected examples follow.

21.2.1 The General Motors Trip Computer

The General Motors Trip Computer was first available as a high-cost option on the Cadillac Seville in 1978. The computer's principal four parts are a function-select keyboard, the central processing unit (CPU), the displays, and the interconnecting special wiring. The CPU translates the various engine and vehicle sensor inputs into the appropriate information needed by the driver and also provides constant speed and fuel displays, generator system information, and diagnostic features.

A block diagram of the bus-oriented CPU designed around the Motorola M6800 microcomputer family with N-channel, 8-bit parallel processing is shown in Fig. 21.4.[3] A 16-bit

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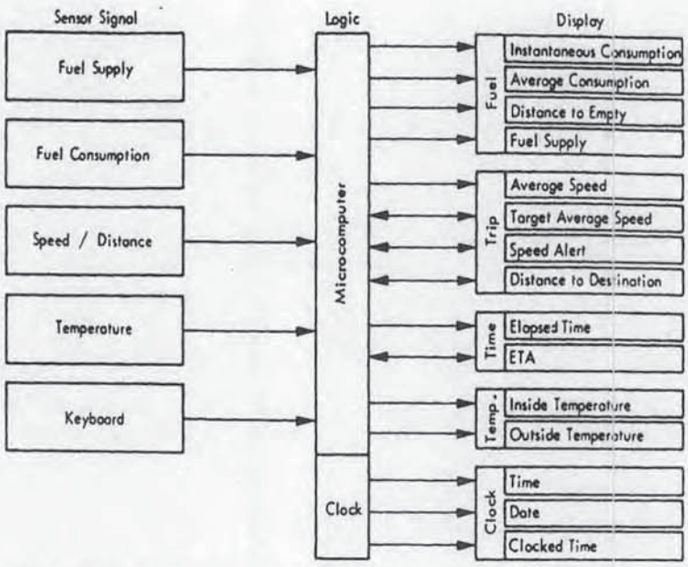


FIGURE 21.3 A full-size basic trip computer. *(Reprinted with permission from SAE Technical Paper 810302 ©1981 Society of Automotive Engineers, Inc.)*

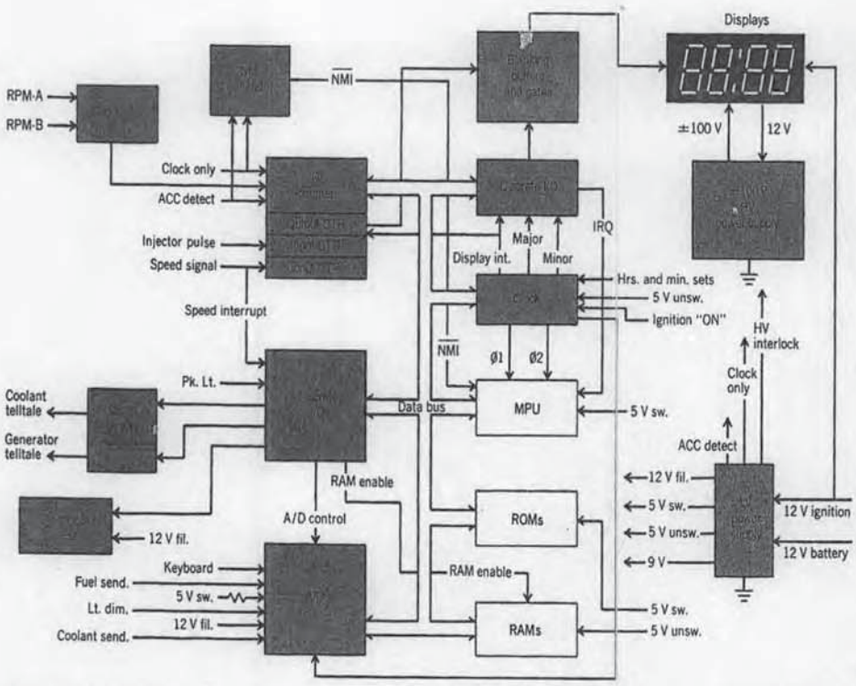


FIGURE 21.4 The central processing unit for the General Motors Trip Computer contains the following software routines in ROM: major loop (fuel-flow content and correction, distance and speed information, trip time and average speed time, fuel sense and display, time-of-day clock, clock colon control, keyboard requests, dimmer information, coolant sensor, system voltage, engine r/min, self-diagnostics); minor loop (keyboard call-up, diagnostic LED control); display-interrupt service (multiplexing, nonvolatile RAM information update, keyboard select saved for minor loop, engine r/min), speed-interrupt service (distance information maintenance for RAM, vehicle-speed information maintenance for RAM); initialization (displays and telltales, setup computer control registers, update trip parameters for "ignition off" time); nonmaskable interrupt service (display blanking, RAM disabling during power down). *(©1978 IEEE)*

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address bus provides addressing capability of up to 65,536 word locations. The ROMs hold the instruction op code and the control program data. The RAMs provide software registers, software accumulators, and a stack area for the control program.

The trip computer contains self-diagnostics. When a light-emitting diode on the outside of the computer case is lit, it indicates certain failures. For example, if after sampling the critical +9 V of the A/D chip multiplexer channel, a failure is noted, it is flagged and saved in the RAM for servicing by the minor loop, Fig. 21.4, and then activates the LED on the computer case by way of the discrete I/O.

21.2.2 Ford's Second Generation Tripminder

Ford Motor Company's 1982 Tripminder was a second-generation vehicle trip computer. It performs computations on five input variables to generate the functions available to the driver. It was available in three versions—high, mid, and low series—for use in the Continental, Ford of Europe Granada, and Ford/Mercury Thunderbird/XR-7, respectively.

A block diagram of the Tripminder hardware is shown in Fig. 21.5*a* and software architecture in Fig. 21.5*b*.[4] The 8050 microprocessor could support 4K of internal ROM and 256 bytes of keep-alive RAM used for trip-log functions.

Computations are performed on five input variables. One of them, time, is produced by a precision crystal oscillator internal to the Tripminder. The others are sensed from the vehicle environment. The European and high-series versions have a distance-to-empty feature requiring a fuel-tank-level input. Driving range available is based on the amount of fuel left in the tank and the historical fuel economy of the car.

Fuel flow information is acceptable in two forms. In carbureted engines, fuel flow data is provided by a fuel flow sensor installed in the fuel line just ahead of the carburetor. The sensor's output of 48,000 pulses per gallon is recorded in an 8-bit event counter in the interface integrated circuit. In fuel injected engines, a buffered form of the fuel injector signal is sent to the event counter to determine the number of fuel injector firings that occurred during a sample period. The signal is also sent to an interval counter to determine the total on time of the fuel injector.

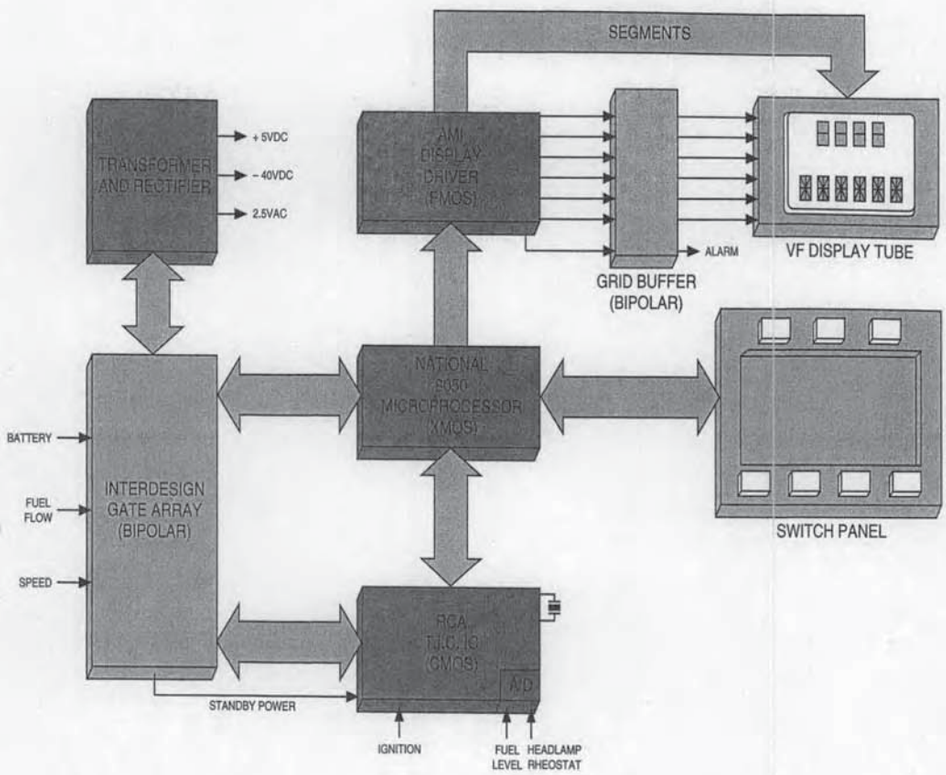
Speed information comes from either an electronic speedometer or from a variable reluctance speed sensor installed in line with the speedometer cable. The data consists of 8000 pulses per mile and is recorded in an event counter.

The TIC integrated circuit performs fundamental system control and timekeeping operations as well as the data conversion functions for the sensor inputs. It is a CMOS device that must be continuously powered. At midnight, when the time clock registers roll over, the TIC circuit automatically starts up the microprocessor to update the software calendars. The TIC circuit also continuously monitors the accessory input signal and the clock keyboard button. Sequencing on and off of the power supplies is controlled by the TIC circuit to make certain that the microprocessor is initialized correctly and that the keep-alive memory in RAM is not accidentally written into during power supply transients.

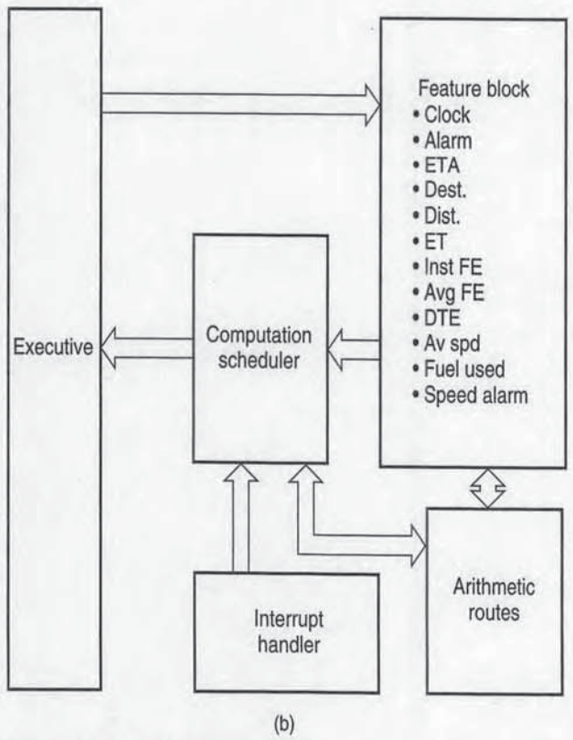
21.3 CONCLUSION

Trip computers vary from relatively simple versions to complex designs that give the driver a wealth of information. Some trip computers also provide a means for on-board diagnostics (see Chap. 22). What a trip computer can do depends on how many sensor inputs are fed to it. But the bottom line, as with any automotive component, is cost tied in with perceived value to the customer.

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(a)



(b)

FIGURE 21.5 (*a*) Hardware architecture and (*b*) software architecture for Ford Motor Company's second generation Tripminder. *(Reprinted with permission from SAE Technical Paper 820107 ©1982 Society of Automotive Engineers, Inc.)*

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CHAPTER 22
ON- AND OFF-BOARD DIAGNOSTICS

Wolfgang Bremer, Frieder Heintz, and Robert Hugel
Robert Bosch GmbH

22.1 WHY DIAGNOSTICS?

The desire for greater safety, driving comfort, and environmental compatibility is leading to a rapid increase in electronic control units and sensors in upper class, medium-sized, and compact vehicles. Additional functions and their corresponding equipment in today's cars create a bewildering tangle of cables and confusing functional connections. As a result, it has become more and more difficult to diagnose faults in such systems and to resolve them within a reasonable period.

22.1.1 Diagnostics in the Past and Today

On-board diagnosis has been limited thus far to a few error displays and fault storage achieved by relatively simple means. It has been left more or less to each manufacturer to decide to what extent diagnosis would be carried out. Diagnosis always means the working together of man and machine and consists essentially of three major components: registration of the actual condition, knowledge of the vehicle and its nominal condition, and strategy—how to find the smallest exchangeable deficient component by means of combining and comparing both the nominal and actual conditions.

All three points are inseparably connected. Only the means to the end have changed over time. The oldest and simplest method of diagnosis is that done with the help of our sense organs, but the limits of this kind of diagnosis are obvious. In fact, the objective in the development of diagnostic techniques is the extension of human abilities with the aid of diagnostic tools in order to be able to measure more precisely and more directly, to compare more objectively, and to draw definite conclusions.

The development of control techniques was essentially determined by the following items: the development of automotive engineering; the structure of workshops—that is, essentially the relation between the costs of labor and materials; and the development of electronics and data processing.

For a long time, motor diagnosis was limited to ignition control and timing. In the 1960s, new exhaust-gas measuring instruments for fuel injection adjustment were developed, but the mechanic still had to make the diagnosis. In the 1980s, the introduction of electronics in the vehicle was followed by a new generation of measuring instruments in the workshops. Not

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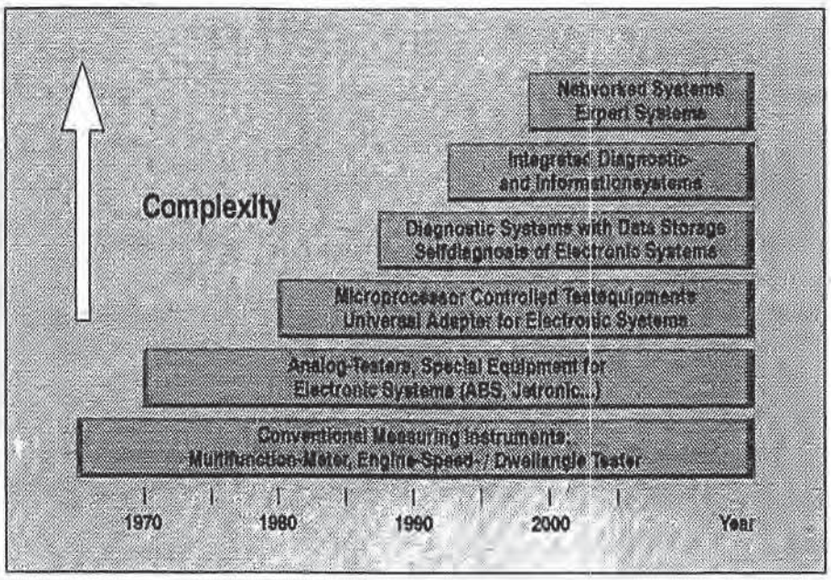


FIGURE 22.1 Evolution of diagnostic test equipment.

only were separate measurements combined with comprehensive test procedures, but also the information about the nominal condition of the vehicle was stored in a data memory.[1] A view of the development is shown in Fig. 22.1.

As more and more electronic systems were added to cars, the more difficult it became to determine the actual condition in case of a defect. Soon a multitude of connecting cables and adapters were required to reach the necessary measuring points. Moreover there was an increasing amount of information needed to make an effective diagnosis. In the majority of workshops, diagnosis is carried out as shown in Fig. 22.2. The most important test points of

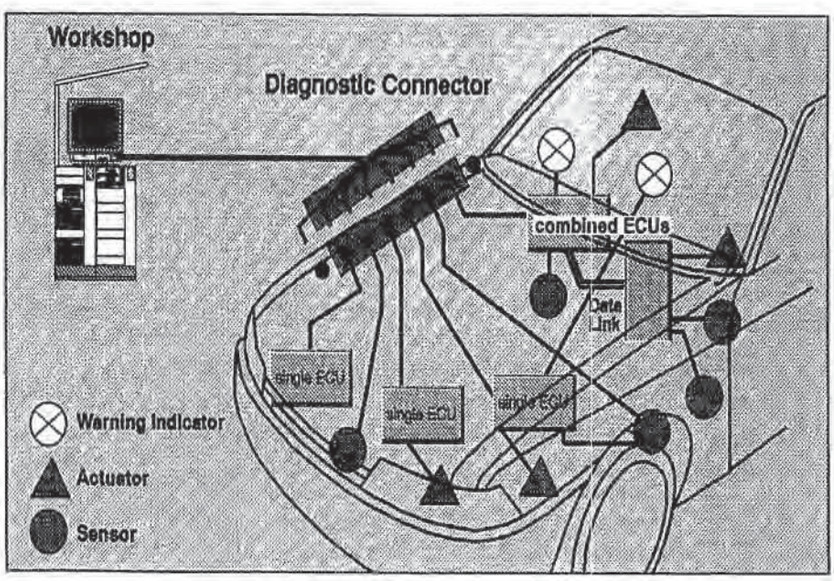


FIGURE 22.2 Present-day diagnostic connector installation in a vehicle.

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control units and sensors are tied to a diagnostic connector which is plugged into the measuring instrument with a corresponding adapter for the respective vehicle. Because of the permanently increasing amount of electronic functions, it is necessary to develop connectors with more and more contacts. It is evident that this method soon will become too unwieldy.

Modern electronics in vehicles support diagnosis by comparing the registered actual values with the internally stored nominal values with the help of control units and their self-diagnosis, thus detecting faults. By interconnecting the measuring instruments, a detailed survey of the entire condition of the vehicle is available and an intelligent on-board diagnostic system is able to carry out a more precise and more definite localization of the defect.[2] With the help of an interconnection and standardization of the interface leading to the external tester, the many different complex and expensive adapters have become superfluous. Modern diagnosis will look like what is shown in Fig. 22.3.

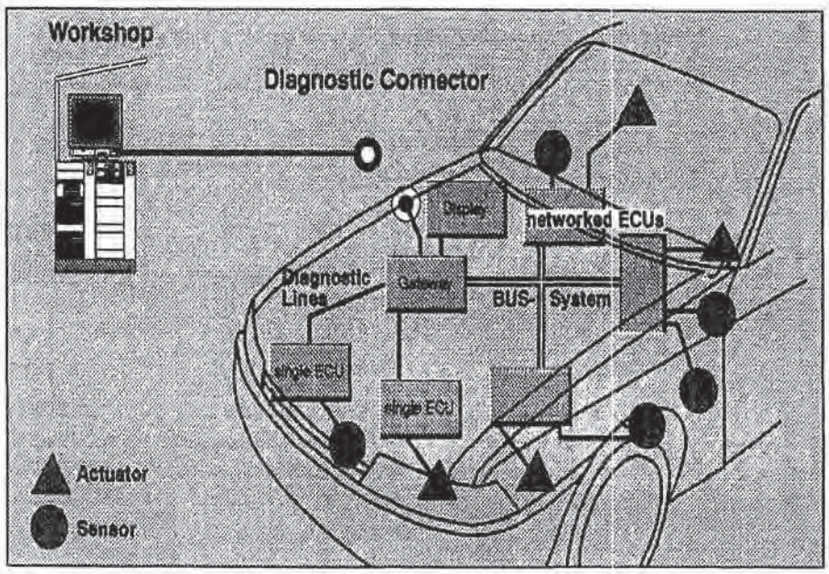


FIGURE 22.3 Future diagnostic connector installation in a vehicle.

Instead of a multiplicity of adapters there is only a single standardized interface, provided by the diagnostic processor. By means of interconnection, the diagnostic processor is provided with all available data and the condition of the vehicle is known. With the help of the diagnostic processor, the external measuring instrument has access to the measuring and diagnostic values of the sensors and is able to directly reach the actuator for measuring purposes.[3]

Such a diagnosis also demands a certain change in the functional structure of a vehicle. Corresponding hierarchical models have already been presented.[4]

22.1.2 Reasons for Diagnostics in Vehicles

Which are the most important reasons for diagnostics as demanded and desired in today's vehicles?

Existing Diagnostic Problems. A number of diagnostic problems must be resolved:

- Early diagnostic information was related only to single components and control units. In case of a defective comprehensive system, every unit, component, sensor, and connecting

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cable of the system had to be tested and controlled. This was a very time consuming and expensive process.

- Because of the single component and control unit checks, it was impossible to analyze all the additional data correlated with a particular defect.
- In the case of a defect in single sensors or units, the car was often inoperable. Taking into consideration all available information about the vehicle, it is possible to use alternative parameters and procedures in order to achieve at least a so-called limp-home function and sometimes continue the use of the vehicle under only slightly limited operating conditions.
- Usually there was only a global error display with an often ambiguous warning light available for the driver. Drivers desire more detailed information and especially guidelines for what procedures should be followed.
- The multitude of adapter cables, plugs, diagnostic equipment, and communication interfaces in a workshop has become so complex that the effectiveness decreased dramatically, with the repair costs increasing disproportionally.

New Legal Proposals. Worldwide new legal proposals and governmental regulations [e.g., California Air Resources Board (CARB), On Board Diagnostics II (OBDII), Environmental Protection Agency (EPA)] are forcing manufacturers and subcontractors to seek more profitable, effective, and convincing diagnosis of vehicles.

Serial Data Networks. New serial data networks for the connection of control units and vehicle body components, installed in the vehicle, offer the possibility of absolutely new optimum approaches and even anticipate maintenance and diagnosis up to the introduction of autodidactic data processing systems and external data bases.[5,6,7,8]

International Initiatives for Standardization. Initiated by legislative and governmental demands for better diagnostics in the area of emission control, initiatives for standardization in the entire diagnostic field in vehicles were launched during recent years to achieve worldwide standardization of tools, interfaces, connectors, and protocols.

22.1.3 Diagnostic Tasks in Vehicles

In order to minimize the number of defects or even to completely avoid them, a vehicle requires regular checks. In case of an inevitable defect, a clear and directed diagnosis is required and has to be followed by a prompt, reliable, and inexpensive repair. Therefore appropriate diagnostic systems are being developed considering the following targets: simplification of maintenance, fault indication in time, guidelines for the driver in case of a defect, and safer and faster repairs with the help of a specific fault indication.

In addition to technical considerations, environmental aspects are now being taken into consideration as reflected in the diagnostic concepts. In the future, only perfect systems will be accepted, in order to keep environmental pollution to a minimum. It is understandable, therefore, that legislators insist on increased monitoring standards, particularly for exhaust-related components.

As an example of the new monitoring standards, consider the requirements of CARB and EPA in the United States and the resulting consequences for diagnosis. At the moment, the extent of such a detailed monitoring has to be a compromise between the different requirements and the possible technical and economical solutions, but the environmental aspects will gain more and more importance. The increased amount of available data will certainly permit a considerably higher rate of in-depth fault localization and will also allow clear fault identification without interactive outside intervention. Having knowledge of the functional interrelationships and access to all essential data, a picture of the defect can be created with the help of individual pieces of information. The driver and the workshop can

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then be provided with appropriate instructions. In this context, on-board expert systems are being considered.

For an effective and successful diagnosis today and in the future the following tasks and targets can be defined.

Fault Storage with Boundary Conditions. A very important aspect of modern diagnosis is the clear and reliable analysis of the respective fault. During the self-diagnosis, it is absolutely necessary to store not only the respective fault information but also all relevant marginal parameters in the control unit, e.g., ambient temperature, velocity, engine speed, engine knock, and so on. The additional data can be stored when a defect occurs as well as during specified intervals around the moment of a defect. Such additional data is called "freeze frame" data.[9]

Fault Localization. Mechanics must be able to locate a defective control unit quickly and then determine which component of that control unit is at fault so that it can be replaced.

Data Correlation, Recognition of Imminent Faults. A large amount of data useful for the analysis of a vehicle is now available and even more will be available in the future. These data will have to be evaluated and compared with the help of modern data processing techniques, including fuzzy logic, neural networks, autodidactic systems, and expert systems. These techniques will not only enable the diagnosis of the actual condition of the vehicle but will also determine future maintenance needs. As a result, the reliability and availability of a vehicle will be increased and the possible consequences of a defect kept to a minimum. The driver can also be forewarned about imminent problems and can then take appropriate steps before starting on a trip.

Parameter Substitution. The breakdown of a sensor in modern diagnostic procedures is not necessarily followed by a lack of the respective information. After having diagnosed a fault, the diagnostic computer—with the aid of the available information—is often able to compute an auxiliary parameter to replace the original one. As a result, either a limp-home condition is possible or else the nominal function can be assured but under slightly limited conditions. Simple examples for such a calculated parameter are vehicle speed (considering the gear and the synchronous speed, or the antilock braking information, or the data of the navigation system), motor temperature (considering the outside temperature and the operating time), and the amount of remaining fuel (considering the last actual fuel content and the calculated consumption).

Providing Guidelines. As mentioned earlier, a diagnostic system has to provide clear information to the driver in case of a defect. A global warning indication is not sufficient. The driver needs to learn the extent of the defect and its consequences by appropriate text, graphics, or synthetic voice. In addition, the driver needs to be told the steps that have to be taken (e.g., "refill cooling water," "minimum speed to the next service station, risk of engine breakdown," "stop, brake system out of order").[10]

The diagnostic monitoring system can also be used, if there is no service station nearby, as a substitutional off-board system. The defect is then localized by an interactive working together of the indicating system and an appropriate input medium.

External Diagnostic Access. For off-board diagnosis, the diagnostic system of the vehicle has to provide a standardized access to all relevant components, control units, and stored information. This standardized access might also be used by the vehicle manufacturer, legisla-

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tor, application engineer, and the end-of-the-line programmer. The access itself has to be controlled with the help of an appropriate mechanism to prevent possible abuse.[11]

Logbook Function. The control unit or the diagnostic computer of the vehicle is supposed to store every repair that has been carried out in the format of a logbook. It should contain the time and name of the workshop, every exchanged and newly installed element, every inspection carried out, and so forth.

22.2 ON-BOARD DIAGNOSTICS

The more complex automobiles became, the greater the number of electronic systems and the more difficult became the registration of the actual condition in case of a defect. To reach the necessary measuring points, many connecting cables and adapters were required. In addition, much data about the different systems and their working together was needed to allow a system-specific diagnosis. Modern electronics with self-diagnosis supports the service mechanic by registrating the actual values, comparing them with the nominal values, and diagnosing faults that are stored for repair purposes. Actually, the internal functions are checked whenever an ECU is turned on.

First, the checksum of the program memory is checked together with its function and the correct version. Then a read and write test of the RAM cells is performed. Special peripheral elements (e.g., AD converters) are also checked within this test cycle. During the entire operating time of the vehicle, the ECUs are constantly supervising the sensors they are connected to. With the help of an adequate interpretation of the hardware, controllers are able to determine whether a sensor has a short circuit to ground or battery voltage, or if a cable to the sensor is interrupted. By comparing the measured values and the stored technical data, a controller is able to determine whether the measured values exceed the limits, drift away, or are still within the tolerable limits. The combination of information provided by other sensors allows the monitoring for plausibleness of the measured values.

Sensors are tested similarly to the way actuators are monitored for short circuits or interruptions of cables. The check is carried out by measuring the electric current or reading the diagnostic output of intelligent driver circuits. The function of an actuator under certain conditions can be tested by powering the actuator and observing the corresponding reaction of the system. If discrepancies to the nominal values are diagnosed, the information is stored in an internal fault memory together with relevant outside parameters, e.g., the motor temperature or the engine speed. Thus, defects that appear once or under certain conditions can be diagnosed. If a fault occurs only once during several journeys, it is deleted. The fault memory can be read later in the workshop and provides valuable information for the mechanic.

In case of a detected defective sensor, the measured values are replaced by nominal values or an alternative value is formed using the information of other sensors to provide at least a limp-home function.

With the help of an appropriate interface, a tester can communicate with the ECUs, read the fault memory and the measured values, and send signals to the actuators. In order to be able to use self-diagnosis as universally as possible, manufacturers aim at the standardization of the interface and the determination of appropriate protocols for data exchange.

Another task of self-diagnosis is the indication of a defect to the driver. Faults are mostly indicated by one or more warning lights on the dashboard. Modern developments aim at more comprehensive information using displays for text and graphics, which provide priority-controlled information for the driver. Legal regulations concerning exhaust-gas gave rise to an essential extension of self diagnosis. The control units have to be able to control all exhaust-relevant functions and components and to clearly indicate a defective function or the exceeding of the permissible exhaust limits. Some of the demanded functions require an enor-

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mous amount of additional instructions; therefore, the extent of self-diagnosis already reaches up to 40 percent of the entire software of the control unit.

22.3 OFF-BOARD DIAGNOSTICS

The continual increase in the use of electronics within the broad range of different vehicles represents one of the major challenges for customer service and workshop operations. Modern diagnosis and information systems must cope with this challenge and manufacturers of test equipments must provide instruments that are flexible and easy to handle. Quick and reliable fault diagnosis in modern vehicles requires extensive technical knowledge, detailed vehicle information, and up-to-date testing systems.

Due to the different demands of the service providers, there are many different test equipments on the market. They can be subdivided into two main categories: handheld or portable instruments and stationary equipments. Handheld instruments are commonly used for the control of engine functions like ignition or fuel injection and the request of error codes of the electronic control units (ECUs). Stationary test equipment, on the other hand, covers the whole range of function and performance checks of the engine, gear, brakes, chassis, and exhaust monitoring.

Most of the common testers are used for the diagnosis of the engine. The Bosch MOT 250, for example, offers the following functions:

- Engine speed by means of the top dead center (TDC) transmitter, cylinder 1 or terminal 1 signal
- Ignition timing with TDC sensor or stroboscope
- Dwell angle in percent, degrees, or dwell time
- On/off-ratio in percent
- Injection timing or other times measured at the valve or other suitable measuring points
- Electric cylinder balance in absolute or relative terms
- Voltage to ground or floating potential including lambda-sensor voltages or dynamic voltage at terminal 1
- Current with two test adapters for maximum 20 A and 600 A
- Resistances from milliohms to megohms
- Temperature with oil-temperature sensor

For most variables, a maximum of four blocks of measured variables can be stored and recalled one after the other. Twelve blocks can be stored for the cylinder balance function. A digital storage oscilloscope records and stores up to 32 oscillograms of ignition voltages, alternator ripple, and current or voltage transients in the electric or electronic systems. Two RS232 interfaces are provided for documentation purposes and data exchange.

For repair, service, and maintenance, many different manuals and microfiches are stored in the workshops. It is a time-consuming task to collect all the necessary information, especially when vehicles of different makes have to be repaired. To avoid unnecessary paper, information and communication systems among workshop, dealer, and manufacturer are built up. The corresponding manuals have to be standardized and distributed on electronic data processing media, preferably on CD-ROMs.

Every garage or workshop, equipped with the appropriate data system (basically a tester connected to a PC), will receive servicing aids and updates via telephone line or by periodic receipt of updated CDs. A committee of the SAE is preparing rules for the standardization of manuals. There are already published draft international standards (DIS) for terms and

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definitions (J1930) used in the manuals, for diagnostic codes/messages (J2012), or electronic access/service information (J2008) (see the following). Most of the available test equipment is capable of storing operator manuals within its memory and offers menu-guided assistance to the service personnel. Automatic vehicle and component identification by the tester and the availability of corresponding data at the workbench eases troubleshooting and repairs.

22.4 LEGISLATION AND STANDARDIZATION

22.4.1 CARB, EPA, OBD II

The following is an abstract of the California Air Resource Board (CARB) Regulations for On-Board-Diagnosis two(OBDII):

> All 1994 and subsequent model-year passenger cars, light-duty trucks, and medium-duty vehicles shall be equipped with a malfunction indicator light (MIL) located on the instrument panel that will automatically inform the vehicle operator in the event of a malfunction of any power train component which can affect emission and which provide input to, or receive output from, the on-board computer(s) or of the malfunction of the on-board computer(s) itself. The MIL shall not be used for any other purpose.
>
> . . . .
>
> All 1994 and subsequent model-year passenger cars, light-duty trucks, and medium-duty vehicles required to have MIL pursuant to paragraph above shall also be equipped with an on-board diagnostic system capable of identifying the likely area of the malfunction by means of fault codes stored in the computer memory. These vehicles shall be equipped with a standardized electrical connector to provide access to the stored fault codes . . . Starting with model-year 1995, manufacturers of non-complying systems shall be subject to fines pursuant to section 43016 of the California Health and Safety Code for each deficiency identified, after the second, in a vehicle model. For the third deficiency and every deficiency thereafter identified in a vehicle model, the fines shall be in the amount of $50 per deficiency per vehicle for non-compliance with any of the monitoring requirements . . .

Systems to Be Monitored

OBD II Functions. These include catalyst monitoring, misfire monitoring, evaporative system monitoring, secondary air system monitoring, fuel systems monitoring, oxygen sensor monitoring, exhaust-gas-recirculation (EGR) system monitoring, and comprehensive component monitoring.

Catalyst. Legal requirements (CARB excerpt): "The diagnostic system shall individually monitor the front catalyst or catalysts which receive untreated engine out exhaust-gas for malfunction. A catalyst is regarded as malfunctioning when the average hydrocarbon conversion efficiency falls between 50 and 60 percent."

Technical solution: In addition to the oxygen sensor upstream the catalyst, another sensor is mounted downstream.

A properly working catalyst shows a storage effect so that the oscillation of the lambda-controller appears damped at the downstream lambda probe. A worn-out catalyst has a reduced damping effect and the signals of up- and downstream sensors are equivalent.

The ratio of the signal amplitudes is a measure of the conversion efficiency. The electronic system that controls the fuel injection monitors these signals together with other relevant engine conditions to derive the catalyst efficiency.

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Misfire Detection. Legal requirements (CARB excerpt): "To avoid catalyst damage, the diagnostic system shall monitor engine misfire and identify the specific cylinder experiencing misfire."

Technical solution: Misfire can be caused by worn-out spark plugs or defective electrical wiring. Unburned fuel reaches the catalyst and may destroy it by overheating. Even the least amount of misfire rates influences the emission and therefore single misfire events must be detected.

The speed of the engine is measured very precisely. In case of misfire, the momentum, which is normally produced by the combustion, is lacking. Thus abnormal variations of speed-changes at steady state conditions may be considered as misfire. To distinguish clearly between misfire and other malfunctions, complicated calculations have to be carried out.

If a certain percentage of misfires within 200 or 1000 revolutions is detected, a fault code is stored in the control unit and the fault is indicated to the driver.

Oxygen Sensor. Legal requirements (CARB excerpt): "The diagnostic system shall monitor the output voltage, the response rate, and any other parameter which can affect emission and all fuel control oxygen sensors for malfunction."

Technical solution: The control unit has a special input circuit for detecting shorts or breaks and monitors the switching frequency of the control loop.

By means of a second lambda probe behind the catalyst, it is possible to monitor the lambda probe in front of the catalyst for its correct position. A lambda probe which is subject to an increased temperature for extensive periods may react slower on variations of the air/fuel mixture, thus increasing the period of the lambda-probe regulation. The diagnostic system of the control unit controls the regular frequency and indicates slow sensors to the driver by means of a warning light.

Heated sensors are monitored for correct heater current and voltage by hardware means within the control unit.

Evaporative System. Legal requirements (CARB excerpt): "The diagnostic system shall control the air flow of the complete evaporative system. In addition, the diagnostic system shall also monitor the complete evaporative system for the emission of HC vapor into the atmosphere by performing a pressure or vacuum check of the complete evaporative system. From time to time, manufacturers may occasionally turn off the evaporative purge system in order to carry out a check."

Technical solution: At idle position, the canister purge valve is activated and the lambda controller is monitored for its reaction. For leak detection of the evaporative system, the output to the active carbon filter is shut off and the canister pressure is decreased to about –1.5 kPa. Then the complete system is turned off and the pressure within the canister is monitored for variation with time. The pressure gradient, together with other parameters like the amount of fuel, may indicate possible leaks.

Secondary Air System. Legal requirements: "Any vehicle equipped with any form of a secondary air delivery system shall have the diagnostic system monitor the proper functioning of the secondary air delivery system and any air switching valve."

Technical solution: The lambda controller is monitored for correlated deviations when the secondary air flow is changed.

Fuel System. Legal requirements: "The diagnostic system shall monitor the fuel delivery system for its ability to provide compliance with emission standards."

Deviations of the stochiometric ratio which last for a longer time are stored within the adaptive mixture controller. If these values exceed defined limits, components of the fuel system obviously do not correspond to the specification.

Exhaust-Gas Recirculation (EGR) System. Legal requirement: "The diagnostic system shall monitor the EGR system on vehicles for low and high flow rate malfunctions."

Technical solution: (1) At overrun, the fuel is cut off and the EGR valve is completely opened. The flow of exhaust gas to the manifold raises the manifold pressure, which is recorded and allows statements about the function of the EGR valve. (2) Another possibility is to control the increase of the manifold intake temperature when the EGR valve is opened.

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In a conclusion to the previously described OBD II requirements and technical solutions, we can define the following four quality demands for electronic control units:

- Guarantee for exhaust-gas-relevant components with repair costs >$300 for seven years or 70,000 miles for all 1990 and subsequent model-year vehicles (CARB).
- Guarantee for exhaust-gas-relevant components with repair costs >$200 for eight years or 80,000 miles for all 1994 and subsequent model-year vehicles (EPA/Clean Air Act).
- Guarantee protocols in case of a reclamation rate of exhaust-gas-relevant components higher than 1 percent (CARB).
- Recall of vehicles in case of a calculated reclamation rate of more than 20,000 ppm within a period of five years/50,000 miles (CARB).

22.4.2 International Standardizations

Because of the manifold requirements on modern diagnostics, the national and international standardization committees soon came to the conclusion that with the help of appropriate and, if possible, international agreements about protocols, connectors, tools and auxiliaries, the process of diagnosis can be standardized, thus reducing time and costs.

Figure 22.4 shows how, in a standardized graphic, control units and diagnostic tools are connected and diagnostic data exchanged.

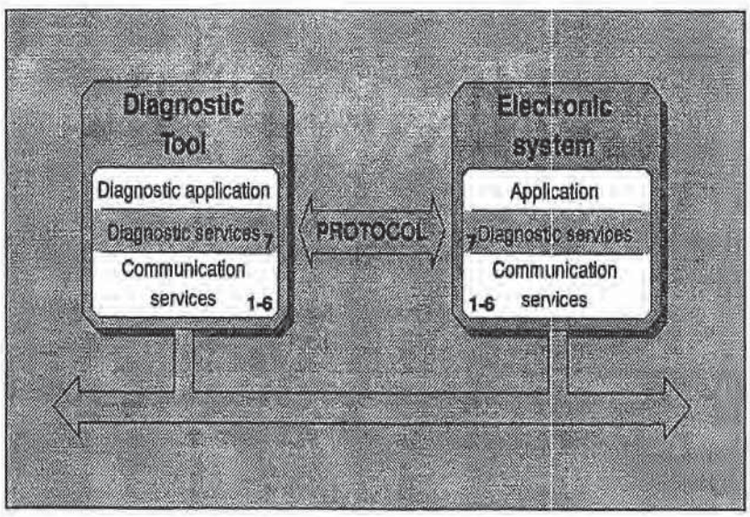


FIGURE 22.4 Standardized testing link according to the OSI model.

For data exchange, electronic systems are structured and described according to a seven-layer model (OSI model, open system interconnection) developed by the ISO (International Standardization Organization). Every unit connected to a data network can be structured with the help of this model—control units as well as diagnostic tools.

The diagnostic services that the controller may use during the diagnostic process are regulated in the seventh layer. Diagnostic service means definite instructions, which actuate determined and standardized diagnostic procedures, e.g. "start diagnostic session," "read diagnostic trouble codes," "read freeze frame data," and so on. There are different sequences of bits and bytes code for such instructions. On the hardware level (plugs, cables, potentials), the sequences are finally transmitted from unit to unit. The ISO and the SAE (Society of Automotive Engineers) developed corresponding standards in the area of service definition

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TABLE 22.1 ISO Diagnostic Services

Diagnostic management
StartDiagnosticSession
StopDiagnosticSession
SecurityAccess
TesterPresent
EcuReset
ReadEcuIdentification
DisableNormalMessageTransmission
EnableNormalMessageTransmission
Data transmission
ReadDataByLocalIdentifier
ReadDataByGlobalIdentifier
ReadMemoryByAddress
WriteDataByLocalIdentifier
WriteDataByGlobalIdentifier
WriteMemoryByAddress
SetDataRates
StopRepeatedDataTransmission
Input/output control
InputOutputControlByGlobalIdentifier
InputOutputControlByLocalIdentifier
Stored data transmission
ReadNumberOfDiagnosticTroubleCodes
ReadDiagnosticTroubleCode
ReadDiagnosticTroubleCodesByStatus
ReadStatusOfDiagnosticTroubleCodes
ReadFreezeFrameData
ClearDiagnosticInformation
Remote activation of routine
StartRoutineByLocalIdentifier
StartRoutineByAddress
StopRoutineByLocalIdentifier
StopRoutineByAddress
RequestRoutineResultsByLocalIdentifier
RequestRoutineResultsByAddress
Upload download
RequestDownload
RequestUpload
TransferData
RequestTransferExit

as well as in the area of communication. Table 22.1 shows the diagnostic services as proposed by the ISO.

Figure 22.5 presents the determined standards with some essential technical details as developed for the field of communication.

Unfortunately the whole spectrum of available standards has become very complex and difficult to use. The following explanations try to provide a unified system for the existing standards in the area of diagnosis.

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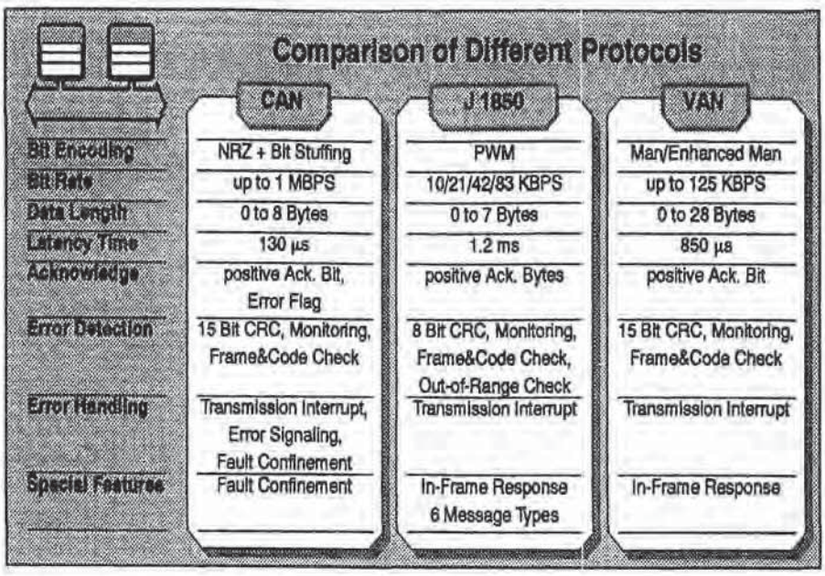


FIGURE 22.5 In-vehicle networks.

Figure 22.6 shows a general model for diagnostic concepts. The three main levels comprehensively describe the whole area of diagnostics. The three levels are hierarchically structured, closely linked together with flowing transition from one level to the other. Although there are certain similarities between this model and the seven-layer model of the OSI, both models do not correlate.

The upper level comprises the elements, which are essential for the user or generator of diagnostic applications. The term "user" includes the driver, the legislator, the mechanic, and the manufacturer. This upper level can be subdivided into three main fields of activities: user

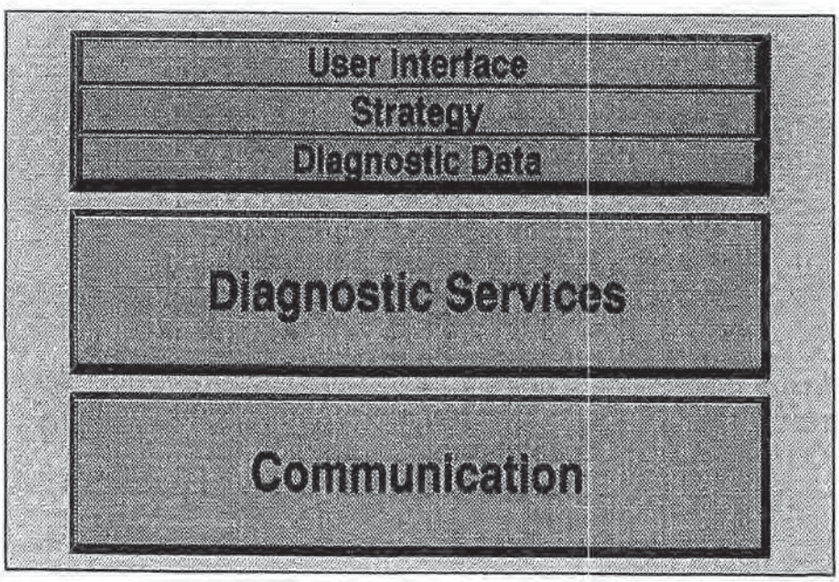


FIGURE 22.6 Model for diagnostic concept.

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interface, strategy, and diagnostic data. Although presented as layers, these activities do not correlate hierarchically, but each is associated with a service or group of services.

The "user interface" describes how information flows between the user and the diagnostic service. This includes a functional description of scan tools, handheld testers, monitoring systems, and so on.

The term "strategies" stands for strategic details, which are essential for the diagnosis or repair of a vehicle, including communication access, diagnostic data and information.

The term "diagnostic data" includes the data that are necessary for the diagnosis itself. The details concerning parameters, trouble codes, and so on are described here.

The intermediate level describes the diagnostic services, defining a set of services and a set of commands for general purpose, which allow the diagnosis of a vehicle. The set of commands is supposed to cover the needs of users concerning repair and maintenance as described by the strategies and diagnostic data.

The lowest level deals with the communication area. It describes every technical detail that is necessary for communication and provides the information about how to start communication (initialization). It also specifies the appropriate Baud rate, the suitable protocol, and the necessary hardware (connector, cable, and so on).

This model offers a general description of the essential fields of diagnostic interest and allows the categorization of all ISO and SAE standardization activities in the three main levels of the diagnostic concept model.

Figures 22.7 and 22.8 are presented in the same graphic form (three-level structure). They provide a summary of the concrete standardization activities of the SAE and ISO. Figure 22.7 shows the existing standards or drafts of automotive diagnosis for general purpose.

The user interface for general purposes is undefined. The SAE J2186 (Data Link Security) and the SAE J2008 (Electronic Access/Service Information) are strategic documents, though most strategies are not standardized and diagnostic data is described in documents SAE J2012 (Diagnostic Codes and Messages) and SAE J2190-2 (Parameters—in preparation).

On the level of diagnostic services, the standardization activities can be divided in two fields called service definition and service implementation. The term "service definition" describes a set of useful diagnostic services, which enable the user to run a diagnostic session



FIGURE 22.7 Realization for general automotive diagnosis.

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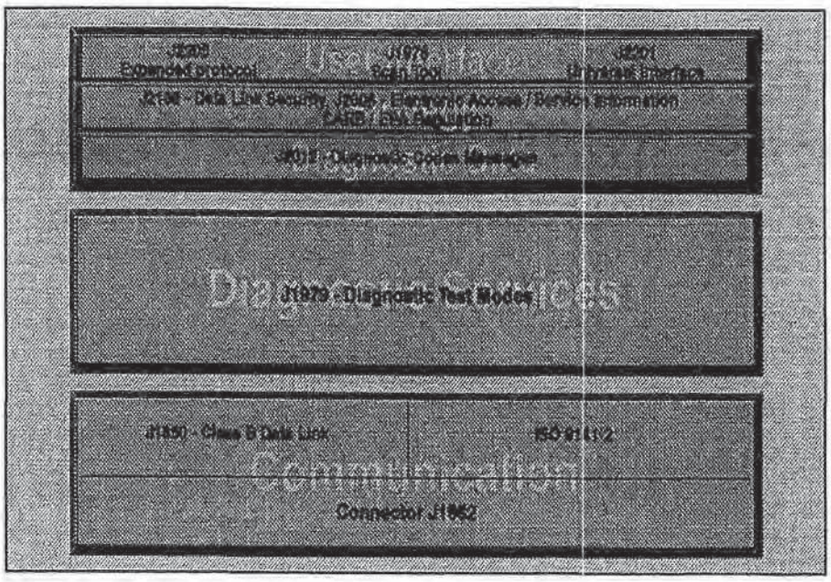


FIGURE 22.8 Realization for CARB and EPA requirements.

independently of the knowledge of any technical detail in the communication area as described in the level below.

This set of diagnostic services for general purpose can now be mapped on different protocols. Any bit representation of the different services can be built up. This is called service implementation. At the moment, there are two implementations available, the SAE J2190 (Diagnostic Test Modes) and the KWP 2000 (ISO Draft: Keyword Protocol 2000). The lowest level (the Communication level) shows the standardized details of communication such as the data formats and the physical layers; e.g., the KWP 2000 uses the physical layer of ISO 9141 or ISO 9141-2, the SAE J2190 uses the SAE J1850 Class B network (ISO/DIS 11519-3). It is shown that communication can also be built up with a CAN or a VAN network.

Figure 22.8 shows the standardization activities for the special requirements of the CARB and the EPA using the same three-level-concept.

The user interface, a generic scan tool, is standardized within the SAE J1978, including the SAE J2205 (Expanded Diagnostic Protocol) and the SAE J2201 (Universal Interface). Some aspects of the diagnostic strategy are described in the SAE J2186 (Data Link Security), the SAE J2008 (Electronic Access/Service Information), and some in the regulations. The diagnostic data is described in the document SAE J2012—Diagnostic Codes and Messages.

The level of diagnostic services defines one SAE J1979 standard—Diagnostic Test Modes. This standard is a closely linked combination of a service definition and a service implementation (referring to the SAE as "modes").

In the field of communication, the possible networks are described in the SAE J1850 (Class B Data Network) and the ISO 9141-2 (CARB Requirements for Interchange of Digital Information).

A standard for the physical connector (SAE J1962) has also been developed. Figure 22.9 shows the status of diagnostic standards for trucks and buses and for passenger cars in Europe and in the United States. It shows also a time schedule for the development of standards. A comparison of the communication and diagnostic services levels has already been realized. The titles of the different SAE and ISO numbers are shown in Tables 22.2 and 22.3, where all ISO and SAE papers, relevant for diagnostics, are listed. Table 22.3 offers a detailed list of trucks and bus activities (J1939).

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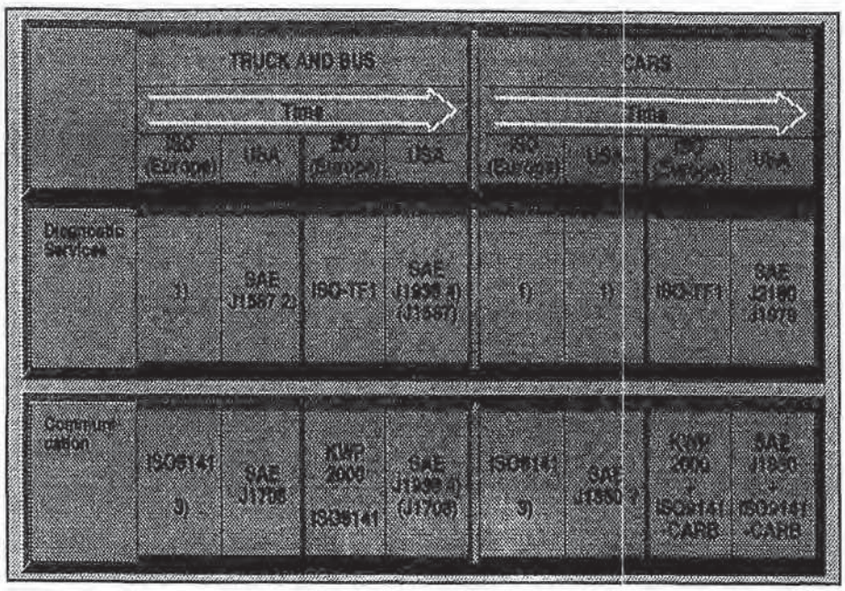


FIGURE 22.9 Status of diagnostic standards.

22.5 FUTURE DIAGNOSTIC CONCEPTS

As yet, most vehicle manufacturers have installed a diagnostic connector in the engine compartment in order to offer essential electric signals for diagnostic purposes. Due to the multitude of different equipments and philosophies of car makers, the connectors have different shapes and contact arrangements. Therefore, a workshop has to keep a lot of different expensive cables and adaptors in store.

For future diagnostic systems, the connection between control unit and vehicle is supposed to be realized with the help of a standardized connector. A connector for the legally demanded exhaust-gas diagnosis was defined by an SAE draft (J1962), concerning form, contact arrangement, and installation position. (Fig. 22.10)

With this connector and a so-called generic scan tool, anyone is able to read the fault-memory in regard to exhaust-gas-relevant defects. The interconnection of the control units allows the access to the entire electronics of the vehicle.

The necessary protocols are partly defined and developed further in standardization committees of the ISO. At the moment, there are two actual standards available:

1. *ISO 9141-2:* Determination of the requirements on hardware and communication protocols. The requirements on hardware are essentially determined by the maximum Baud rate of data transfer and the maximum number of control units simultaneously connected with the diagnostic cable.

   Communication is started by means of a trigger address, and is followed by a synchronization byte of the control unit(s), which is necessary for the automatic setting of the Baud rate. The trigger address calls either a particular control unit or a function, that may also address several control units.

   After transmission of the synchronization byte, the control unit waits for the tester to set the Baud rate, then sends two key-bytes that inform the tester about the suitable data transfer protocol. The tester responds with the last inverted key-byte, in order to confirm the correct receipt. The connection between tester and control unit is now established.

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TABLE 22.2 ISO and SAE Documents

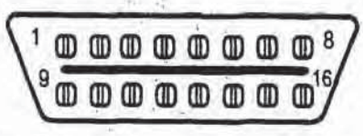
ISO 9141		Road Vehicles—Diagnostic System—Requirements for Interchange of Digital Information
ISO/DIS 9141-2		Road Vehicles—Diagnostic System—Part 2: CARB Requirements for Interchange of Digital Information
ISO/DIS 11519-1		Road Vehicles—Low-Speed Serial Data Communication—Part 1: General Definitions
ISO/DIS 11519-2		Road Vehicles—Low-Speed Serial Data Communication—Part 2: Low Speed Controller Area Network (CAN)
ISO/DIS 11519-3		Road Vehicles—Low-Speed Serial Data Communication—Part 3: Vehicle Area Network (VAN)
ISO/DIS 11519-4		Road Vehicles—Low-Speed Serial Data Communication—Part 4: Class B Data Communication Network Interface (J1850)
ISO/DIS 11898		Road Vehicles—Interchange of Digital Information—Controller Area Network (CAN) for High-Speed Communication
ISO/WD 14229		Diagnostic Systems—Diagnostic Services Specification
ISO/WD 14230		Diagnostic Systems—Keyword Protocol 2000 (3 parts: 1: Physical Layer, 2: Data Link Layer, 3: Implementation)
SAE J 1213/1	IR	Glossary of Vehicle Networks for Multiplexing and Data Communications
SAE J 1583	IR	Controller Area Network (CAN), An In-Vehicle Serial Communication Protocol
SAE J 1587	RP	Joint SAE/TMC Electronic Data Interchange Between Microcomputer Systems in Heavy-Duty Vehicle Applications
SAE J 1699	RP	J 1850 Verification Test Procedures
SAE J 1708	RP	Serial Data Communications Between Microcomputer Systems in Heavy-Duty Vehicle Application
SAE J 1724		Vehicle Electronic Identification (New Task Force)
SAE J 1850	RP	Class B Data Communication Network Interface
SAE J 1930	RP	Electrical/Electronic Systems Diagnostic Terms, Definitions, Abreviations and Acronyms
SAE J1939/xx		Truck + Bus, Details next page
SAE J 1962	RP	Diagnostic Connector
SAE J 1978	RP	OBD II Scan Tool
SAE J 1979	RP	E/E Diagnostic Test Modes
SAE J 2008	RP	Electronic Access/Service Information
SAE J 2012	RP	Diagnostic Trouble Code Definitions
SAE J 2037	IR	Off-Board Diagnostic Message Formats
SAE J 2054	IR	E/E Diagnostic Data Communications
SAE J 2056/1	RP	Class C Application Requirement Considerations (Part 2: IR: Survey of Known Protocols, Part 3: IR: Selection of Transmission Media)
SAE J 2057/1	IR	Class A Application/Definition (Part 3: IR: Class A Multiplexing Sensors, Part 4: IR: Class A Multiplexing Architecture Strategies)
SAE J 2106	IR	Token Slot Network for Automotive Control
SAE J 2112	IR	Diagnostic Technician Questionnaire Summary
SAE J 2178	RP	Class B Data Communication Network Messages (Part 1: Detailed Header Formats and Physical Address Assignments, Part 2: Data Parameter Definitions, Part 3: Frame Ids for Single Byte Forms of Headers, Part 4: Message Definition for Three Byte Headers)
SAE J 2186	RP	E/E Data Link Security
SAE J 2190	RP	Enhanced E/E Diagnostic Test Modes
SAE J 2201	RP	Universal Interface for OBD II Scan Tool
SAE J 2205	RP	Diagnostic Specific Functionality Protocol
SAE J 2216	RP	Application of the Clean Air Act Amendment of 1990 (Section 207, Paragraph M5)

RP = Recommended Practice, IR = Information Report

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TABLE 22.3 SAE Truck and Bus Documents

SAE J 1939	RP	Serial Control and Communication Vehicle Network (Class C)
SAE J 1939/01		Truck and Bus Control and Communicatior Vehicle Network (Class C)
SAE J 1939/02		Agricultural Equipment Control and Communication Network
SAE J 1939/1x		Physical Layer, x refers to a specific version
SAE J 1939/11		Physical Layer, 250 kBaud, Twisted Shielded Pair
SAE J 1939/12		Physical Layer, 125 kBaud, Twisted Pair
SAE J 1939/13		Physical Layer, 250 kBaud, Twisted Pair with Ground
SAE J 1939/14		Physical Layer, 1 MBaud, Fiber Optic
SAE J 1939/15		Physical Layer, 50 kBaud, German Agricultural
SAE J 1939/21		CAN 29 Bit Identifier Data Link Layer
SAE J 1939/3x		Network Layer, x refers to a specific version
SAE J 1939/31		Truck + Bus Network Layer
SAE J 1939/4x		Transport Layer, x refers to a specific version
SAE J 1939/5x		Session Layer, x refers to a specific version
SAE J 1939/6x		Presentation Layer, x refers to a specific version
SAE J 1939/7x		Application Layer, x refers to a specific version
SAE J 1939/71		Truck, Bus, Agricultural and Construction Equipment Application Layer
SAE J 1939/72		Virtual Terminal
SAE J 1939/73		Application Layer—Diagnostics
SAE J 1939/81		Network Management
SAE J 1939/??		Tractor-Trailer-Interface



PIN #	Assignment
1	discretionary
2	BUS + Line of SAE J1850
3	discretionary
4	Chassis Ground
5	Signal Ground
6	discretionary
7	K Line of ISO 9141-2
8	discretionary
9	discretionary
10	BUS - Line of SAE J1850
11	discretionary
12	discretionary
13	discretionary
14	discretionary
15	L Line of ISO 9141-2
16	Unswitched Vehicle Battery Positive

Note: Assignment of pins 1, 3, 6, 8, 9, 11, 12, 13, and 14 is left to the discretion of the vehicle manufacturer

FIGURE 22.10 SAE J1962 diagnostic connector.

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2. *Interface according to the SAE J1850 (Class B Data Communication Network Interface):* The SAE J1850 defines means and methods for serial data exchange for automotive application at the physical and data link layer of the OSI model. It is used for networked systems and for diagnostic purposes.

   Two implementations are characterized: pulse-width modulation (PWM) at 41.6 kbps transmitted on twisted pair wires, and variable pulse-width modulation (VPM) at 10.4 kbps, transmitted on a single wire.[12]

A generic scan tool, as mentioned, therefore, has to handle the three different interfaces.

A new protocol, *Keyword 2000,* is prepared by the ISO committees. It is supposed to combine the protocols that have been used up to now.

With the introduction of more and more diagnostic functions and networked systems in the vehicle, the functional structure will be modified (Fig. 22.11).

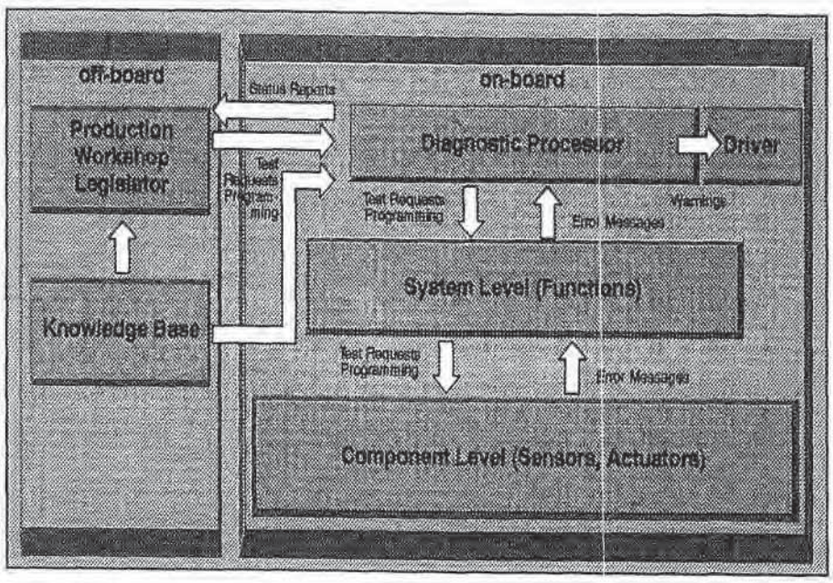


FIGURE 22.11 Logical structure for future diagnosis.

A diagnostic processor on top of a hierarchical structure of functions has access to every system via the network. It can request status information of the functions of the levels below, or of the sensors and actuators, and receives warning messages if problems are detected by the self-diagnosis of the different subsystems. The diagnostic processor serves as a man-machine interface to the driver and as a gate to the outside. It is the only secure access to the entire system of the vehicle.

GLOSSARY

CAN Controller Area Network (standardized protocol developed by Bosch for networked systems).

CARB California Air Resources Board.

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CD-ROM Compact disk read only memory, a data storage medium.

DIS Draft International Standard.

ECU Electronic control unit.

EGR Exhaust-gas recirculation.

EPA Environmental Protection Agency.

Freeze frame Faults stored together with various related parameters.

HC Hydrocarbon.

ISO International Standardization Organization.

ISO 9141-2 Standardized protocol for data exchange between ECUs and testers.

Lambda controller Electronic system for controlling the air/fuel ratio.

Lambda sensor A sensor for air/fuel ratio (oxygen sensor).

MIL Malfunction indicator lamp (indicates emission-related faults to the driver).

OBDII On Board Diagnostics II.

Off-board diagnosis Diagnosis performed by means outside a vehicle.

On-board diagnosis Diagnosis performed by means within a vehicle.

OSI Open System Interconnection.

PC Personal computer.

PWM Pulse-width modulation.

RS 232 Standardized data link (hardware).

Scan tool Small tester that can be connected to the diagnostic connector to interrogate emission-related fault codes.

SAE Society of Automotive Engineers.

TDC Top dead center.

Terminal 1 Connection to a signal related to ignition timing.

VAN Vehicle Area Network (French proposal for network protocol).

VPM Variable pulse-width modulation.

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ABOUT THE AUTHORS

WOLFGANG BREMER studied electrical communication techniques from 1962 to 1968 at the University of Karlsruhe (Germany). Afterwards he was engaged with Siemens AG in Karlsruhe in the development of high-precision electronic balances. Since 1970, he has been working in the advanced engineering department of measurement and information techniques of Robert Bosch GmbH and is responsible for the development of serial communication and diagnostic systems in the chassis area of vehicles. He is working in several ISO and SAE committees and working groups in the field of diagnosis.

FRIEDER HEINTZ studied electrical communication techniques from 1954 to 1959 at the University of Karlsruhe. Afterwards he was engaged in research and development of process-control computers with Siemens AG in Karlsruhe, Munich, and New York. Since 1969, he has been the head of the advanced engineering department for measurement and information techniques at Robert Bosch GmbH. For 20 years, he has managed national and international working groups for diagnosis and serial data transfer in vehicles within the ISO (International Organization for Standardization).

ROBERT HUGEL studied physics at the University of Karlsruhe from 1967 to 1972. Then he was engaged for six years in the development, production, and sales of infrared spectrometers, two years in the development of laser-based measuring systems, and the last 13 years in developing various automotive electronics at Robert Bosch in the advanced engineering department for measurement and information techniques.

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P · A · R · T · 5

SAFETY, CONVENIENCE, ENTERTAINMENT, AND OTHER SYSTEMS

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CHAPTER 23
PASSENGER SAFETY AND CONVENIENCE

Bernhard K. Mattes
Electrical Engineer
Robert Bosch GmbH

23.1 PASSENGER SAFETY SYSTEMS

Electronically controlled passenger safety systems, such as air bags, seat belt tensioner, and rollover sensor systems, help to avoid injuries or to reduce injury severity in an accident. If the passenger compartment cell is not too heavily deformed, then these systems are effective in minimizing the acceleration or load forces acting on the vehicle occupants. During a rollover accident, the rollover protection system helps provide the necessary survival space. In an open vehicle, a rollover bar, as well as protection elements such as extending headrests behind the rear seats, considerably increase occupant safety.

Such occupant protection systems are also classified as passive restraint systems, since the protective function is independent of any active contribution by the passengers.

23.1.1 Air Bag and Seat Belt Tensioner Sensor Systems: Principle Sensor Function and Timing Sequences

The functional components of electronically controlled air bag and seat belt tensioner initiation consist of crash detection sensors, signal processing, squib triggering, and system monitoring. Whereas a vehicle in a crash situation is rapidly decelerated by contact with an external obstacle, the occupants continue to move forward until restrained or contact within the vehicle occurs (steering wheel, windshield, dashboard, or other rigid structural parts). Air bags and seat belt tensioners are designed to reduce impacts of passengers within the vehicle.

The igniter (squib) activates the pyrotechnical inflator used for both air bag deployment and seat belt tightening. The sensor range comprises an angular sensitivity of ±30° to the longitudinal axis. Normally, electronic sensor units contain one or more accelerometers with main sensitivity along the longitudinal axis.

Crash conditions demand a timely activation of restraining devices. It is equally important, however, that they are also released only when required.

Depending on the kind of collision (frontal, oblique, offset, pole, underride, etc.) the triggering time must be calculated correctly, so that the allowed forward displacement will not be exceeded by the time the air bag is inflated or the seat belts are tensioned.

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In most cases, the allowable forward passenger travel with an air bag system is 12.5 cm (5-inches rule). For seat belt tensioning systems, the acceptable displacement drops to about 1 cm. Approximately 30 ms are required to inflate air bags, and the time required to tension a seat belt with a pyrotechnically activated seat belt retractor is approximately 10 ms. Thus, trigger commands must be given by the time the maximally allowable forward displacement will be reached minus the activation time of the respective restraining device. Effective injury prevention requires timely firing based on detection of acceleration or deceleration crash signals and their processing by the crash discrimination algorithm or electromechanical sensor.

Different crash-sensing schemes are shown in Fig. 23.1.

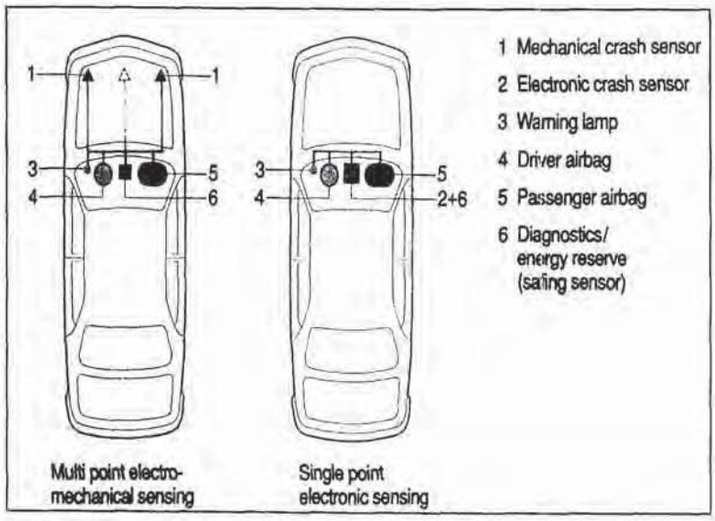


FIGURE 23.1 Crash-sensing schemes.

23.1.2 Multipoint Electromechanical Sensing Systems or Distributed Air Bag Systems

A distributed air bag sensing system or multipoint electromechanical sensing system consists of two to four electromechanical crash discrimination sensors, strategically mounted in the vehicle's crush zone, plus an additional arming sensor mounted in the passenger compartment inside an electronic control unit including diagnostics, energy reserve, and voltage converter.

Sensors. Two typical types of electromechanical sensors are based on the *ball-in-tube* respectively or the *rolamite* principle. The function of the ball-in-tube sensor is shown in Fig. 23.2. A ball held in position by a permanent magnet begins to move if the inertial force acting on it due to the vehicle's deceleration exceeds the magnetic restraining force. A narrow air gap between ball and tube results in viscous air damping and integration behavior of the relative motion. Upon reaching the other end of the tube, the gold-plated ball closes a mechanical switch.

Closure of at least one of the sensors located in the vehicle's crush zone and simultaneous closure of the arming switch inside the passenger compartment directly connect the igniters to battery plus and minus and initiate air bag deployment. The two-stage passenger inflator is ignited in series. A transistor turns on the ignition current for the second stage approximately 10 to 15 ms after the first stage. This delay time provides a softer passenger bag inflation and slower pressure increase inside the passenger compartment.

Such electromechanical spring mass sensors obey second-order differential equations of motion. Parameters like restraining magnetic force, damping factor, mass of the ball and

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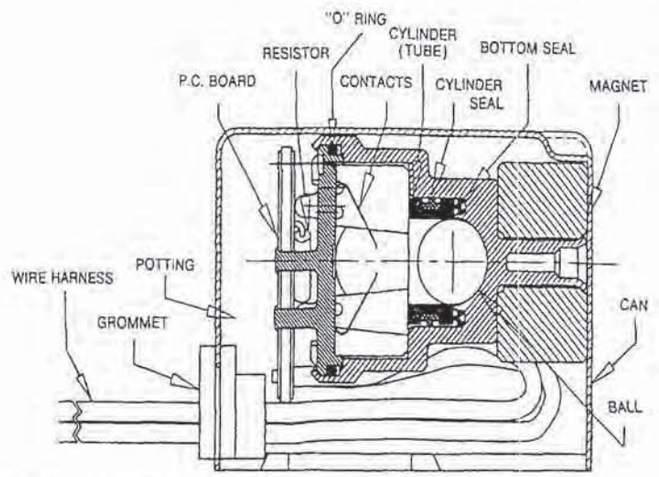


FIGURE 23.2 Ball-in-tube sensor. (*Courtesy Breed Technologies Inc.*)

travel distance determine the sensor's dynamic characteristics and have to be designed according to the vehicle's crash behavior.

The function of the rolamite sensor is as follows. A sheet metal spring band wound around a metal cylinder keeps the roller in its rest position as long as the retaining spring force is bigger than the inertial force acting on the roller cylinder. The rolling of the cylinder over the convex guide is thus kinematically constrained by the guide and the spring to translation along the guide's surface. After having reached or exceeded a specified travel distance, the firing contact is closed.

Normally, the arming sensor inside the diagnostics and energy reserve module is of the same type as the discriminating sensors used in the crush zone.

The advantage of such systems is that the discriminating sensors can be installed in front end positions where high acceleration amplitudes can be sensed in early stages of impact. Disadvantages range from no crash prediction capabilities, no sensor "stuck open" indication in the field, high cost and installation expense, as well as no seat belt tensioner function.

Diagnostics and Energy Reserve Module. A system readiness indicator is legally required for air bag-equipped vehicles (with the exception of all-mechanical systems). This means that air bag system-readiness has to be constantly monitored. Electronic diagnostics and energy reserve modules *periodically* perform the following diagnostic functions:

Monitor. This diagnostic function includes the following checks:

- All ignition loops for too high or too low resistances
- All ignition loops for leakages to battery plus or minus
- External crash discrimination sensors for continuity (there is a diagnostic resistor in parallel to the contact), for cable harness short circuits to battery plus or ground, and for too long contact closure (longer than 1 s)
- Internal arming sensor for continuity and for too long contact closure
- Warning lamp output for short circuits to battery plus or minus and for interruption
- Energy reserve capacitor(s) for correct voltage(s) and capacitance(s)

Control. This diagnostic function includes the following checks:

- Battery supply for too low and too high voltage
- Internal regulated voltage (normally = 5 V) for too low or too high level
- Diagnostics interface for short circuits

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After the initialization phase at power turn-on, the following checks are done once:

- RAM, ROM, EEPROM-read check
- Watchdog check
- Output transistor check for 2d passenger stage (if it exists)

Each fault type is characterized by a special fault code and stored into EEPROM after being judged as faulty. There are different modes of fault assessment and different degrees of fault tolerance.

Fault Clock. State-of-the-art diagnostics and energy reserve modules have one fault clock counting the elapsed time of the faults in total. But there are also modules with individual fault clocks for each fault type.

Storage capacity of the fault time counter normally includes 50 to 100 h with a time resolution of 1 to 5 min.

Crash Recorder. The sequence of crash-relevant events like closure of discriminating sensors, arming sensor, battery voltage level, energy reserve voltage, turn-on of power stages (if existing), can be stored in the EEPROM. This can be done in the form of time-discrete "snapshots" of system conditions for approximately 10 to 20 ms before and approximately 30 to 50 ms after deployment. Advanced crash recorders also store acceleration and deceleration values of some time period before and after the firing moment. This is done to get information about impact energy of real-world crashes.

Serial Diagnostic Interface. EEPROM content (type of unit, fault codes, fault time, crash recorder) can be retrieved via a bidirectional diagnostics interface. Initiation of communication, diagnostics concept, and software depend on the car manufacturer's requirements.

Energy Reserve and Voltage Converter. If battery supply is lost in a crash, ignition function and crash recorder storage is maintained by the energy reserve. This backup supply is performed by one or more capacitors (acting as energy reservoir(s). For the ignition loops, the energy reserve is wired or with vehicle battery voltage. For the monitoring circuits part, the energy reserve is switched on to the voltage regulator input in case of too low battery. Survival time of such components ranges between 0.1 and 1 s.

There are systems with an individual energy reserve for each ignition loop as well as one for the monitoring circuit. In such systems, there is no loss of function for the rest of the ignition loops and the crash recorder if one loop gets short circuited in a crash and its energy reserve capacitor is discharged.

A step-up converter keeps the energy reserve(s) charged up to voltages nominally higher than battery voltage (e.g., $V_{ER} = 22$ V to $V_{ER} = 35$ V).

23.1.3 Single-Point Electronic Sensing Systems or Central Air Bag Systems

With single-point electronic sensing systems (or central air bag systems), the electronic control module is located in the passenger compartment. There are no external sensors in the crush zone. The electronic circuits include acceleration sensors, signal-processing algorithms, diagnostics, output stages, energy reserve, and voltage converter.

Historical Evolution. Production of single-point sensing electronic air bag units started in 1980. This first concept used a strain gage acceleration sensor and a mercury switch as "arming" or "safing" sensor. The signal processing was performed by analog integration of the acceleration signal and resulted in a value related to velocity change during the impact, a so-called Δv-value.

If Δv exceeded a vehicle-specifically set threshold and the mercury switch was closed, then the restraining devices were triggered. The first systems comprised three electronic components: sensor, analog circuitry, and diagnostic unit; voltage converter unit; and energy reserve unit.

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In the beginning of 1987, another analog integrating system went into production and consisted of two electronic components: sensor and diagnostic unit, and voltage converter and energy reserve unit. This was the first air bag sensor system based on using a piezoelectric accelerometer, and contained a microcontroller only for monitoring functions. Storage of fault codes, fault clock, and crash recorder in an EEPROM were included as well. The unit was designed for triggering the driver air bag, as well as the driver and passenger belt tensioners.

Mid-1987 marked the production start of the first air bag sensor unit with a digital single-point sensing algorithm. With this system, all the functions could be integrated into one box. Figure 23.3 shows a block diagram of this unit.

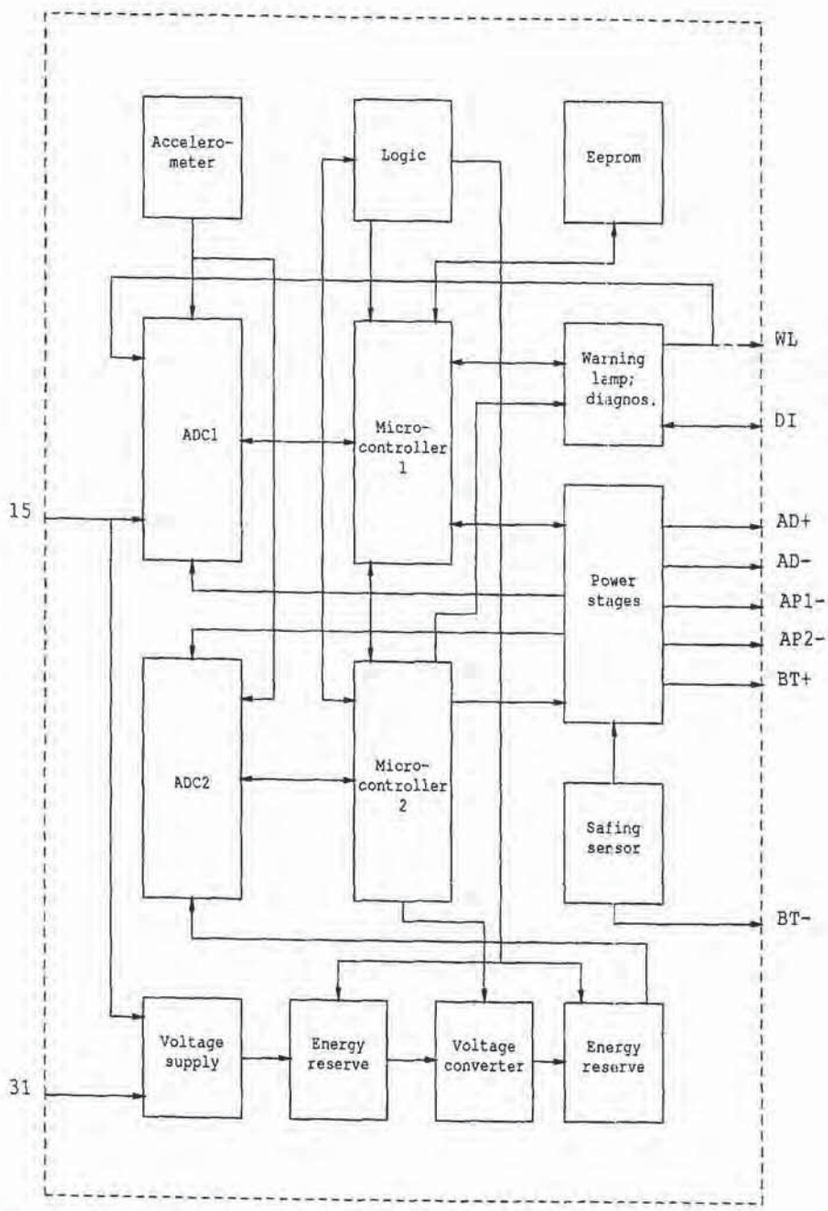


FIGURE 23.3 Block diagram AB 3-ECU.

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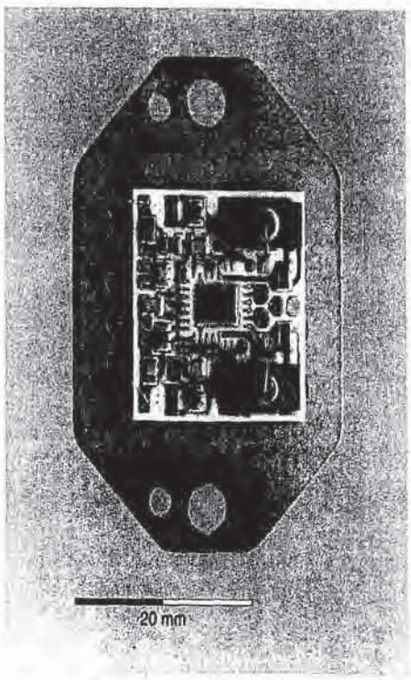


FIGURE 23.4 Piezoelectric accelerometer BSA 6.

For redundancy against inadvertent deployment, this unit was a two-microcontroller design (parallel processing) and contained a mercury switch as arming sensor. In 1989, this mercury switch was replaced by a reed switch.

Current Systems. The key features of a single-point air bag electronic control unit (ECU) are the accelerometer, the digital single-point sensing algorithm, the degree of function availability, the safety against inadvertent release, and the degree of fault tolerance of the system.

Electronic Accelerometers.

Piezoelectric accelerometers. Current accelerometers have been upgraded and are robust against electromagnetic interferences. Dual-channel accelerometers exist that deliver differential mode output signals and offer the possibility to design all-electronic air bag ECUs and remove the need for the untestable mechanical arming sensor. Inverse polarity of the sensor signals allows the unit to distinguish from common mode signals which can result from electrical disturbances. Figure 23.4 shows a dual-channel accelerometer.

Diagnosis of the electrical function of these sensors can be performed after initialization, and, thus, function reliability and system readiness are monitorable. Other piezoelectric accelerometers contain mechanically deflectable sensing elements, (e.g. by piezoelectric actuators), for verification of system integrity.

Micromachined accelerometers. Micromachined accelerometers can be mounted directly on the printed circuit board. The required interface circuitry is included on the same chip with the monolithic capacitive accelerometer. High linearity is guaranteed by closed-loop operation. This means that the movable beam is always electrostatically centered by a feedback voltage proportional to deflection (= acceleration/deceleration). The measurement range is ±50 g. For self-test, the functional beam is electrostatically deflected.

Single-point sensing algorithm. Different types of digital crash-sensing algorithms are currently in use. The sampling rate of the acceleration signal varies between 0.5 and 1 ms.

Mathematical manipulation of the crash signal (differentiation, multiplication, integration) and release threshold variation by software allows an early discrimination of different impact types (frontal, oblique, offset, pole, underride). Furthermore, application of the appropriate prediction model for forward displacement and determination of the correct trigger point is possible.

Digital sensing algorithms increase the possibility both to detect problem crashes such as underrides with perceived damage, and to distinguish between deployment and nondeployment impacts. This shows a distinct improvement over hardwired analog integration systems. The digital approach allows the end of line programming of sensitivity parameters for different car models. Thus sensitivity parameters are programmed into the EEPROM of the microcontroller which allow the use of the same ROM-mask for different car types.

Electronic control modules. Today, state-of-the-art ECUs use a one-channel acceleration sensor and an arming sensor in series to the output stages. Such units are a mix of electronic and mechanical control. The first *all-electronic* single-point sensing ECU went into production in mid-1992. This module incorporated a dual-channel electronic accelerometer and no mechanical safing switch. Figure 23.5 shows the block diagram of a state-of-the-art electronic control module.

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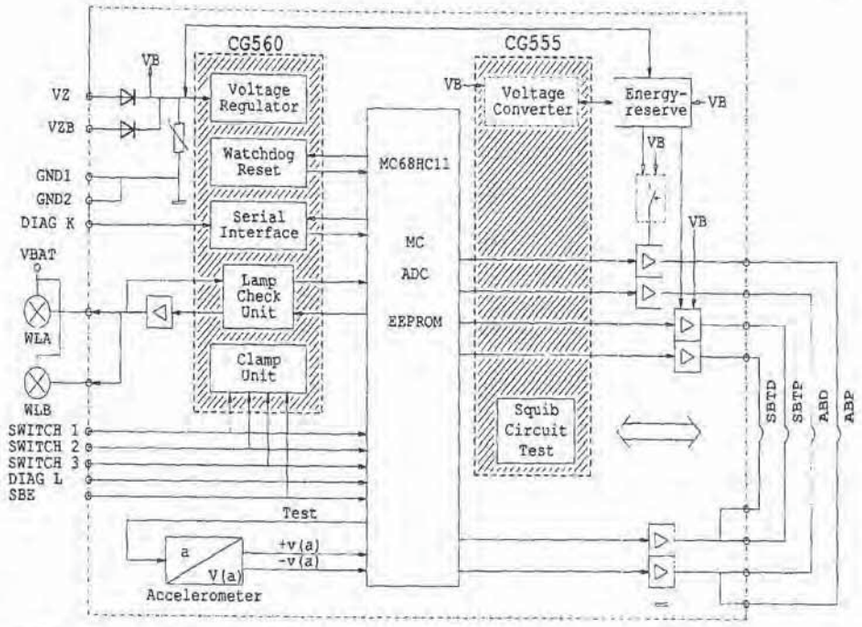


FIGURE 23.5 Block diagram AB6.3-ECU.

AC-firing. Normally squibs are fired with a dc pulse (dc-firing). The first unit with ac-firing went into production in mid-1993. With ac-firing, there is a capacitor inside the squib connector in series to the squib. This capacitor is periodically charged up and discharged so that a firing is only possible with alternating current (ac-firing).

AC-firing was introduced because of faults occurring in the vehicle periphery (outside the ECU). Typical faults consist of short circuits in the air bag module (= squib + inflator + bag + cover) by metal (splinters), defects in the contact unit for the driver air bag (= clock spring), and short circuits in the harness. Igniters are very sensitive to short current pulses (3 A for 60 μs can be sufficient to fire the air bag).

The main benefit of ac-firing is an immunity to all short circuits to dc-vehicle voltages with and without the ECU, as well as immunity from inadvertent deployments with all types of static ECU defects. The danger of false triggering is reduced because the push-pull output stages can only fire if activated with the correct asynchronous sequence of pulses by the microcontroller. A microcontroller disturbance inadvertently producing such a pulse sequence is highly unlikely.

A disadvantage of the current ac-firing system is the more complex ignition loop diagnostics required in the ECU. These diagnostics have to monitor the resistance and capacitance in the loop.

23.1.4 Rollover Sensors

Convertibles can overturn in almost any direction (although a backward turnover around the lateral axis is not very likely). Thus a rollover sensor unit has to sense in practically every direction in the horizontal plane. The kind of sensing and the signal evaluation times are the differences between rollover and air bag sensor units. A rollover accident has to be detected within approximately 200 ms; the activation time of the mechanical protection device takes approximately 300 ms.

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The following rollover sensing concepts are used. The first concept (URS = *Überrollsensor*) went into production in 1989: omnidirectional tilt switch in conjunction with rear-axle switches, and longitudinal and lateral accelerometers. These are the same ones as used for air bag ECUs.

The tilt switch consists of a rocker cylinder with a permanent magnet mounted on top. A Hall-IC placed in the lid of the switch senses the rocker cylinders position. The discrimination threshold can be adjusted to the desired angle (e.g., 22°).

Rear-axle switches open if one or both half-axles of the vehicle are completely unloaded. This means that a potential vehicle rollover is indicated by an airborne wheel.

The system cannot release the rollover protection device (e.g., the rollover bar) if the respective rear wheel cannot move any more because of a fender deformed during impact. To avoid this, and for redundancy purposes, the sensor unit also senses the acceleration in every horizontal direction. It contains a longitudinal and a lateral piezoelectric accelerometer whose signals are squared and added. Exceeding the release threshold of approximately 5 g causes activation of the rollover protection element(s) located behind the rear seats. This sensor also unlocks the central locking system after a vehicle rollover.

Rear-axle switches are one way to provide a redundant signal for the rollover indication. Another system (ÜRSS = *Überroll-Schutz-System*) is based on a combination of three "spirit level" sensors, optically evaluated by LEDs and photo transistor-light barriers, and a vertical gravitation switch consisting of a magnet, a spring, and a reed contact.

Two of the level sensors are mounted ±52° to the horizontal plane and sense overturning around the vehicle's longitudinal axis. They also close if an acceleration greater than 1.3 g is exceeded for more than 80 ms. The third-level sensor is inclined by 80° to the horizontal plane and senses overturning around the lateral axis in the forward direction. This sensor closes for an acceleration exceeding 5.7 g for more than 80 ms.

The reed contact in the vertical acceleration switch is closed after the vehicle loses ground contact, since it is no longer possible to sense gravity in the vehicle if it is airborne. Thus, a spring with a restoring force of approximately 10 percent of the magnet's normal weight is enough to move the magnet over the reed contact and cause its closure. The rollover protection is then activated after a delay of approximately 300 ms. This activation can be initiated either by one of the level sensors or by the vertical acceleration switch.

A release of the rollover protection equipment in the case of a backward turnover around the vehicle's lateral axis would require an additional fourth-level sensor in the sensor unit.

23.1.5 Tire Pressure Control Systems

Tires must have the correct pressure in order to provide expected driving performance like the transfer of high breaking or lateral adhesion forces to the road surface. They must have good aquaplaning properties, which also depend on the tire pressure. In addition to safety considerations, improved economy can be expected since low tire pressure generally increases rubber abrasion and fuel consumption.

Electronic tire pressure control systems alert the driver in case of pressure loss. Low pressure indication is performed using a reference pressure switch mounted in the rim which compares the tire pressure with the reference pressure in a box hermetically sealed by a high-grade steel diaphragm. A contact opens if tire pressure falls below the reference pressure. Temperature dependancy of the pressure switch is negligible since the temperature of tire air is practically identical to temperature of reference gas.

A high-frequency sensor mounted on the axle detects if the pressure switch is closed. At each pass, the closed pressure switch contact activates a serial resonance circuit by energy absorption out of the axle-mounted high-frequency transmitter. So, rotation can only be sensed if the tire pressure is high enough.

An ECU for each wheel compares transmitter signal with wheel rotation signal of a rotation sensor. As there is a defined relation between these signals, any discrepancy within a specified driving distance can be detected, and the driver warned.

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23.2 PASSENGER CONVENIENCE SYSTEMS

23.2.1 Electromechanical Window Drives

There are three different systems currently in use.

Lift Mechanism System. An electric gear motor drives a spur gear meshing in a gear segment. This segment acts on the window lift mechanism.

Flexible Cable System. An electric gear motor drives a system of flexible cables to lift the window.

Stiff Cable System. An electric gear motor is connected with the window via a tension and compression stiff cable. This cable is driven by a toothed wheel.

Window Lift Motors. The limited space inside the door requires window lift motors with a flat design. The lift mechanism consists of a self-locking worm gear system, which keeps its position if not intentionally activated and which must resist trials to open the window by force. An elastic claw clutch provides good damping behavior.

Window Lift Controls. Activation is performed using rocker switches.

Best driver comfort results from a combination of window drives and the central door-locking system. Here the windows are either automatically closed after leaving and locking the vehicle, or they are driven to a designated ventilating position. Such an automatic system requires the use of a driving force limiting or jamming protection. This protection must be effective during upward motion of the window within a range of 200 to 4 mm before the upper window stop.

Jamming force must not exceed 100 N, and the rise of force must remain less than 10 N/mm. Hall sensors monitor the rotation speed of the lift motors. If a speed decrease is detected, the rotation direction is immediately reversed. A complete window closure is enabled by turning off the jamming protection just before the window is driven into the door gasket. Thus, the motor can be driven just to blocking (if necessary). On this occasion, initialization of the window position is done.

An ECU for all window lifts can either be mounted centrally, or the electronic controls can be integrated into the window lift motors in order to save harness expense. Such drives would be preferable when used in conjunction with bus systems.

23.2.2 Electromechanical Sunroof Drives

State-of-the-art sunroof drives incorporate the functions of a lifting and sliding roof. Lifting or sliding motions are initiated by electronic or electromechanical controls. Electromechanical controls include mechanical interlocks of limit switches which allow the closed sunroof to be opened or lifted. Reversing the polarity of the drive motor lowers or closes an opened or lifted sunroof. In case the sunroof control is connected to a central locking system, then an electronic unit with jamming protection would be advantageous.

Additional functions such as preselectable position control, closing if demanded by a rain detector, and data bus connection can be realized with low extra expense.

The permanent magnet drive motor has a rated output of approximately 40 W and is coupled to a worm gear unit. Sunroof motors have a thermal overload protection implemented by thermal circuit breakers. The sunroof is moved either by flexible cable drives or by contraction/tension-stiff cables. It must be possible to close the sunroof using simple on-board tools in case there is a failure of the electrical system.

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23.2.3 Electromechanical Seat and Steering Wheel Adjustment

Electrically adjustable seats are especially well suited for vehicles frequently driven by different persons of various size. After each driver change, the seat can be adjusted to best fit the new driver's requirements.

Up to five motors per front seat allow the following position changes: height adjustment of front edge of seat plane, height adjustment of rear edge of seat plane, longitudinal adjustment of seat, tilt adjustment of back rest, and height adjustment of headrest. Electric motors drive gear units via flexible shafts for longitudinal and vertical adjustments of the seat.

There are seat adjustment controls currently on the market with programmable nonvolatile memories, allowing a readjustment of the seat to positions stored in the EEPROM. Adjustments of the external mirror and the height of the seat belt guide can be programmed as well, according to individual demands. Furthermore, seating comfort in passenger cars is improved using electromechanically adjustable steering columns and tiltable steering wheels. The adjustment is performed via a self-locking gear unit with an electric motor and is integrated directly into the steering column. Adjustment can be achieved by manual activation of a position switch, or by connection to the programmable seat memory unit.

23.2.4 Central Locking Systems

Central locking of the doors, trunk lid, and tank cap is done either by pneumatic or electromotor driven actuators.

With the pneumatic system a bipressure pump provides the over- and underpressure to the system. To achieve this, the pump is driven by an electromotor in both rotation directions. The system can be operated from different locations: central position switch, driver door lock, passenger door lock, and trunk lid lock.

All-electric motor-driven central locking systems are based on the same concept. A small electric motor with reduction gear drives to position a bar for closing or opening the lock.

In case of power loss, it must be possible to open the doors with the mechanical key or with the internal door handle. On central locking systems with integrated theft alarm, opening is only possible with the mechanical vehicle key.

There are central locking systems which can be operated by ultrasonic remote control. These systems offer keyless closure or entry and thus high operational comfort.

23.2.5 Reverse Parking Warner

The system consists of an ECU, LCD, and sensors. It is equipped with ultrasonic transmitter/receiver sensors using the echo depth sounder method. Bursts of ultrasonic waves at approximately 30 kHz are transmitted for 30 ms. The travel time of the first echo signal gives information about the distance to the obstacle.

Upon shifting into the rear gear, the system is activated and completes a self-check by turning on all display characters for a specified short time period and checking the ultrasonic sensors. A space up to 0 to 160 cm behind the vehicle is observed and divided into different warning sectors. The most critical distance is an obstacle within 30 cm. In this case, the optical display flashes and the acoustical warner gives a permanent signal.

23.2.6 Emergency Light Flasher

An ECU turns on the blinking lights. Synchronous flashing of all blinkers of a vehicle must be possible with the ignition turned on or off. A specific control lamp to indicate the status of the emergency light flashers must be included inside the vehicle. Usually this lamp is integrated into the on/off switch.

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GLOSSARY

Accelerometer Inertial deflection of this sensing element results in an electric signal proportional to acceleration or deceleration of the vehicle.

Airbag Gas-filled cushion for impact energy absorption of vehicle occupants during a crash.

Allowable forward displacement Forward displacement of the occupant which is allowed before the restraining device has reached its full protection capability.

Arming sensor An electromechanical acceleration switch integrated in the electronic control unit located inside the passenger compartment. Activation of the restraining device is only possible if the arming sensor completes the triggering circuit.

EEPROM Electrically erasable and programmable read only memory.

Energy reserve Backup power supply for the restraining system in case of battery loss.

Forward displacement Forward travel of the occupant during a crash which occurs until there is contact with the restraining device or vehicle interior.

Hall IC Integrated circuit containing a Hall sensor plus appropriate evaluation circuitry. The Hall sensor delivers an electric voltage proportional to the magnetic field strength by which it is affected.

Igniter Electrically activated initiation element for firing of an inflator.

Inflator Gas-producing unit for air bag inflation or activation of seat belt tensioner.

Piezoelectric Materials, e.g., special ceramics, which have the capability to convert mechanical deformation into electric signals (voltage and/or charge) and vice versa, are known as piezoelectric materials.

RAM Random access memory.

Reed contact Mechanical, magnetic-field-sensitive switch, hermetically sealed inside a glass tube.

Restraining device Air bag, seat belt, and seat belt tensioner.

ROM Read only memory.

Safing sensor Another expression for arming sensor.

Seat belt tensioner Pyrotechnically or spring-activated device to tighten the seat belt during a crash.

Squib Electrically activated initiation element for firing an inflator (another expression for igniter).

Voltage converter Electronic device to keep the energy reserve charged up to a voltage normally higher than battery voltage.

Watchdog Electronic circuit for checking the correct flow of the microcontroller program.

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ABOUT THE AUTHOR

Bernhard Mattes has been employed with Robert Bosch GmbH since he was graduated from the Technical University of Stuttgart, Germany, as a Diplom-Ingenieur in 1968. He began work at Bosch as an electrical engineer in an automotive electronics design department and has been a section manager since 1984. His working fields at Bosch have included electronic gear box controls, cruise controls, crash-sensing systems for front and side impacts, sensing systems for rollovers, accelerometer and safing sensor development, and tilt and rotation sensor development.

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CHAPTER 24
ANTITHEFT SYSTEMS

Shinichi Kato
Manager, Electronics Design Section No. 2
Nissan Motor Co., Ltd.

24.1 VEHICLE THEFT CIRCUMSTANCES

24.1.1 Vehicle Theft in the United States

In the United States, the number of thefts from vehicles exceeds the number of actual vehicles stolen. A much larger profile is given to stolen cars, however, because of the economic losses suffered by car owners and the tie-in with stolen cars and drug abuse and other crimes.

The number of vehicle thefts in the United States has increased continuously to a 1991 level of approximately 1.7 million. The ease with which thefts can be carried out, the light punishments given to car thieves, and the ready availability of car theft tools and information on how to use them, has led to a systematic network of organized car crimes and the establishment of black markets for both stolen cars and parts.

24.1.2 Vehicle Theft in Europe

By 1992, the number of vehicle thefts in France, Germany, and the United Kingdom totaled 1.08 million, a radical 64 percent increase since 1988. The breakdown of communism in eastern Europe, adding to the existing black market for vehicles and spare parts, the trend toward joyriding in stolen vehicles, and other social problems similar to those in the United States, have all been contributing factors in the increase.

24.1.3 Vehicle Theft Worldwide

The United Kingdom has the largest incidence of vehicle theft followed in order by Australia, Sweden, the United States, and France.

24.1.4 Reasons for Vehicle Theft

The reasons for vehicle theft vary from country to country and between different areas of the same country. In the United Kingdom and Australia, for example, joyriding is the cause of most auto thefts. In the United States, on the other hand, the theft of vehicle contents ranks highest.

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24.1.5 Methods of Entry

In the United States, "slim-jims" or similar devices to unlock car doors and gain entry are the most popular among car thieves. Vehicle contents can then be removed or the steering lock broken and the vehicle hot-wired and driven away. The use of roughly ground ceramic has recently gained popularity over traditional methods of breaking windows such as hammers or spring-punches because of ceramic's ease of use and lack of noise when used.

With the advent of keyless entry systems, devices to "steal" the code while the driver operates the keyfob and transmit it back when the thief chooses, have been developed and readily available to the aspiring thief.

24.2 OVERVIEW OF ANTITHEFT REGULATIONS

The total cost to the public of vehicle thefts in the United States alone is estimated at $8.3 billion per year, taking into account the vehicle and insurance losses and the expense of police time. Due to these economic pressures and spiraling vehicle-theft-related crime, regulations are now being introduced to help protect the vehicle-buying public and insurance companies.

24.2.1 Vehicle Security Regulations in the United States

Three types of vehicle security regulations exist in the United States:

- The vehicle must be fitted with an audible warning that operates when the ignition key remains in the ignition and the driver's door is opened.
- As vehicle theft is not consistent among vehicle types and different areas of the country, 11 states (Florida, Illinois, Kentucky, Massachusetts, Michigan, New York, New Jersey, Pennsylvania, Rhode Island, Texas, and Washington) have introduced regulations to deduct 5 to 15 percent from insurance premiums if vehicles are equipped with certain antitheft systems.
- The Vehicle Theft Act (1986) makes it mandatory for vehicles with a particular theft rating or above to have specified parts of the vehicle clearly marked.

Although this places a cost burden on car makers, they do not need to mark parts on vehicles they equip with antitheft systems approved by the National Highway Traffic and Safety Administration.

24.2.2 Vehicle Safety Regulations in Europe

The United Kingdom. In an attempt to improve vehicle security, insurance companies in Europe define the effectiveness of individual antitheft systems. For example, in the United Kingdom, Thatcham (a survey division of the Association of British Insurers) classifies all vehicles with regard to their antitheft worthiness. This is done on a points basis, with points awarded as shown in Fig. 24.1.

Effective in 1994, Thatcham criteria indicate that the two most important attributes of a vehicle security system are a two-way mobilizer to prevent theft of the vehicle and interior sensors to deter unauthorized entry and theft from the vehicle. Any vehicle judged to have adequate antitheft devices gets significant savings on insurance premiums, thereby offering a powerful incentive to car buyers.

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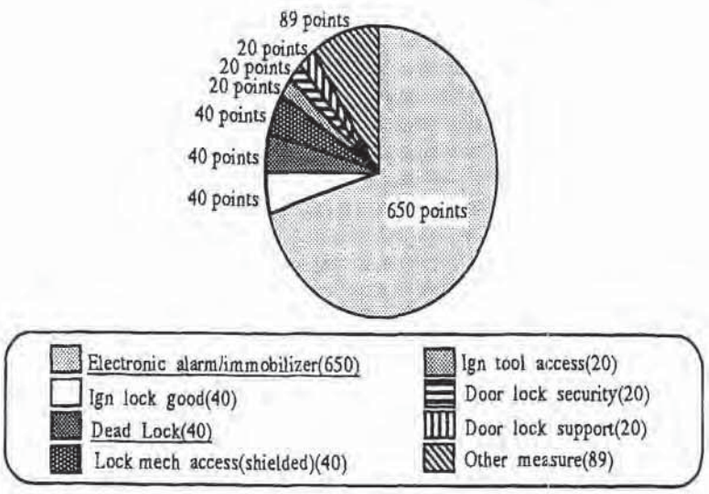


FIGURE 24.1 United Kingdom's Thatcham point system, which assigns points to various antitheft devices.

Germany. In Germany, the country's largest vehicle insurer is Allianz. It announced the policy detailed in Table 24.1 whereby heavy financial penalties are introduced to encourage car owners to ensure that their vehicles meet security standards. These penalties exist in the form of 10 percent premium increases and only 90 percent repayments from insurers in the case of a stolen vehicle that has no antitheft systems. As in the United Kingdom, the application of antitheft systems is likely to spread as more customers demand more secure vehicles from car makers.

TABLE 24.1 Allianz Insurance Company Antitheft Policy

Timing	Scope	Antitheft system	Impact noncompliance
07/01/93	Vehicle to be fitted with aftermarket system	Immobilizer step 1: interrupt at least 3 systems • Starter circuit • Fuel supply • Ignition system • Other system	In case of theft claim, customer only gets back 90 percent of car value
01/01/95	Standard fitment for all new registrations	Immobilizer step 2: engine management operation (electronic code)	↑

24.3 A BASIC ANTITHEFT SYSTEM

A basic antitheft system, Fig. 24.2, must do three things: sense unauthorized entry into the vehicle or unauthorized movement of the vehicle, detect unauthorized attempts to start the vehicle or to disarm the alarm system, and upon detecting any unauthorized act actuate an

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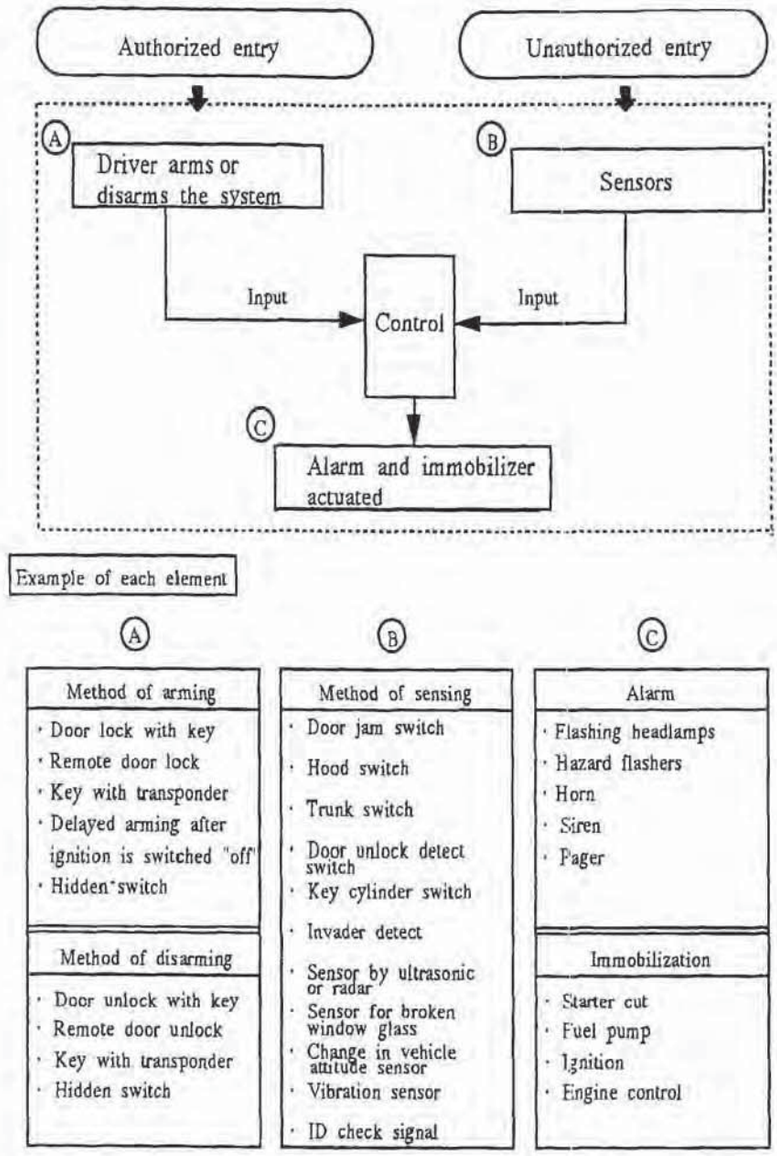


FIGURE 24.2 The basic structure of an antitheft system.

alarm and inhibit the vehicle from starting. Many vehicles now include visual indication in the form of stickers or flashing lights to indicate that they are equipped with an antitheft system.

Antitheft systems use active and passive arming systems. In an active system, the driver can arm the system with an ultrasonic or infrared keyfob or by throwing a hidden switch. In a passive arming system, operating the door key switch automatically arms the system when the driver leaves the vehicle. Insurers in the United States feel that the passive system is more effective and, consequently, give a larger insurance premium deduction for vehicles equipped with such systems. Two thirds of all vehicle security systems are passive, while almost all factory fit systems fall into this category.

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24.3.1 Unauthorized Entry Detection

A tamper switch detects any abnormal forces applied to the door and trunk lock key cylinders, while make-break switches sense opening of all apertures. Ultrasonic beams inside the vehicle can detect the vibration from broken glass or movement within the car. The trigger level of these units is particularly sensitive, because too low a level can lead to false alarms.

24.3.2 Alarm and Immobilization

Alarm activation is indicated by the sounding of the car horn or siren combined with the flashing of the vehicle's headlights and taillights. A recent innovation has been the application of radio paging systems to indicate stolen vehicles. The vehicle is also immobilized by causing an interrupt in circuits vital to vehicle operation such as the starter motor, fuel pump, and ignition systems.

24.3.3 A Typical System Example

The following explanation relates to one of the more popular vehicle alarm configurations shown in Figs. 24.3 and Fig. 24.4. Abnormal conditions or unauthorized entries are detected as inputs from door, hood, and trunk switches, ignition switch, and ultrasonic sensors. When any of these conditions occurs, the horn sounds and the vehicle's lights flash for a predetermined period (usually one to three minutes).

A circuit example using a custom integrated circuit is shown in Fig. 24.4. A flow chart of the system operation is shown in Fig. 24.5.

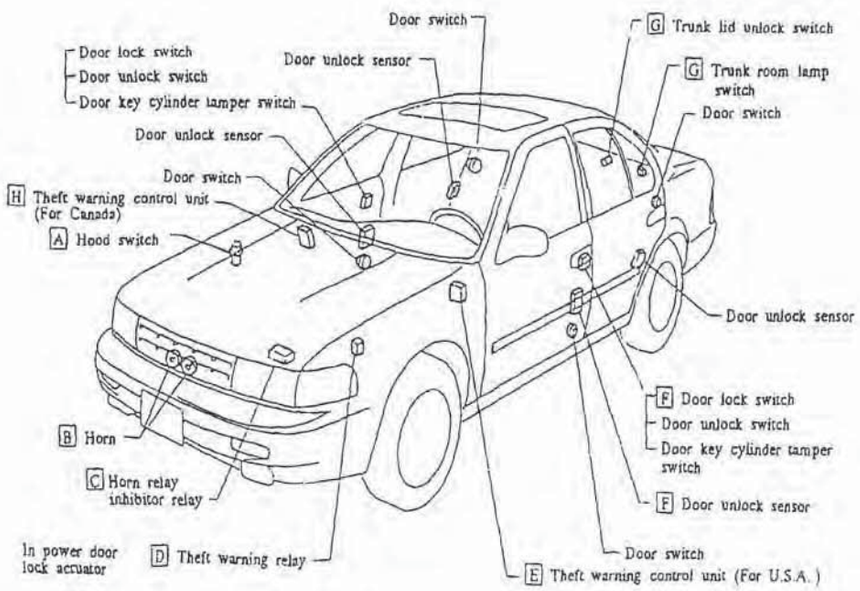


FIGURE 24.3 Component parts and harness connector location for an antitheft warning system.

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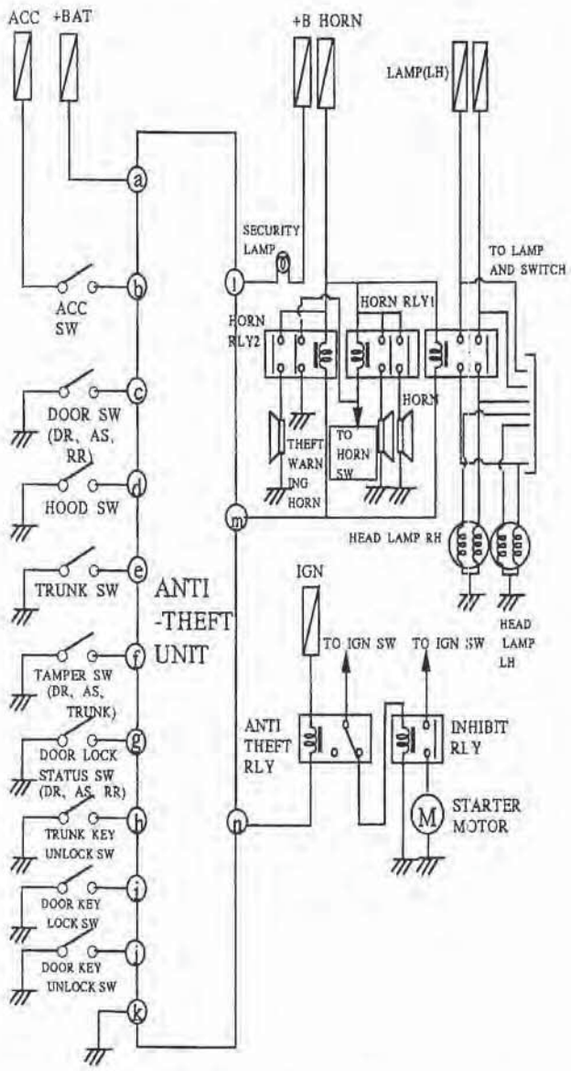


FIGURE 24.4 Circuit diagram of an antitheft system using a custom IC.

24.3.4 Immobilizer

Because of the frequency of false alarms activated by oversensitive invasion sensors, vehicles with alarms sounding are increasingly being ignored by people in the vicinity. Therefore, as a deterrent to vehicle theft, unauthorized entry detection systems alone are no longer considered effective by insurance companies. They prefer—and reduce premium reductions accordingly—to have, in addition, an immobilizer to electrically or mechanically disable the vehicle unless it is correctly disarmed.

Now that most vehicles are equipped with electronic engine control units, car makers feel that they provide the best means for immobilization. This is accomplished with three basic driver interfaces for arming and disarming (Fig. 24.6):

- An ID code input to the ECU by means of a keyboard, which may be separate or combined with another electronic dashboard device such as the radio

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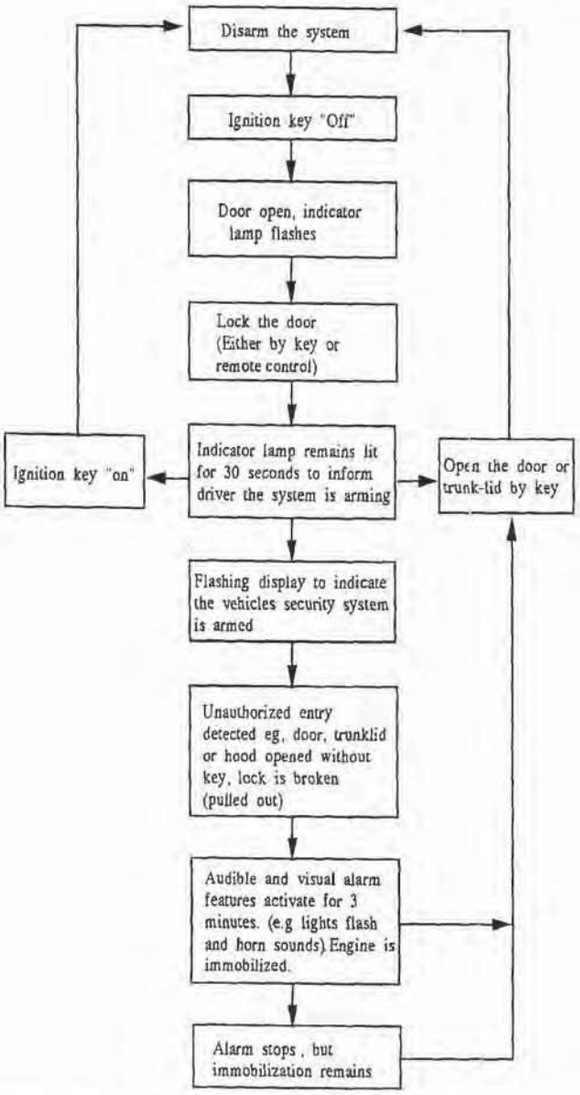


FIGURE 24.5 A flowchart for the system shown in Fig. 24.4.

- An ID signal transmitted by a keyfob to a receiver and decoding unit in the vehicle
- An ID signal received from a transponder built into the ignition key

The transponder built into the ignition key is the most recent innovation (Fig. 24.7). The ignition key contains a transponder device. A reader unit is installed in the vehicle close to the ignition key cylinder. A "power pulse" is transmitted by the reader's antenna shortly after the ignition key is inserted into the lock. This power pulse is received as energy by the transponder and stored in a capacitor. The power is then used to transmit an ID code signal back to the reader. The reader identifies the received signal as authorized or not and, if authorized, enables the ECU to start the vehicle.

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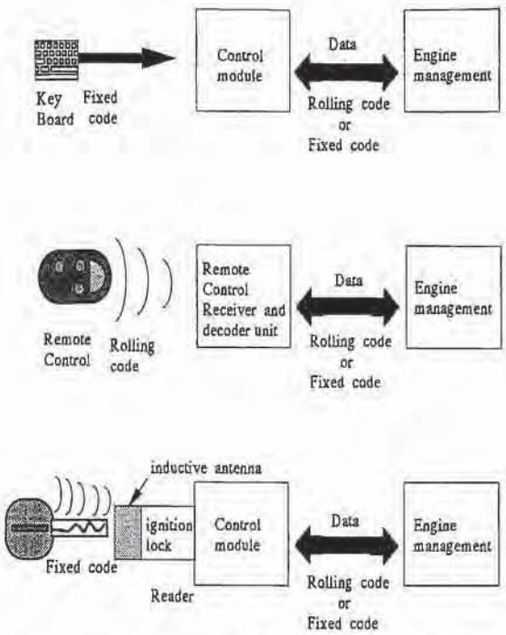


FIGURE 24.6 Three methods for arming and disarming an antitheft system.

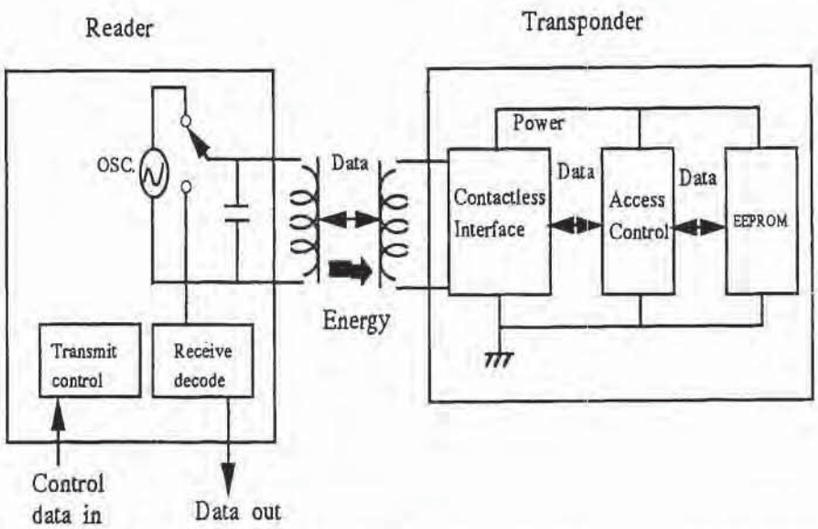


FIGURE 24.7 A block diagram of a typical antitheft system incorporating a transponder built into the ignition key and a reader unit installed near the ignition key cylinder.

ABOUT THE AUTHOR

Shinichi Kato was graduated from Tokyo Institute of Technology in 1973 and joined Nissan Motors Co. Ltd. that same year in charge of electric parts design. He was sent to Nissan Research and Development in Michigan in 1988, where he was in charge of the Ford and Nissan joint project as an electrical design engineer. He returned to Japan in 1992 as the manager of Nissan's electrical design department.

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CHAPTER 25
ENTERTAINMENT PRODUCTS

Tom Chrapkiewicz
Philips Semiconductors

25.1 FUNDAMENTALS OF AUDIO SYSTEMS

The purpose of an automotive audio system is to present a realistic illusion of a musical event. While this chapter is concerned primarily with automotive audio systems, it is appropriate to cover some of the basics of audio systems and the human auditory system.

25.1.1 Characteristics of Sound

Sound has a dual nature: it may be considered a physical disturbance in a medium such as air, or it may be considered a psychophysical perception resulting from nerve impulses stimulating the acoustic cortex of the brain. In audio, we are vitally concerned with both. The ear itself determines the quality of sound signals, but the sound is carried to the ear through physical stimuli. Acoustics is the branch of physics that deals with this transmission of sound in a medium to the ear. The complex relationship process that relates stimulus and sensation is the field of psychoacoustics.

Basic Acoustics[1]. For sound to be transmitted from one place to another, a medium is required that has elasticity and inertia. Air has these characteristics, as do other materials such as water, steel, wood, etc. When an air particle is moved by something vibrating, it moves, passing on momentum to adjoining particles as it strikes them. The original air particle is then pulled back toward its equilibrium position by elastic forces residing in the air. Any particular air particle vibrates about its equilibrium position, receives momentum from collisions, and passes momentum on to other particles, which pass it on to others, and so on. Consider a wave traveling through a pond of water. The wave progresses through the water, but each individual water molecule remains at (relatively) the same location. The actual transmission of sound through a medium is a type of longitudinal wave propagation.

The velocity at which an acoustic wave moves through a medium is dependent on that medium. The velocity of sound in air at standard temperature and pressure is approximately 344 m/s. This is considerably slower than the speed of light (3×10^8 m/s). Table 25.1 gives the velocity of sound in different media.

Any audible sound is of an alternating character with a characteristic frequency and amplitude. As this sound moves through the air, it has a particular wavelength, determined by its frequency and propagation velocity. The wavelength is calculated as:

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TABLE 25.1 The Speed of Sound in Various Media

Media	Speed of sound, m/s	Speed of sound, ft/s
Air, 21 °C	344	1,129
Fresh water	1,480	4,856
Salt water, 21 °C, 3.5% salinity	1,520	4,987
Plexiglass	1,800	5,906
Wood, soft	3,350	10,991
Fir timber	3,800	12,467
Concrete	3,400	11,155
Mild steel	5,050	16,568
Aluminum	5,150	16,896
Glass	5,200	17,060
Gypsum board	6,800	22,310

$$\lambda = \frac{c}{f}$$

Thus, a sound with a frequency of 1000 Hz has a wavelength of about 0.344 m.

25.1.2 Characteristics of Audible Sound

Amplitude Range of Sound. Obviously, sounds can be very loud or very quiet. Since the range of levels of sound is so large, a logarithmic scale is used. The unit of this measurement level is the Bel (named after Alexander Graham Bell). The threshold of hearing is about 20×10^{-6} Pa (1 Pascal = 1 Newton per square meter). The threshold of pain is over 100 Pa. This represents a ratio of over 5 million. In logarithmic terms, this ratio of 5 million is log (p1/p2) or about 6.7. Since one Bel represents a rather large difference, the decibel (or one-tenth of a Bel) is usually used. So, a ratio in decibels (or dB) is $10 \times \log$ (p1/p2). Also, since the square of sound pressure is proportional to acoustic power, we use $20 \times \log$ (p1/p2). Thus, the *dynamic range,* as it's called, of the human auditory system is: $20 \times \log (100/20 \times 10^{-6})$ or about 134 dB.

Frequency Range of Sound. As mentioned, any sound has a characteristic frequency. The average range of the human auditory system is from 20 Hz to 20 kHz. This represents a wavelength range of 1.72 cm at 20 kHz to 17.2 m at 20 Hz. A particular sound does not consist of all frequencies within this range, but only one or (usually) several frequencies (recall Fourier). Also, the human auditory system does not respond equally to all frequencies. The human auditory system is most sensitive at about 3 kHz. Some well-known frequency ranges are detailed in Fig. 25.1.

25.1.3 Basic Psychoacoustics[2]

The Human Hearing System. The human ear is commonly considered to have three parts: the outer, middle, and inner ear.[2,3] The sound is gathered and modified by the pinna, directed down the auditory canal, and terminates in the tympanic membrane (eardrum). The ear canal is about 0.7 cm in diameter and about 3 cm long. Notice that a quarter-wavelength of a wave 3 cm long is 2870 Hz, which is near the frequency at which the human auditory system is most sensitive. The other side of the tympanic membrane faces the middle ear. The middle ear is filled with air, and air pressure equalization takes place through the Eustachian tube opening into the pharynx (throat) so that static pressure is the same on both sides of the eardrum.

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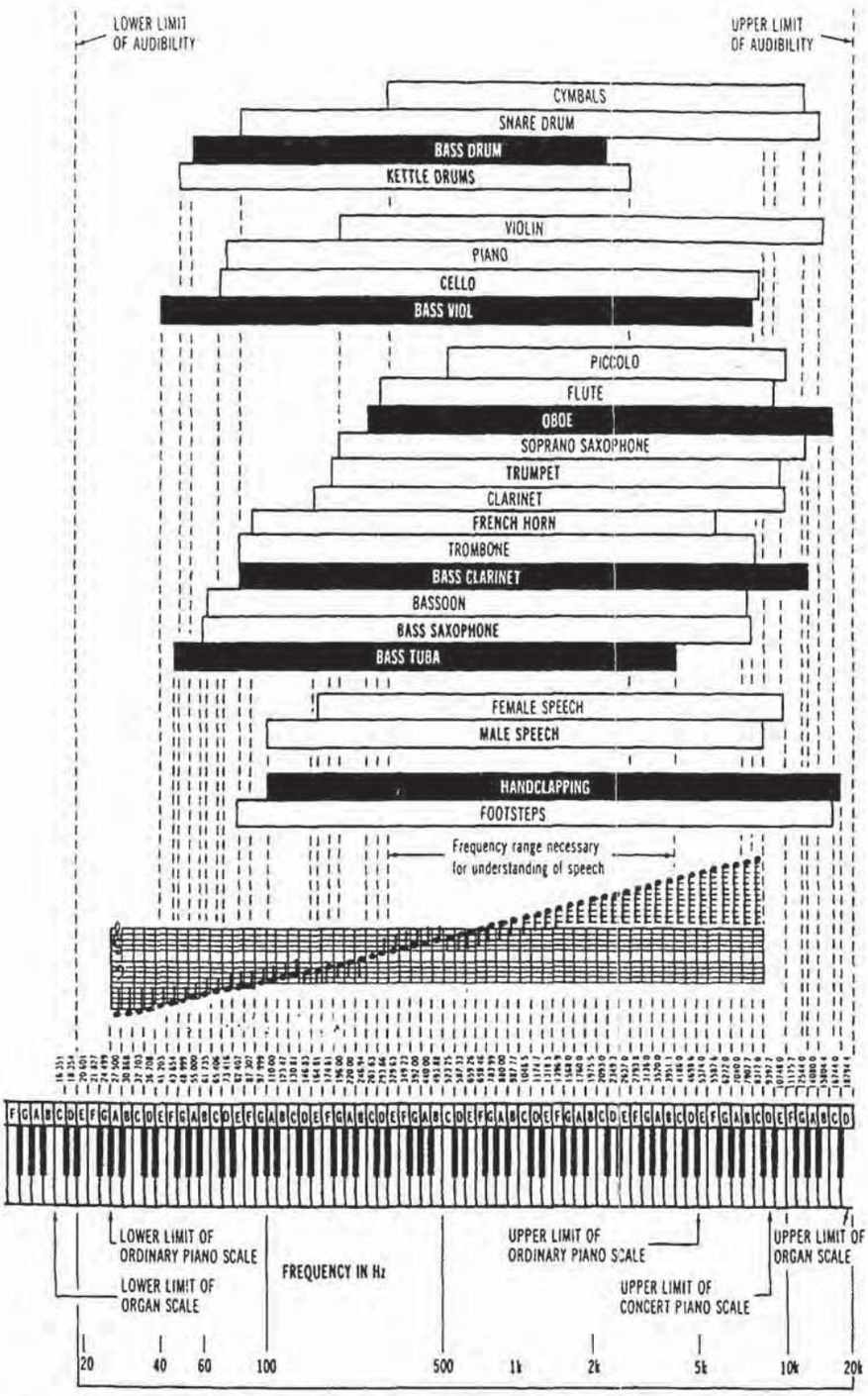


FIGURE 25.1 Audible frequency detail.

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Fastened to the tympanic membrane is one of the ossicles. The three bones of the ossicles form a lever, the end of which excites the oval window of the cochlea. The cochlea is filled with an incompressible liquid which carries the sound waves. The cochlea is lined with hair cells (about 25,000) that send nerve impulses to the brain. The cochlea is basically a mechanical-to-electric transducer.

25.1.4 Psychoacoustic Phenomena

Localization. In localizing a sound, our ear and brain mechanism utilizes several types of angle-dependent data. Due to air absorption, there are the amplitude differences between the sounds arriving at the two ears. Since our ears are 8 or 9 inches apart, there is a time delay between sounds arriving at the two ears.

There are also differences in the spectrum of the sound entering the two ears. These differences are caused by reflections on the pinna and head diffraction. It has long been believed that both ears are necessary for localization, but more recent studies have shown that listeners can be trained to localize with only one ear.[4] Ear canal measurements have shown frequency nulls around 8.2 kHz. This implies a reflected wave with a delay of about 61 μs. In an audio system with multiple loudspeakers, the ear senses multiple sound sources. The auditory system uses the timing and spectral clues to localize the apparent sound sources. In addition to the real sources (the loudspeakers), the auditory system creates virtual sources between the real sources. This effect is known as imaging. The image (sometimes also referred to as the sound stage) is used by media producers to enhance the aural experience of the listener.

Echo Perception. As noted previously, time delays of less than hundreds of microseconds are utilized as localization clues in the hearing system. For delays much greater than this, but less than about 50 ms, the auditory system integrates the energy, and perceives a fuller sound than without the delays. The precedence effect refers to the fact that if a delayed signal reaches the listener from a different direction within 50 ms of the first, the apparent sound source is still in the direction of the original signal. For delays greater than 50 ms, the listener perceives a discrete echo. Additions of echoes are used in room or hall simulation (see Sec. 25.4.2).

25.2 A BRIEF HISTORY OF AUTOMOTIVE ENTERTAINMENT

It is most curious that the gestation of both radio broadcasting and the automobile occurred almost simultaneously. In 1885, Karl Benz produced the first automobile at Mannheim, Germany. It was powered by a spark-ignited gasoline engine. In 1886, Professor Heinrich Hertz of Karlsrule Polytechnic in Germany demonstrated the transmission of electromagnetic energy from a spark.

The first automotive entertainment system was installed in 1926. William M. Heina filed a patent Sept. 16, 1926, for a "Portable Radio Apparatus." It was issued as patent #1,626,464 on April 26, 1947. The patent made no revolutionary claims, but it served as a model for many future installations. Unsubstantiated reports indicate that Radio Auto Distributors and All American Mohawk had offered automotive radios in 1926.[5] Many milestones in radio broadcasting had already occurred. In 1910, spark-gap transmission tests of the Chalmers-Detroit Motor Car Company and the 1915 experiments of DeForest and Sarnoff led to the first broadcasts of the Detroit Station 8MK (later to become WWJ) on Aug. 20, 1920, and the broadcasts of KDKA on Nov. 2, 1920 (earlier known as 8XK).

The radio circuits of the day were based on vacuum-tube designs and consequently required high voltages and power consumption. By 1931, the dynamic loudspeaker (which was pioneered by Magnavox in 1928) was installed in automobiles. (This is the fundamentally the same type of loudspeaker used today) This offered quite an advantage, since earlier elec-

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trodynamic loudspeakers had quiescent current consumption of about 1 A. Tremendous growth had occurred leading to 1930. By that time many manufacturers of automotive radios were in existence: Automatic Radio Manufacturing Company, United American Bosch Corporation, Carteret Radio Laboratories, Inc., Crosley Radio Corporation, Charles Hoodwin Co., Galvin Mfg. Corporation (later to become Motorola), National Company, Philco-Transitone, Pilot Radio & Tube Corporation, Sparks-Withington Company, and The United States Radio & Television Corporation.

The predominant medium of transmission to the automobile was via the AM band. While FM had been in existence since 1940, it was not until 1957 that the first FM radios were installed in automobiles. The year 1966 gave us the first OEM installation of 8-track tape players after a joint effort among Ford Motor, Lear Manufacturing, Motorola, and RCA. This was the medium of choice through the early 1970s, only to be replaced by the more rugged compact cassette (see Sec. 25.3.1 on Media). There were other short-lived intermediate media such as vinyl records and other obscure tape cartridges. Their life and breadth of application were very limited, although they paved the way for the media of today. Modern media such as the compact disk have limited installation rates. The medium provides superior performance, yet is not nearly as popular as cassette installations. The near-future of media may rest with the digital compact cassette (DCC) or the MiniDisc (MD).

25.3 CONTEMPORARY AUDIO SYSTEMS

An audio system could more correctly be called a high-fidelity sound reproduction system. The goal of any audio system, be it in an automobile, home, or movie theater, is to reproduce an actual or intended acoustic event. Most commercially available recordings (cassette, compact disc, or LP record) are recordings of actual acoustic events—that is, all performers performing together interacting with each other. Modern multitrack recording technology, however, has removed this restriction from the artists. The intended or virtual event that is captured may have never really occurred; it may be an imaginary event in the mind of the producer. A duet may be performed with the singers separated by many miles and even years.[6] Modern digital signal-processing (DSP) technology has allowed the artist to create not only virtual events such as this, but also virtual performers that have not ever performed a piece.[7]

The first audio system was invented by Thomas Edison between August and December 1877.[8,9] This hand-cranked system consisted of a grooved metal cylinder, a mouthpiece, and tin foil as the recording medium. The indentations in the foil cylinder were an analog reproduction of the sound waves impressed on the foil. These analog indentations were of a vertical or "hill-and-dale" nature. By 1896, Emile Berliner developed the disc recording system, in which the sound was stored on a flat disc as lateral grooves in the surface of the disc. This basic method has remained in use to this day (1994) on records otherwise known as LPs (although LPs are increasingly difficult to find). By 1926, the recording and playback of these discs had been transformed from a strictly acoustical system to an electrical system. In 1931, Alan Blumlein of Columbia Laboratories conducted experiments in stereo reproduction of sound (from the Greek *stereos*, meaning solid). These systems required two information channels and early attempts to do this on a disc failed. By 1957, commercially available stereo records became available. These had the two channels of information stored in the two walls of a single groove. It was not until the 1970s that stereo records became universal and the older, monaural records were no longer produced. During this same time period, the system of magnetic tape for audio storage was being developed, first in Germany in the 1940s and imported to the United States by the Ampex Corporation. This system stores one or more channels of information in analog form on an oxide- or metal-coated plastic tape. This system is still in use today in the form of the analog cassette (originally called the compact cassette). The compact cassette was developed in the late 1960s by Philips Corporation for use in dictation equipment

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and was shortly thereafter adapted to audio system usage. In the late 1970s, Philips and Sony Corporation began development of the compact disc system. This was the first consumer system to use a digital storage medium. The information is stored in digital form using an optical medium. By the late 1980s, the compact disc was the dominant format in dollar sales. In the early 1990s, there were several competing digital audio recording formats [digital audio tape (DAT), digital compact cassette (DCC), and recordable minicompact disc) for the home, although it is not yet clear which one will dominate the market.

A typical audio system controls a stereo signal which is obtained from any medium such as a radio broadcast tuner (AM, FM, etc.), turntable (record player), cassette tape, or compact disc. These media contain two discrete channels (left and right) of sound. Ideally, there is an infinite amount of separation between these two channels, but the human auditory system cannot distinguish separation beyond about 25 dB. In actual recordings, the information contained in these two channels is usually very similar, but different depending on the tastes of the musician and producer. The differences in the two channels is what gives recordings vastly different spatial characteristics.

Typically, these two channels are first processed by the volume, tone, and balance controls and are ultimately transformed to an acoustic signal at the loudspeakers. The analog signal levels in a modern audio system are about –10 dBu (where 0 dBu is 0.775 V), or about 0.3 V RMS with very little current capability (on the order of milliamperes). This is what is commonly referred to as a *line-level* signal. After the power amplifier stage, the signal is at a level of about 1 to 50 V with a current capability of up to 10 A. Recall that these analog signals have a 20-Hz to 20-kHz bandwidth and a 90-dB dynamic range. Digital signals in a consumer audio system (while currently rare but gaining popularity), are about 0.5 V peak-to-peak, requiring a bandwidth of about 4 megabits per second.

25.3.1 Media

AM and AM Stereo. Amplitude modulation is defined as the process of changing the amplitude of a high-frequency carrier in accordance with the amplitude of the signal to be transmitted. Commercial AM broadcasting in the United States is within the carrier band of 530 to 1600 kHz. When there is no signal to be transmitted, the carrier is of a constant frequency and amplitude. When an audio signal is to be transmitted, the amplitude of the carrier is modulated in accordance with the amplitude of the audio signal. Within the 530- to 1600-kHz band, each AM station is spaced 10 kHz apart. This allows for a maximum audio frequency of about 10 kHz to be transmitted. Thus, the AM media is limited to a maximum transmitted signal frequency of 10 kHz and a dynamic range of about 40 dB. Primary markets for AM are news, talk radio, sports, and limited music broadcasts. The nature of the AM system allows for easy corruption of the amplitude envelope from atmospheric noise, electromagnetic interference, and lightning.[10]

Experimentation as early as the 1950s and 1960s by Philco and CBS proposed AM stereo broadcasting.[11] These systems were not compatible with existing monaural systems and were consequently rejected by the Federal Communications Commission (FCC). By the late 1970s, several competing and compatible AM stereo systems were proposed. The most notable competitors were Harris, Motorola, and Kahn. The system that is in widespread use today is the Motorola C-Quam® System.[11]

FM and FM Multiplex Stereo. Frequency modulation is defined as the process of changing the frequency of a high-frequency carrier in accordance with the amplitude of the signal to be transmitted. Commercial FM broadcasting in the United States is within the carrier band of 88 to 108 MHz. When there is no signal to be transmitted, the carrier is of a constant frequency and amplitude. When an audio signal is transmitted, the frequency of the carrier is modulated in accordance with the amplitude of the audio signal. Notice that the amplitude of the transmitted modulated carrier is of a constant amplitude at all times. See Fig. 25.2 for an example

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of a typical signal and the resultant carrier in an FM system. Within the 88- to 108-MHz band, each FM station is spaced 200 kHz apart. This allows for a maximum audio frequency of about 15 kHz to be transmitted. Thus, the FM medium is limited to a maximum transmitted signal frequency of 15 kHz. Primary markets for FM have been music. The nature of the FM system provides for a very robust noise-free transmission, since any amplitude irregularities of the received signal can be ignored. Any interference which may cause amplitude irregularities can therefore be eliminated.

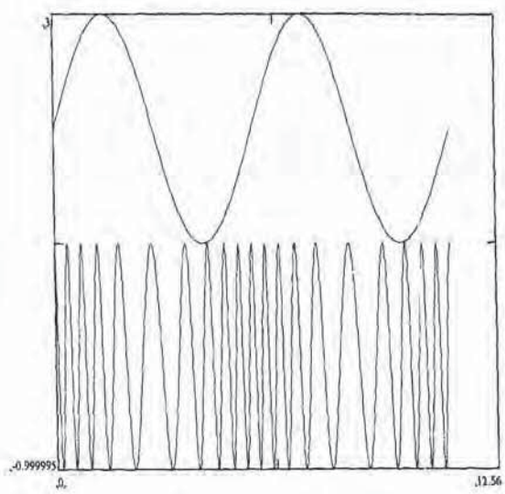


FIGURE 25.2 Signal and FM modulated carrier.

The Frequency Modulation Multiplex (FM MPX) system was developed in the early 1960s as an extension of the existing FM system. Channel-spacing is maintained at 200-kHz increments. A sum signal, the sum of the left and right channels (L + R), is frequency modulated on the carrier frequency exactly as in the monaural system. A 19-kHz pilot at 10 percent modulation level indicates the presence of a stereo signal. A difference signal (L-R) is modulated about a suppressed subcarrier of 38 kHz. The FM stereo tuner circuit demodulates and decodes these signals and outputs the left and right audio signals for further audio processing. The audio signals are limited to a 15-kHz bandwidth and a dynamic range of greater than 60 dB.[12]

FM Reception Difficulties. Due to the relatively high carrier frequency, FM broadcast reception is less susceptible to the interference and poor reception of AM systems. However, FM reception can be limited by signal cancellation which is commonly called multipath distortion.[13–15] Multipath distortion is the loss of FM signal encountered when a direct and reflected signal simultaneously arrive at the receiver out of phase and cancel, resulting in a loss of signal. Since in an automotive receiver, the receiver is constantly moving through these null zones, the familiar spitting sound results. A method for compensating for these signal losses is what is called a diversity antenna system. This is a system of two or more antennas in extreme locations on the vehicle. Since the antennas will be more than one half-wavelength apart, at least one of them will not be in a null zone. The tuner then monitors the signal content at all antennas and switches to the antenna with the best signal. Antenna switching can be accomplished in less than 30 μs of detecting multipath interference. To eliminate antenna switching noise, the switching can be synchronized with the zero crossings of the audio signal.[14–18]

The second most common FM reception problem is ignition noise.[13,14] This problem continues to increase as automotive ignition systems become increasingly complex. This problem is exacerbated by the fact that conventional methods of eliminating high-frequency radiation,

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such as resistance wires and grounding straps, do not eliminate the problems in the FM frequency band.

The circuit that detects and eliminates ignition noise is known by several different names: electronic ignition suppression (EIS), interference absorption circuit (IAC), and noise blanker (NB). Strategies for detecting ignition noise pulses vary greatly among manufacturers. The noise-blanking system may momentarily mute the audio signal or perform some type of piecewise linear approximation to the signal being repaired.

Analog Cassette. The analog compact cassette (commonly known today as the cassette) is based on conventional multiple-track stereo analog magnetic recording technology.[14,19] The cassette as we know it today was developed in 1963 by Philips Corporation primarily as a dictation medium. Advances in magnetic tape formulations and the advent of the Dolby™ B Type Noise Reduction System transformed the cassette into a high-fidelity music storage medium. Modern cassette players can achieve a dynamic range of over 70 dB and a frequency response approaching 20 kHz. Through the early 1990s, the cassette continued to be the largest revenue-producing medium for prerecorded music. More recent advances such as improved noise reduction systems and improved tape formulations are continuing to extend the life of this robust magnetic medium. As a result of its maturity and ruggedness, the cassette continues to be the most popular music carrier for automotive applications.

Compact Disc. The fundamental technology that led to the development of the compact disc[14] began in the 1970s at Philips Laboratories. The compact disc format as it exists today was codeveloped in 1980 by Philips Corporation and Sony Corporation. The basic system is an optical, noncontact system, which is also used for video (laser disc), information storage (CD-ROM), interactive media (CD-I), photo storage (Photo-CD), and other applications (CD-V, CD-G).

The playback system for a compact disc is composed of two basic subsystems: the servo and control system and the audio data processing system (Fig. 25.3). The data is read from the disc via a laser diode pickup. The focus and tracking of the pickup is controlled via the closed loop servo control system. The audio information is stored in digital form at a sampling rate of 44.1 kHz (early proposals called for a rate of 44.056 kHz for compatibility with existing video storage formats) with a resolution of 16 bits. This provides a dynamic range of over 90 dB and frequency response to 20 kHz. This digital bitstream is stored as a continuous spiral

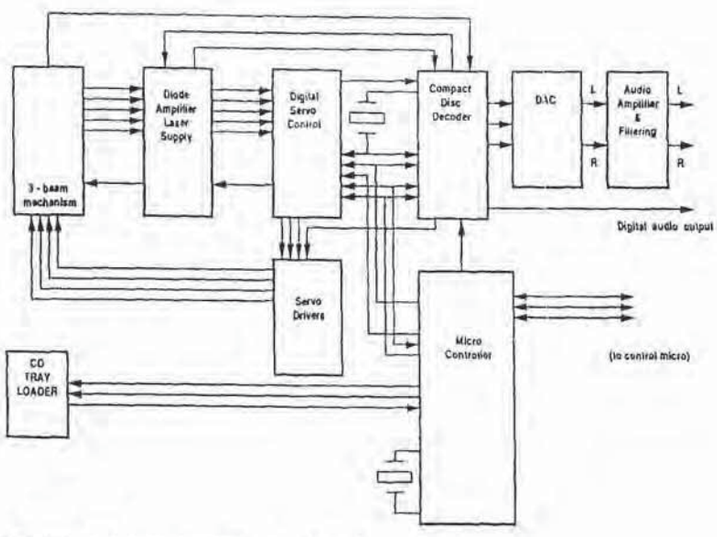


FIGURE 25.3 Typical compact disc playback system.

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track beginning at the center of the disc. The data is interleaved throughout the disc to provide robustness to errors due to scratches or dust. To further minimize errors, a Cross Interleaved Reed-Solomon Code (CIRC) is used. Due to the overhead required for interleaving and error correction, the raw bit rate from a compact disc is about 4 megabits per second. The ultimate output of a CD system can be a stereo analog output and/or a digital bitstream output. This digital output has been error-corrected and can be in one of several forms. The most common are the IEC[20] serial format which is also known as SPDIF (Sony-Philips Digital Interface Format) or I²S. The IEC format is transmitted via a single wire or possibly via a fiber optic cable. The I²S format contains separate data, bit clock, and word (L/R) clock signals.[18]

25.3.2 Signal Processing

Frequency Response Modification: Tone Controls and Graphic Equalizers and Loudness Compensation. Personal taste is certainly an important aspect in the enjoyment of any audio system. Given that the listener is presented with a music source that is somewhat flat in the frequency domain, that listener may still prefer to accentuate (boost) or attenuate (cut) certain frequency bands. The bass and treble controls provided on most of even the simplest automotive radios provide the user with the flexibility to do this. The bass control can either boost or cut the low-frequency extreme of the audio spectrum; the treble control can boost or cut the high-frequency extreme of the audio spectrum. Figure 25.4 shows the response of a typical set of bass and treble controls. For further frequency content modification, a graphic equalizer provides greater flexibility and control over the audio spectrum. This device divides the audio spectrum into several bands and allows boost or cut within these bands. Figure 25.5 shows a composite response of a typical graphic equalizer. The type of frequency response alterations described here are user-adjustable. Many automotive audio systems, particularly the higher-end systems, employ fixed equaliza-

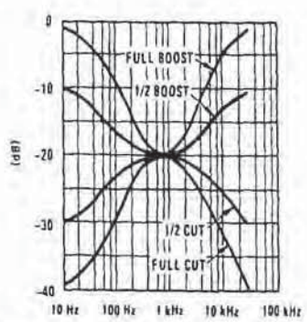


FIGURE 25.4 Bass/treble characteristic.

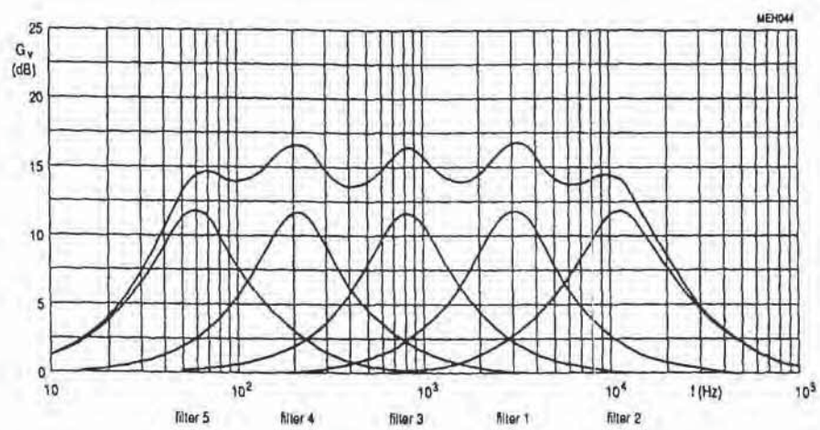


FIGURE 25.5 Graphic equalizer characteristic.

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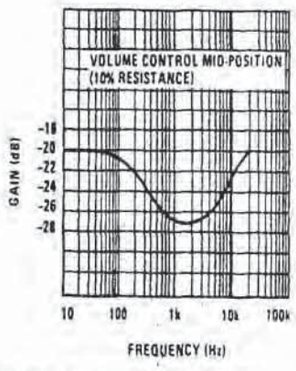


FIGURE 25.6 Loudness characteristic.

tion, which compensates for the acoustics of the vehicle interior. This type of vehicle-specific equalization is not adjustable by the user, but certainly provides an improved sound quality in the vehicle (see Vehicle Acoustics in Sec. 25.3.3).

Given the nonlinear response of the human ear to changes in level (recall the amplitude response curves), many users find it desirable to have the audio system automatically compensate for the decreasing sensitivity of the ear at low frequencies. The loudness feature is a type of automatic low-frequency boost. At lower settings of the volume control, the low-frequency output of the system is automatically boosted. This has the added benefit in an automotive environment in that a significant portion of the noise floor in an automobile cabin is low frequency (see Fig. 25.6 for a typical loudness characteristic). Some loudness characteristics also boost the high frequencies at lower volume settings. The loudness function is often hardwired into the audio system and cannot be defeated by the user.

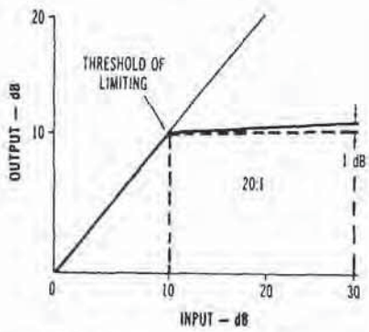


FIGURE 25.7 Limiter characteristic.

Dynamic Range Modification: Compressors and Limiters. Given the extreme capabilities of digital media such as the compact disk, compressors and/or limiters may be installed in the audio system. In order to limit these excursions, a limiting circuit may be applied (see Fig. 25.7 for the transfer function of a typical limiter). Note that in this example transfer function. for a signal above the threshold, a 20-dB change in input level will result in a 1-dB change in output level.

Wide dynamic range results in music with both extremely loud and extremely quiet passages. Given that the noise floor in an automobile environment is about 50 dB, quiet passages below that level will not be heard. A compressor will not only make the louder sounds quieter, but will also make the quieter sounds louder, thus bringing the low signal levels above the noise floor. Limiter and compressor functions may be user-switchable or hardwired on by the system manufacturer.

Power Amplifiers. For the listener to perceive sound, the air must be compressed. The transducer that accomplishes this is the loudspeaker. The power amplifiers in the audio system are responsible for providing the relatively high current drive to these loudspeakers. Modern automotive audio systems have six or more separate channel amplifiers, each of which may be required to provide up to 24 W. In order to achieve these power levels with an automobile voltage source of about 14 V, circuit techniques such as bridge-tied-load (BTL) are used.[14] Other techniques on the horizon promise more efficient delivery of power.

25.3.3 System Considerations

Signal Distribution. In the earliest days of automotive audio systems, the output of the radio was a simple loudspeaker signal which drove the loudspeaker directly. Modern systems,

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with multiple tuners and speakers, require new signal distribution for signal distribution. Further, the automotive audio system may have other essential portions of the system located outside of the traditional location in the instrument panel. For instance, recent systems locate the tuner directly at the antenna to reduce losses in the antenna wiring. Also, to reduce the I^2R losses in the speaker wiring and connectors, audio amplifiers will be located at or near the loudspeakers. This siting also minimizes the weight of lengthy high-gage wiring to the loudspeakers.

With these requirements, it is now required that system suppliers distribute audio and possibly RF signals throughout the vehicle. Depending on the noise environment of the vehicle, this may require something more elaborate than the old standard 14-gage lengths of stranded wire. Audio signals with a bandwidth of 20 kHz and nominal peak-to-peak amplitudes of 3 V must be distributed with great care. Alternatives are balanced signal drivers driving a twisted pair of wires which may have an integral shield. The twisted wire and shield minimize noise coupling into the wire. Then a receiving amplifier with good common mode rejection ratio is used to cancel out any noise pickup that may have occurred.

With increased digitization of the automotive audio system, it is worth considering distributing the signal in digital form[20] (see Sec. 25.4.1 on Media and sec. 25.4 on Future Trends). This provides a most robust method of distributing the signal without concern for noise pickup. The distribution media can be wire or fiber optic cable. If a wire is used, a shielded cable should be used to prevent radiation from the signal cable.

Standards are being proposed which may lead to control information being simultaneously transmitted along with the digital audio bitstream.[21] Thus, signal and control information share the same signal distribution media, further lessening the weight and cost impacts of multiple interconnects. This is an extension to the SPDIF standard which would provide for the automotive audio system components to be tied together via a "ring" not unlike a business computer network.

Vehicle Acoustics (Vehicle Cabin Characteristics). The interior cabin of a vehicle presents a most challenging acoustic environment. The small cabin dimensions produce standing waves which cause peaks and valleys in the low-frequency acoustic response of the vehicle interior. The highly absorptive materials (carpeting, seat material) combined with highly reflective glass, generate frequency response abberations across the audio frequency band. It should be noted that when making acoustic measurements on a vehicle, one must not rely on spot measurements. The response at any one point in the interior volume is quite irregular, and the response at various points throughout the interior volume can vary greatly. It is recommended that some type of averaged response be used to give an accurate view of what the response at various points in the interior truly is.[22]

Several techniques can be used to combat problems in vehicle acoustic problems. Acoustically transparent materials for speaker grilles are essential. Some common sense is easy to apply here: Carpeting is not acoustically transparent. Loudspeakers aimed at the listener's ears rather than pointed at a reflective surface (or within a map pocket) provide a more acoustically transparent response. Many premium or high-level audio systems provide fixed equalization, which is usually applied in the head unit or power amplifier signal processing sections. This equalization is ideally the mirror image of the vehicle cabin response, resulting in a combined response that is near flat.[22]

There is an easy way to demonstrate the frequency response irregularities caused by reflective surfaces: listen to someone talking with their hands cupped around both sides of their mouth, as they would do while shouting, or have that person hold two hardcover textbooks on either side of their mouth while talking.[23] The nasal type of sound experienced is due to the reflections within the hands or books.

A more subtle experience while listening to an automotive audio system is that of the virtual acoustic image. A note on imaging is appropriate here. Presumably, one has experienced the virtual image formed while listening to a home audio system. Any musical material that is produced equally from the left and right speakers of a properly set up audio system will

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appear to come from a virtual loudspeaker midway between the two real speakers. The ideal acoustic image within a vehicle would be front and center with the musical instruments spread across the vehicle interior. Due to the nonideal placement of the loudspeakers, the image in the vehicle may appear somewhere in the floor, the back seat, or some other nonideal location. A simple approach—although often difficult to execute—to combat this problem is to locate the loudspeakers at or close to ear level and direct them at the listener's ears. Furthermore, in a vehicle, the listener(s) are never located centrally between the loudspeakers. An interesting approach to fixing the noncentral location of the listener is to apply delays appropriate to center the image.[24]

25.4 FUTURE TRENDS

The future of automotive audio systems proves to be most exciting. Driven by the rapid increase of more powerful microcomputers, new communication techniques, improved media, and data storage techniques, the systems will change drastically through the end of this millennium.

25.4.1 Media

Radio Broadcast Data System (RBDS). The Radio Broadcast Data System is an extension of the Radio Data System (RDS) which has been in use in the European community since 1984. The system allows the broadcaster to transmit text information at the rate of about 1200 bits per second. The information is transmitted on a 57-kHz suppressed subcarrier as part of the FM MPX signal.[25,26]

RBDS was developed for the North American market by the National Radio Systems Committee (NRSC), a joint committee composed of the Electronic Industries Association (EIA) and the National Association of Broadcasters (NAB). The possibilities for applications of text transmission to the vehicle are numerous. For instance, song title and artist, traffic, accident and road hazard information, stock information, or weather. In emergency situations, the audio system can be enabled to interrupt the cassette, CD, or normal radio broadcast to alert the user, then return. Currently there are at least 50 FM stations in the United States transmitting and testing the RBDS system.[27] The system is not quite mature as of this writing, but it is anticipated to mature rapidly over the next five years.

Digital Audio Broadcast (DAB). Digital Audio Broadcasting is designed to provide high-quality, multiservice digital radio broadcasting for reception by stationary and automotive receivers. It is being designed to operate at any frequency up to 3 GHz. The system as being investigated has been developed by the Eureka 147 Consortium. This system is being demonstrated and extensively tested in Europe, Canada, and the United States. The system is a rugged, yet highly spectrum- and power-efficient sound and data broadcasting system. It uses advanced digital techniques to remove redundancy and perceptually irrevelant information from the audio source signal, then applies closely controlled redundancy to the transmitted signal for error correction (see section on recordable media that follows). The transmitted information is then spread in both the frequency and the time domains so a high-quality signal is obtained in the receiver, even under severe multipath propagation conditions. The feature of frequency reuse will permit broadcasters to be extended, virtually without limit, using additional transmitters, all operating on the same radiated frequency. A common worldwide frequency in the L band (around 1.5 GHz) is being considered, although some disagreement still exists.[28,29] The implemenation of DAB is inevitable. The only question is when.

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Recordable Media. Recent advances in recording technologies and digital signal processing have driven the development of two competing recordable media formats: digital compact cassette (DCC) and MiniDisc. The digital audio tape (DAT) has not been forgotten, but its position as an automotive medium is dubious.

Digital Compact Cassette. The DCC was invented by Philips as the marriage of the compact cassette and compact disk quality digital audio. Market forces of existing libraries of analog cassettes were deciding factors in developing a physically compatible format. A DCC player can also play analog compact cassettes. Although very similar physically, construction and recording technique used in the DCC is vastly different from the analog compact cassette. The DCC is a stationary head magnetic recording system using nine parallel tracks, each 185 mm wide. To achieve these miniature dimensions, the DCC record/playback head assembly calls on the high-tech thin-film head technology already well proven in multichannel professional recording. In order to accommodate playback of analog compact cassettes, the head unit also provides analog heads (Fig. 25.8).

In order to achieve high-quality digital audio in a limited bandwidth, the DCC relies on the psychoacoustic properties of the human hearing system. The DCC system compresses the digital audio data according to the masking properties of the human hearing system. The threshold of hearing referred to earlier in this chapter is a static characteristic and is actually a dynamic threshold. The characteristics vary with the type of sound presented to the ear (Fig. 25.9). When the ear is presented with a relatively loud sound, it cannot detect a quieter one. This phenomenon depends on the relative frequency and amplitude of the signals involved. Philips has developed the precision adaptive sub-coding (PASC) technique which implements in high-speed digital signal processing (DSP) circuits the masking properties of the human hearing system. The system determines what portion of the audible spectrum the listener is able to hear and dedicates signal processing and compression algorithms to store that portion of the signal most efficiently.[30] Testing has shown that the DCC system is actually capable of storing digital audio data to a better resolution than the compact disc.[31]

Eight of the nine tracks contain all the PASC and error correction data. The ninth track holds mainly track and time information, similar to the compact disc. The PASC data is spread across the tape in a checkerboard pattern that increases the system's robustness against dropouts. This technique is similar to the interleaving of data used in the compact disc. Cross Interleaved Reed-Solomon Code (CIRC) protects the data against further errors. Like with the compact disc, a significant portion of data can be lost without affecting the data output

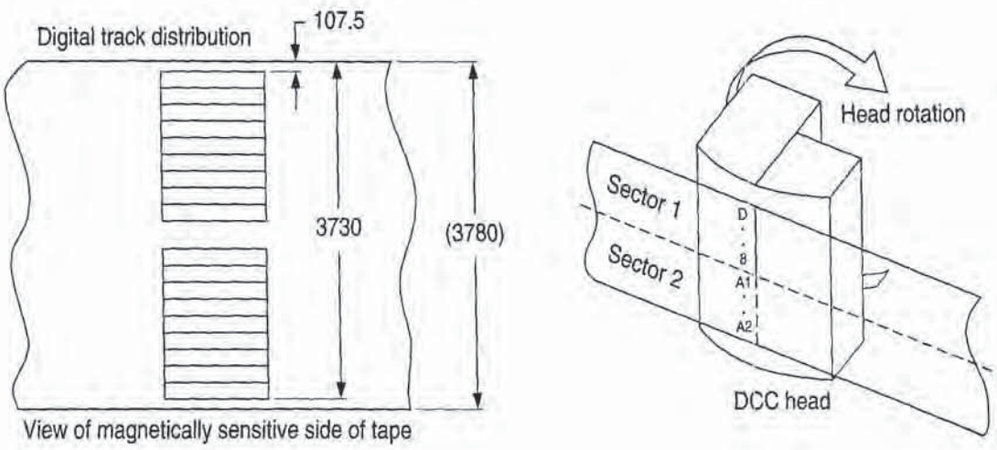


FIGURE 25.8 DCC head assembly.

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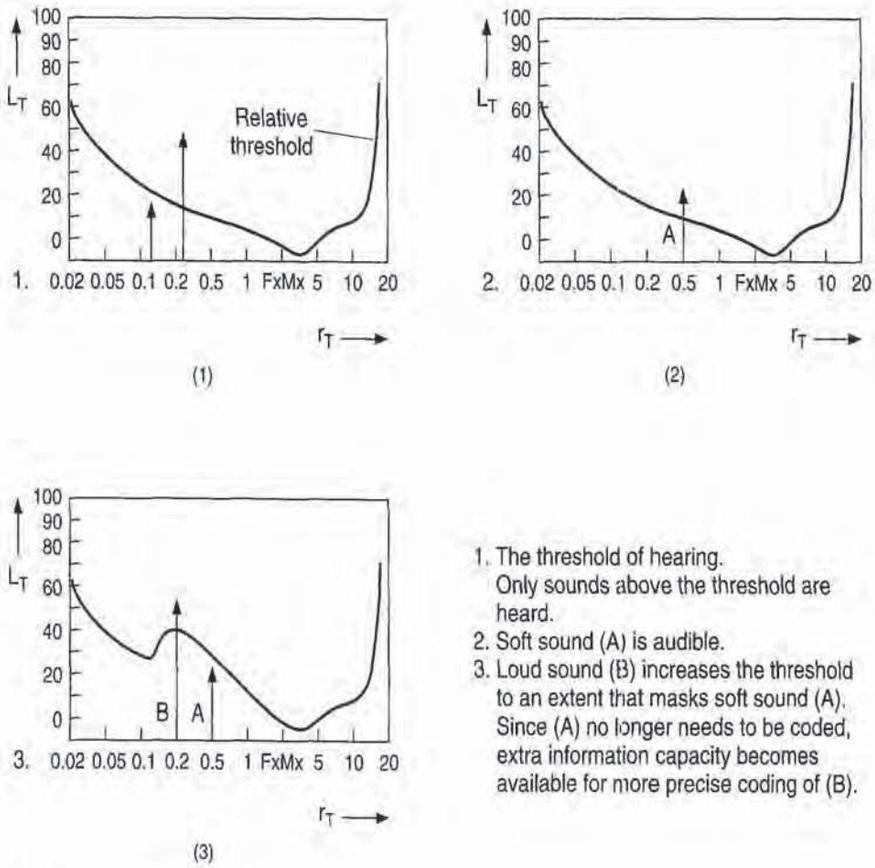


FIGURE 25.9 Hearing threshold.

(Fig. 25.10). The data storage requirements of the DCC require a digital bitstream of a maximum of 353 kilobits per second. This is as compared to the uncompressed bitstream which has a data rate of 1.4 megabits per second. This is a data reduction of four times. Notice that this requires a significant amount of computational power. Special-purpose, hardwired digital signal processors are used to accomplish the decoding task in real time (see Fig. 25.11 for a block diagram of and Table 25.2 for specifications of a complete DCC system).

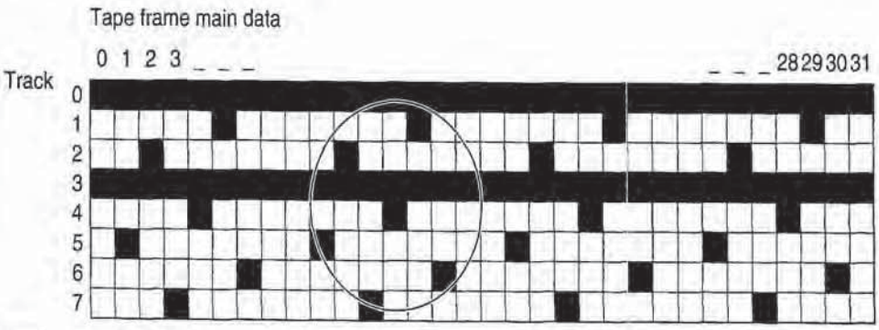


FIGURE 25.10 DCC data storage. A block as large as the circle, or an entire track can be lost without affecting data recovery.

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TABLE 25.2 Digital Compact Cassette Technical Specifications

Achievable audio performance	
Number of channels	Stereo
Frequency range at fs = 48 kHz	5–20,000 Hz
at fs = 44.1 kHz	5–20,000 Hz
at fs = 32 kHz	5–14,500 Hz
Dynamic range	>105 dB
THD (including noise)	>95 dB
Wow and flutter	Quartz crystal precision
Signal format	
Sampling frequencies	48 kHz, 44.1 kHz, 32 kHz
Coding	PASC
Audio bit rate	384 bits/s (at 48 kHz)
Error correction systems	C1, C2 Reed-Solomon block code
Modulation system	8–10 (ETM)
Pre-emphasis	Optional
Cassette	
Recording time	Up to 2 × 45 min (D90) Provision for 2 × 60 min (D120)
Tape type	(Video) chrome or equivalent
Tape width	3.78 mm
Tape speed	4.76 cm/s
Number of tracks	8 digital audio, 1 subcode
Track width	>185 μm
Track pitch	195 μm

MiniDisc (MD). The MiniDisc[32] was developed by Sony as a combination of the compact disc and a recordable medium. The recording technology used is a magneto-optical (MO) system. The form factor of the medium is very similar to a common 3.5-in floppy disk. The encoding technique in principle is similar to the PASC system. The encoding technique employed here is known as ATRAC. The MD is certainly a rugged portable medium, although subjective testing indicates that the response of the MD ATRAC system is not quite capable of encoding compact disc quality sound.

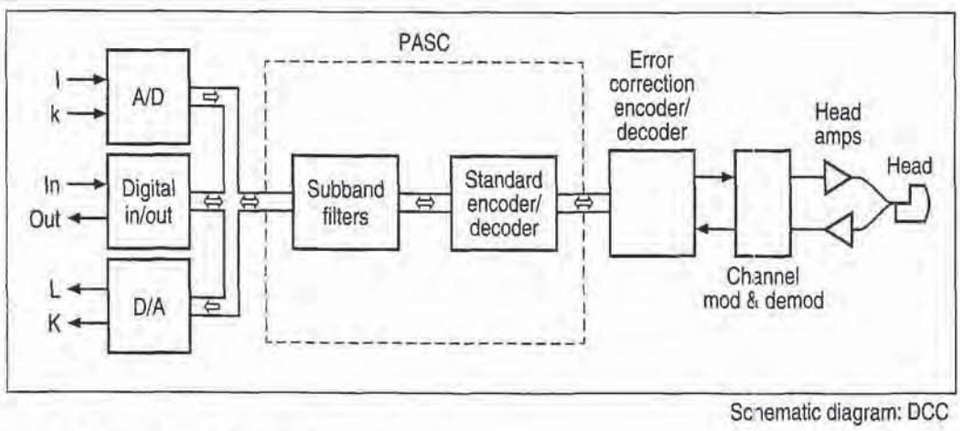


FIGURE 25.11 Complete DCC playback system.

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25.4.2 Signal Processing

Digital Signal Processing Technology. Currently, we are within a radical change in signal processing in all fields of consumer and industrial electronics. The proliferation of sound capabilities in the commonplace personal computer is a testament to this change, with further improvements and functionality coming yearly. Driven by the requirement of increased feature content and the rapidly reducing price of high-speed digital semiconductors, we will truly see a radical change in signal-processing architectures through the end of the century. Consider that the price of a state-of-the-art programmable digital signal processor (DSP) integrated circuit in 1980 was hundreds of dollars. This part could perform on the order of 1 to 5 million instructions per second (MIPS).[33] Today, a state-of-the-art programmable DSP is certainly less than one hundred dollars, with numerous units available for five dollars. Furthermore, today's DSPs will support advanced features such as shared memory, parallel processing, and high-level language support. We are beginning to see further levels of functional integration whereby formerly external functions such as analog-to-digital converters, digital-to-analog converters, and memory management units are integrated directly on the DSP. Simultaneously, these parts are exceeding 50 MIPS.[34] Additional advances are being made in integrating fixed function digital logic on the DSP. The result is that future DSPs will be tailored to specific tasks with further reduced cost. Current state-of-the-art integrated circuit manufacturing technologies are at the 1-micron feature width. Trends indicate that this will be approaching (and likely surpassing) the 0.5-micron level within the next decade. Thus, we can expect a quadrupling of functionality in the same silicon die area.

Automotive Audio Applications. Certainly the impact of the rapid advances in DSP technology on automotive entertainment systems will be far reaching. The initial impact has already happened in the area of simple audio signal processing. Numerous aftermarket and OEM offerings contain room emulation or Hall effect features. Similar to the effect available in home entertainment systems, this effect simply emulates the reflective and absorptive properties of various listening environments in the automobile. The user can then experience the ambience of a jazz room, stadium, or concert hall. Here, DSP is an enabling technology. While room emulation can be done in analog technology, it is most expensive and performs poorly. Given the sampling frequency of 44.1 kHz of most digital audio media, the DSP must be capable of processing the signal data within one sample period (about 27 μs). This is relatively easy with available DSP chips. The proliferation of digital media furthers this enabling. Analog media must first be converted to digital before the signal can be processed in the digital domain. Given that a medium (DCC, MD, or DAB) exists in a digital form, processing the signal immediately is straightforward; no conversion is necessary. A discussion of the relative merits of analog versus digital signal processing is beyond the scope of this discussion. The significant features of digital signal processing are accurate design results, ease of feature addition and extension, predictable quality, and ease of manufacturability. Consider the requirement for the addition of adding particular equalizer characteristics to an analog radio that does not have the equalizer feature installed. Considerable redesign is required to add the analog components required to achieve the equalizer function. In a DSP system, adding the equalizer function is simply a matter of adding the proper algorithms in the coding of the processor to achieve the desired signal response.

With the rapid increase in speed of DSP circuits, the amount of signal processing that can be done with the DSP is rapidly increasing. Speeds of commercially available DSP chips are such that they are capable of processing the multiplex signals of an FM receiver. Now the methods of combating multiplex distortion and other reception problems are transferred from the realm of analog circuits to the implementation of DSP algorithms. This movement of the processing towards the front end of the receiver will continue. Processing the radio frequency signal directly seems to be just over the horizon.

The signal-processing capabilities of automotive entertainment systems have seen a many-orders-of-magnitude increase and have been driven by the fact that, today, transistors are less

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costly than staples.[35] Consider that in 1930 we had radios with six vacuum tubes. Before the year 2000 we will have audio systems with multiple control microprocessors and multiple DSPs totaling the equivalent of hundreds of thousands of transistors performing calculations on the order of GIPS (10^9 instructions per second).

GLOSSARY

Acoustics The study of the generation, transmission, and reception of sound.

Analog signal A signal in which the information of interest is communicated in the form of a continuous signal. The magnitude of this signal is proportional (or *analog*ous) to the actual quantity of interest.

CIRC (Cross Interleaved Reed-Solomon Code) The encoding process used for playback error correction in the compact disc playback system.

Digital signal A signal in which the information of interest is communication in the form of a number. The magnitude of this number is proportional to (within the limitations of the resolution of the number) the actual quantity of interest.

Digital signal processing (often abbreviated DSP—as a verb). The processing of analog signals which have been converted to digital form. The processing usually involves repeated additions and multiplications.

Digital signal processor (often abbreviated DSP—as a noun). A monolithic integrated circuit optimized for digital signal-processing applications. Portions of the device are similar to a conventional microprocessor. The architecture is highly optimized for the rapid, repeated additions and multiplications required for digital signal processing. Digital signal processors may be implemented as programmable devices or may be realized as dedicated high-speed logic.

Dynamic loudness compensation A type of loudness compensation which is dependent on the actual signal level rather than the position of the volume control. This is greatly enabled through the use of digital signal processor integrated circuits.

Equalization The modification of the frequency response of a system. This may be done to compensate for deficiencies in the transmission/reception system or based on the subjective requirements of the user.

Loudness compensation The characteristic of an audio system to boost the low- and (sometimes) high-frequency components of an audio signal. This is to compensate for the human ear's decreasing sensitivities at these ends of the spectrum. The amount of boost is usually dependent on the position of the volume or level control. See also **Dynamic loudness compensation**.

Monaural Traditionally refers to an audio signal that has only one channel of information. Also may refer to the signal component in a stereo transmission which is common between the two (left and right) channels. Also commonly referred to as "mono."

Multiplex stereo The system standardized in the early 1960s to transmit and receive a stereo signal. This system was designed to be compatible with existing FM systems which were monaural. See text for details.

Psychoacoustics The study of the interaction of acoustics and the human hearing and brain systems.

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Signal A fluctuating quantity that is proportional to some physical quantity. In the context here, the signal is usually in the form of a voltage or current. See also **Analog signal** and **Digital signal**.

Signal processing Modification of the time or frequency characteristics of a signal.

Stereo Classically, from the Greek *stereos*, meaning "solid." Traditionally refers to an audio system which has two or more independent channels of audio information. A typical stereo system consists of primarily a left and a right channel. Modern surround sound systems contain from four to as many as seven channels of information.

Sound A vibratory disturbance in the pressure and density of a fluid or in the elastic strain in a solid, with frequency in the range of about 20 to 20,000 cycles per second, capable of being detected by the organs of the human hearing system.

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ABOUT THE AUTHOR

Thomas Chrapkiewicz has been an applications engineer for Philips Semiconductors since 1993. As an analog design engineer from 1977 to 1983 at both ADM Technology (formerly Audio Designs and Manufacturing) and Harris Broadcast Products, he designed audio circuits and systems for broadcast, recording, and film applications. He then spent 10 years designing analog and digital signal-processing circuits for Ford Motor Co.

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CHAPTER 26
MULTIPLEX WIRING SYSTEMS

Fred Miesterfeld
Chrysler Corporation

26.1 VEHICLE MULTIPLEXING

Production and proposed passenger vehicle multiplexing and data communications network systems will be thoroughly examined in this chapter. The systems covered are those methods that are relevant to the electronic engineer who has the assignment of applying multiplexing techniques to high-volume production. In passenger vehicle design, cost is the universal method of determining whether or not a design will be put into production. If a multiplex network design can be applied while delivering functional improvements at a system-cost saving, then this design is the most likely network design to be accepted.

The SAE Vehicle Network for Multiplexing and Data Communications (Multiplex) Committee has defined[1] three classes of vehicle data communication networks:

Class A. A potential multiplex system usage where vehicle wiring is reduced by the transmission and reception of multiple signals over the same signal bus between nodes that would have ordinarily been accomplished by individual wires in a conventionally wired vehicle. The nodes used to accomplish multiplexed body wiring typically did not exist in the same or similar form in a conventionally wired vehicle.

Class B. A potential multiplex system usage where data (e.g., parametric data values) are transferred between nodes to eliminate redundant sensors and other system elements. The nodes in this form of a multiplex system typically already existed as stand-alone modules in a conventionally wired vehicle.

Class C. A potential multiplex system usage where high data rate signals, typically associated with real-time control systems, such as engine controls and antilock brakes, are sent over the signal bus to facilitate distributed control and to further reduce vehicle wiring.

The Class B network is intended to be a functional superset of the Class A network; i.e., the Class B bus must be capable of communications that would perform all of the functions of a Class A bus. This feature protects the use of the same bus for all Class A and Class B functions or an alternate configuration of both buses with a *gateway* device. In a similar manner, the Class C bus is intended as a functional superset of the Class B bus.

Generally, this section will deal only with the requirements for the lowest three layers of the seven-layer ISO open system interconnects (OSI) model (Ref. ISO 7498). These layers in descending order are the network layer, data link layer, and the physical layer.

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26.1.1 Background of Vehicle Network Architectures

A wide variety of network topologies[2] can be envisioned by network designers. The message structure described in this section is very flexible and useful in exchanging information between network nodes. The following discussion describes two network architectures which are likely configurations that can use this message definition set: a single-network architecture and a multiple-network architecture.

The selection would be application-specific and, thus, it is the system designer's choice as to which network architectures to use. It should be noted that the hardware that supports these two message structures is generally not interchangeable. It is recommended that care be taken in choosing which message definition to use, because the selection is generally irreversible because of hardware limitations.

Header Selection. The header field (header) is a one-, two-, or three-byte field within a frame and contains information about the message priority, message source, target address, message type, and in-frame response. The multiple network architecture is usually associated with the single-byte header protocol. Figure 26.1 (1) illustrates the header byte as the message identifier (ID), which is primarily used for functional "broadcast"-type messages and implicitly defines all the required information about the message. It is unnecessary to specify the source or destination of functional-type messages. Reception becomes the exclusive responsibility of the receiving node. Figure 26.1 (2) also illustrates header bytes, which are primarily used for physical-type messages, and has two bytes: the first is the ID and the second is the target address.

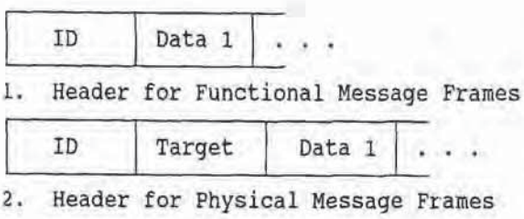


FIGURE 26.1 Single-byte header protocol.

The single-network architecture is usually associated with the multiple-byte header protocol, shown in Fig. 26.2. The first byte of the frame defines the priority and message types, functional or physical.

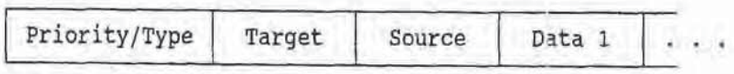


FIGURE 26.2 Multiple-byte header protocol.

Architecture Selection. Consideration must be given by the network designer as to whether a single-network architecture or a multiple-network architecture is preferable for an application. For example, a multiple-network architecture could be based on one network optimized around data communication (Class B) protocol requirements, and another network optimized around sensor type (Class A) multiplexing requirements. The Class B network may be characterized such that low latency is a significant requirement of the protocol and where the short functional type of messages can most effectively be used. A Class A network could handle the vehicle's event-driven multiplexing requirements. See the next section on Class A networking for more information on Class A multiplexing considerations.

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Without regard to either the header or architecture selection, in Class B communications the network consists of the interconnection of intelligent nodes such as an engine controller, a body computer, a vehicle instrument cluster, and other modules. Such a network normally does not significantly reduce the base vehicle wiring but provides an intermodule data communications capability for distributed processing. The data shared between modules may be repetitive in nature and sometimes requires handshaking between modules or acknowledgment of data reception. As a result of handling the repetitive data and response-type data, a network can be optimized around functional addressing. Functional addressing sends data on the network, which can be received by one or more nodes without regard to the physical location of the module but only by their "interest" in those specific functions. In general, the transmitting node does not care which, if any, nodes receive the data it is sending. When physical addressing is required in a data communications network (Class B), it is usually for vehicle maintenance purposes and can be easily handled without reducing network bandwidth.

The nature of Class A multiplexing requires the interconnection of limited intelligence nodes, often simply sensors or actuators. These Class A networks can significantly reduce the base vehicle wiring as well as potentially remove redundant sensors from the vehicle. The data shared between nodes in this case are generally event-driven in nature. In most vehicles, the number of event-driven signals predominates, but they are only needed infrequently. The message to "turn headlamps on," for example, can be easily seen as event-driven. Because these messages are infrequent (only sent once when the signal changes) they generally require acknowledgment, either within the same message or a separate handshake/response message.

The single-network architecture carries both the Class A and Class B messages on one network and the multiple-byte header has the advantage of having more bits available for use in assigning message identifiers, priorities, message types, etc. The characteristics of both time-critical and event-driven messages must be accommodated on a message-by-message basis. In general, this level of complexity will need the flexibility of the multiple-byte header structure. It should be clear that both network architectures must be cost effective for the application and the specific nodes on each network.

The multiple network architecture tends to separate the Class A messages from the Class B messages and optimize each network and node interface for the specific characteristics of each network class. The time-critical messages could be exchanged on one network, while the event-driven messages are sent on another. For example, the data communication (Class B) repetitive messages can be handled on one network and the sensor and control (Class A) multiplexing requirements on another network. This architecture requires both networks to work together to achieve the total vehicle network requirements. If information is needed between the multiple networks, care must be exercised to meet the needs of each of the networks. This concept of multiple networks is not limited to two, but can be extended to several separate networks if desired.

Class A Network. Class A multiplexing[3] is most appropriate for low-speed body wiring and control functions. The example most often used to illustrate the benefits of Class A multiplexing is the base exterior lighting circuit. However, this example is the hardest function to cost-justify. The base exterior lighting system is extremely simple and very low cost. A multiplex network applied to this lighting system could result in increased wiring complexity and cost. Data integrity in the lighting system can be a stringent requirement for Class A multiplexing; e.g., a single-bit error that results in headlights "off" when they should be "on." Adequate data integrity in a Class A multiplex network is a constraint and bit-error checking may be required.

In the future, the results could change if new features, such as low-current switching or lamp-outage warning, became a requirement or new lamp technology, such as smart bulbs, became a reality. In general, the addition of new features will play a major role as to when and how multiplexing will become a cost-effective solution.

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Other Driving Forces. The design of vehicles to minimize manufacturing complexity is a major force that will lead to architecture partitioning development. The properly developed multiplex architecture can be very effective in reducing the number of parts in the assembly plants and built-in testability can substantially reduce vehicle build test time.

Example Class A Systems. To illustrate how a Class A multiplex network could be used to simplify the vehicle wiring situation, consider the vehicle theft alarm system shown in Fig. 26.3. Although this example does not represent the epitome in theft alarm features, it does illustrate the nonmultiplexed condition. The horn actuator and the sensor switches are all wired directly to the theft alarm module. The module is then armed by activating the dash arm switch. The module can be disarmed by either the driver door key switch, passenger door key switch, or the trunk key switch. When the module is armed, the horn is sounded when the hood, door, or trunk is tampered with.

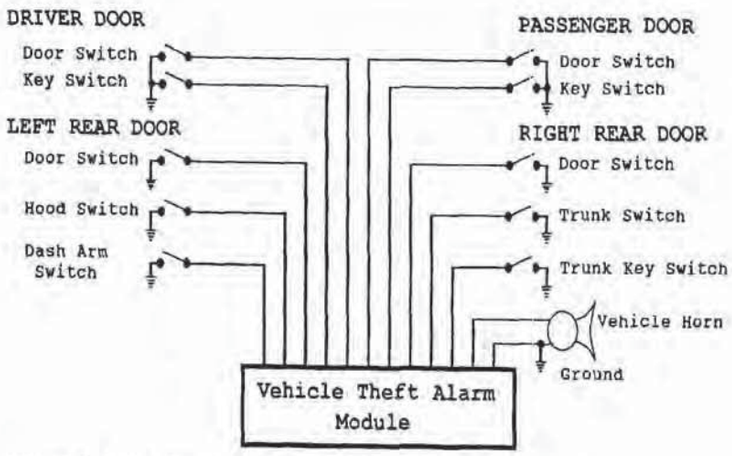


FIGURE 26.3 Vehicle theft alarm system.

The vehicle theft alarm system shown in Fig. 26.4 illustrates a near-optimal configuration of a Class A network. The sensors and actuators are integrated with the multiplexing electronics so that they can communicate over a single wire to the theft alarm module. The integration of electronics into the sensors and actuator improve sensor diagnostics because the sensor status and condition can be reported back to the controlling module. The integrity of the sensor status and condition can be linked to the mechanical operation of the sensor. This level of switch integrity cannot be achieved with normal switch-biasing methods. In a theft alarm system, there is an added benefit: the sensor condition can be used to set off the alarm and foil the tampering of a would-be thief.

The I/O requirements support T-tap connections, which can be highly automated in the production of wiring harnesses, reducing the wire bundle size and eliminating dual crimps. The configuration also supports the concept of adding sensors or actuators as the option requires without changing the theft alarm module configuration to support the optional features. This expandability feature allows the cost of the option to drive the system cost.

To show how this configuration is flexible and easily expandable, consider the example condition in which some versions of theft alarms are built as originally described, but an upscaled version is offered as an option in which the unit is armed by the driver locking the doors. To support this option, the dash arm switch would be eliminated and the driver door lock switch would be configured with the integrated switch multiplex at a different address. The same theft alarm module's software could then reconfigure itself without hardware modifications.

There are approximately seven sensors to every actuator in a real vehicle body system. This theft alarm system is typical with 10 sensors (switches) to one actuator (horn).

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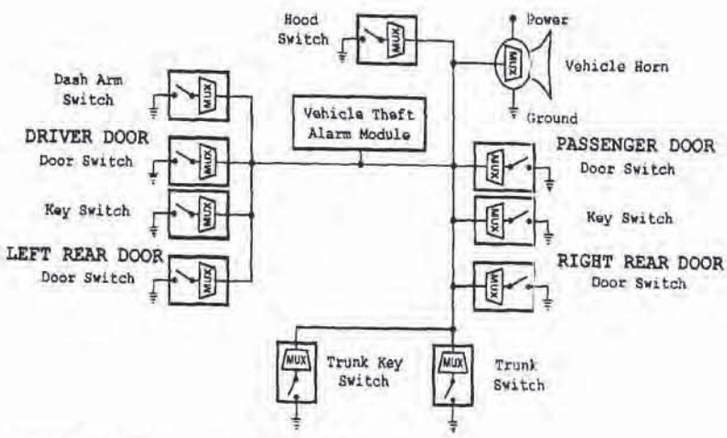


FIGURE 26.4 Multiplexed vehicle theft alarm system.

The sensors and multiplexing electronics can be integrated into the switch component. This configuration eliminates separate wiring and mounting of the multiplex module. Some component manufacturers have even been working on two wire (signal and ground) sensors in which the power to run the sensor has been supplied by the multiplex signal. For an example component, see Sec. 26.3.7. These sensors have been designed to include the multiplex circuit integrated with the Hall effect device in the same TO92 size package. The multiplexer portion is very small and requires approximately 300 logic gates.

The actuator driver and multiplexer can similarly be integrated into the horn or motor. This configuration also reduces wiring and mounting complexity. Actuators normally require more power then sensors and usually require three wires; signal, power, and ground. However, some manufacturers are developing a method to eliminate one of these wires by placing the signal on the power wire.

Class B Data Communications. The vehicle system designer now has many architecture partitioning options. A prime example is when to integrate many features into a module or when to employ a dedicated node. Care must be taken or the partitioning strategy may not achieve optimal results. The issue is much more complex when vehicle multiplexing is involved in this partitioning strategy. The most popular networking strategy is the Class B single-network architecture. However, this architectural strategy does not always result in an optimal solution.

A hypothetical vehicle will be described to illustrate this point. Figure 26.5 illustrates the part of a data communications network that contains a body computer, an instrument cluster, and a message center. In this example, all the sensors that feed the network enter through the body computer.

As illustrated in Fig. 26.5, all sensors are wired directly to the body computer. This example shows that for a base vehicle with only a small amount of electronic content, where all the sensors are directly wired to the body computer, the wire bundle size and number of connector pins is attainable. As additional features are made standard, either by consumer demands or government regulations, it becomes more and more difficult to implement the required system. This added complexity is due to the tremendous number of interconnecting wires from sensors to the modules. The build complexity and troubleshooting problems make this option a limited solution for this partitioning strategy.

The Class B single-network architecture strategy would solve this complex problem by adding a sensor node and reducing the number of interconnecting wires. Conventional sensors are connected directly to the node which serves as a gateway to the other modules over the Class B data network. Figure 26.6 illustrates the dramatic reduction in the number of cir-

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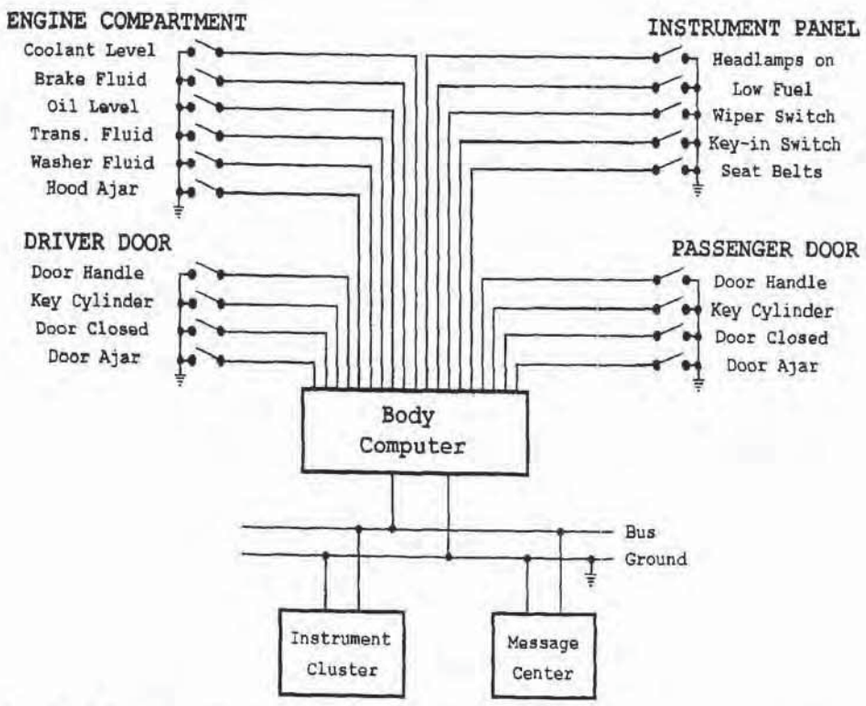


FIGURE 26.5 Data communications network with body computer, instrument cluster, and message center.

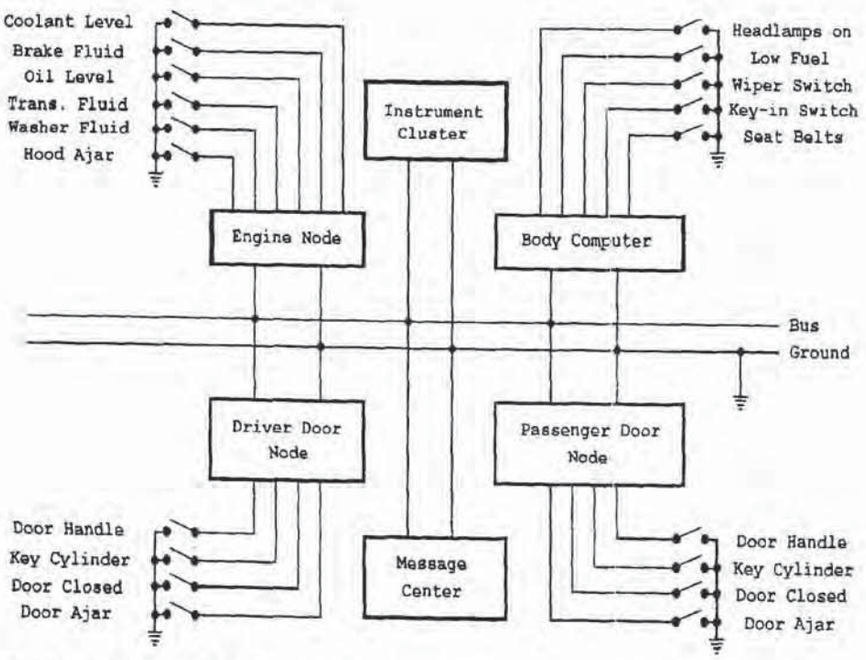


FIGURE 26.6 Data link with body computer, instrument cluster, message center, and three sensor nodes.

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cuits required. This method is effective in reducing the number of sensor wires connected through "crunch points" such as the bulkhead or door hinge. This reduction in wiring, however, is obtained at the expense of three added sensor nodes.

Class B multiplexing is a very useful technique for reducing many of the problems encountered by the automotive system engineers. This section will demonstrate that in many situations the multiplex strategy, shown by Fig. 26.6, leads to a less than optimum system architecture. It is highly desirable to have a multiplexing architecture which would permit the use of smaller module connectors, reduce the number of wires crowding through the congested areas, and attain a solution without introducing more modules to mount, wire, and service.

Engine Compartment Node. In this hypothetical example, it may be desirable to integrate the node with the engine controller module, which would reduce module count and wiring circuits at the same time. The integration solution is not always possible because the engine controller already has an uncontrollably large module connector and would add a separate part just to cover an option.

Door Nodes. In this hypothetical example, the best location for the door node would be inside the door (See Fig. 26.7). By placement inside the door, the number of circuits through the door hinge is minimized, but without making further improvements the same wiring complexity inside the door still exists. These further improvements generally could integrate the electronics and mechanics into a single package.

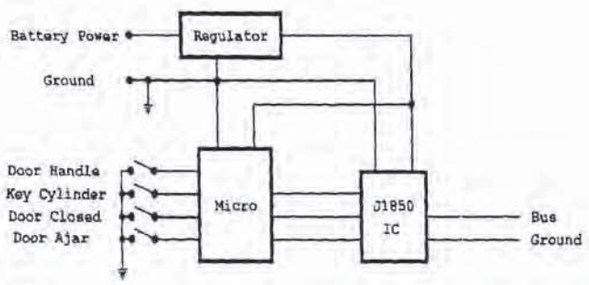


FIGURE 26.7 A driver door node.

General Node Concerns. General node concerns include the following:

- In order to achieve minimum cost, nodes tend to become application-specific and not generic because they usually can cover only one feature product.
- To cover more than one product, nodes tend to become intelligent and employ a microcomputer, and may negatively impact the system cost and complexity.
- Using conventional sensors remote from the node does not normally improve sensor diagnostics; e.g., the node cannot tell if the sensor switch is off or if the wire is disconnected. Refer to the previous section, "Example Class A Systems," for a discussion on switch integrity.
- The door node illustrated in Fig. 26.7, and nodes in general, can be effective in some wire bundle size and weight reduction but further improvements are possible with Class A sensor/actuator networking. The number of connector pins for the system can also be reduced with Class A networking.

Multiple Network Architecture. The multiple network architecture is the second strategy that solves many of these concerns. This architecture requires the development of many types of specialized network hardware components to efficiently handle each application. These components are connected together by a gateway on the Class B network for diagnostics purposes. Figure 26.8 illustrates this local area network (LAN) solution.

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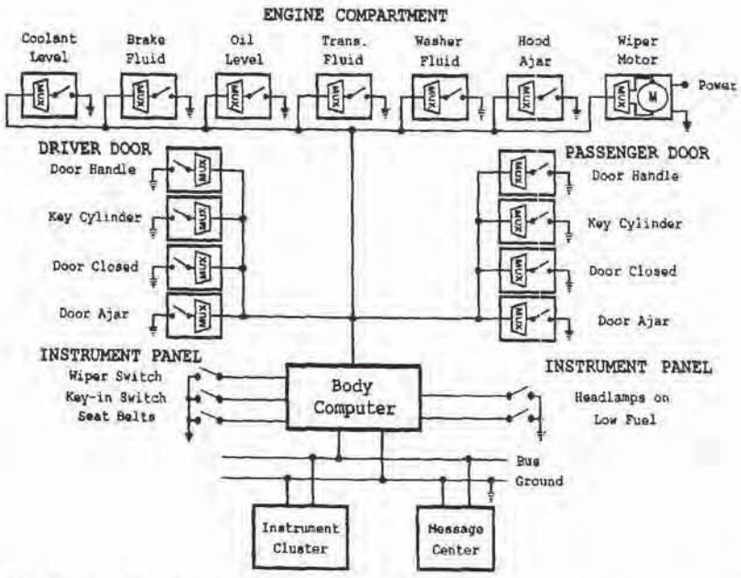


FIGURE 26.8 Data link with body computer, instrument cluster, message center, and Class A network for sensors.

Multiple network architecture strategy requires the integration of electronics into the sensors, actuators, and motors so that they can communicate over a single wire into the module that utilizes them. Since the sensor and actuator components contain the added multiplex electronics, the separate installation and wiring of the multiplex module is eliminated. Unlike the single-network architecture strategy, the integration of electronics into the sensors, actuators, and motors normally does improve sensor diagnostics because the sensor status and condition can be reported back to the controlling module. This method makes use of a Class A LAN without adding components to the vehicle system.

Figure 26.8 shows that the Class A LAN eliminates the need for the engine compartment node and two-door sensor module while still reducing wiring at the crunch points. The multiplex architecture shown in Fig. 26.8 significantly simplifies the same system shown in Fig. 26.6. This simplification is made possible by separating the Class B intermodule communications network from the Class A sensor-to-module communications.

The Class A LAN connects all the multiplexed components in parallel. The I/O requirements support T-tap connections, which can be highly automated in the production of wiring harnesses. This configuration reduces bundle size and eliminates dual crimps. The configuration also supports the concept of adding sensors or actuators, as the option requires, without changing the body computer configuration to support the option. This add-on feature allows the option to dictate the cost and not the cost of the added node dominating.

The two different Class A networks using multiplexed sensors are shown in Fig. 26.8 and Fig. 26.9 and illustrate a body computer flexibility trait that is not available in the other architectural approaches. The typical base vehicle using the Class A network is shown in Fig. 26.9. The body computer in the base, medium, and premium vehicle systems all have the wiper switch, seat belt switch, headlamps on, low fuel level, key-in ignition switch, Class A interface, and the Class B multiplex interface. This trait across option rates allows additional inputs to be connected without modifying the hardware in the body computer.

Unlike this hypothetical situation just used for illustration purposes, a real vehicle will have several actuators as well as sensors connected to the body computer. As it was previously discussed, there are approximately seven sensors to every actuator in a real vehicle body system. For illustrative purposes, 14 sensors and one actuator (wiper motor) were shown in this example. The principles shown, however, apply similarly to any number of actuators.

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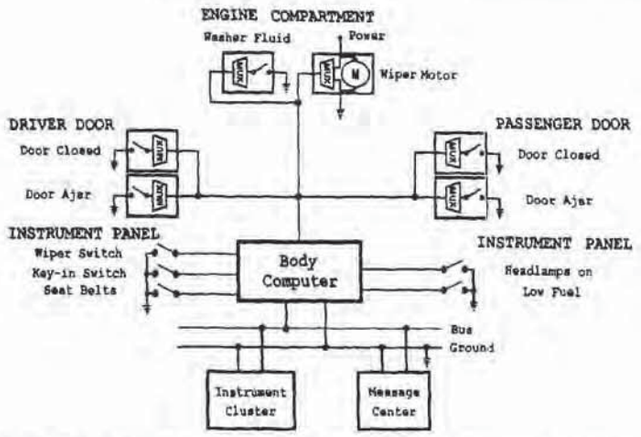


FIGURE 26.9 Base vehicle with Class B data link, body computer, instrument cluster, message center, and Class A network for sensors.

Class C Real-Time Control. The Class C network is the least mature network, and consensus of opinion on requirements does not yet exist. Experts cannot agree on many facets and many of the requirements are controversial. Many automotive engineers believe that an adequate statistical latency achievable with a bit-by-bit arbitration-based media access protocol is sufficient for real-time distributed Class C multiplexing. Others believe a token-passing media access protocol is required because a maximum latency is guaranteed, because with an arbitration-based media access only a statistical maximum latency is achievable. There are still others who argue that both the arbitration-based and token-passing media access is not good enough for tightly looped distributed processing because both methods have too great a variation in latency time. They argue that a time-triggered media access method is required because the network variations in latency should not affect tightly looped processing times. Other factors such as required data rates and the physical media type also remain open. It is clear that more research and development is required to resolve these questions.

26.2 ENCODING TECHNIQUES

The data encoding technique[4] has a significant effect on the radiated EMI. In order to achieve the highest possible data rate, it is important to choose a data-encoding technique that has the fewest transitions per bit with the maximum amount of time between transitions and bit-synchronized so that invalid bit testing can be effective. PWM, for example, has two transitions per bit with ½ bit times between transitions. NRZ has a maximum of one transition per bit but is increased to provide for synchronization. Some of the disk drive encoding techniques such as modified frequency modulation (MFM) are synchronous with fewer than one transition per bit. (See Table 26.1 for a comparison chart of a selection of encoding techniques used in vehicle multiplexing.)

The variable column in the table describes an attribute whereby the transmission time for data byte is a variable quantity depending on the data value. VPWM and Bit-Stuf NRZ both have variable byte repetition rate (*data variability*).

Some of the bit-encoding techniques synchronize on transitions that fall on or within the bit boundaries. 10-bit NRZ, Bit-Stuf NRZ, and E-MAN all employ added transitions for synchronization (*clock synchronization*).

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TABLE 26.1 Comparison of Multiplexing Bit-Encoding Techniques

	PWM	VPWM	10-Bit NRZ	Bit-Stuf NRZ	L-MAN	E-MAN	MFM
Variable	No	Yes	No	Yes	No	No	No
Synchronizing	Yes	Yes	No	No	Yes	No	Yes
Arbitrates	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Transition/bit	2	1	≤1.25	≤1.015	≤2	≤1.25	≤1
Max data rate	7.1 K	11.2 K	13.5 K	16.6 K	8.4 K	13.5 K	16.8 K
dBV < PWM	Base	9	11	14	5	11	15
Oscillator tolerance	±29.2%	±29.2%	±5.1%	±9.7%	±29.2%	±9.7%	±10.7%
Integrity	Perfect	Good	Fair	Fair	Perfect	Fair	Superb

All of the encoding techniques considered are capable of bit-by-bit arbitration. This is not commonly recognized with some of the encoding techniques, e.g. MFM, and will be addressed in Sec. 26.2.7 (*arbitrates*). Bit-by-bit arbitration is calculated on the number of *transitions per bit* of data.

A suitable data-encoding technique should not generate excessive levels of EMI, and this consideration is a dominating challenge in making an encoding choice. The CISPR Standard* is usually considered adequate. This factor determines the *maximum allowable data rate* of the encoding technique, in order to maintain a level of EMI below the CISPR standard break point, i.e., –60 dBV at 500 kHz. The values predicted in Table 26.2 used the same technique described in the next section.

Equation (26.1) in Fig. 26.10 can be used to predict[5] the EMI levels radiated by a single wire in a vehicle wiring harness. The technique was used to calculate and plot a Fourier series of a sample trapezoid wave to determine the values given in Table 26.2. The calculations assumed a 10.4 Kbps data rate at a 42 percent factor of the minimum feature size (minimum pulse width) to determine the rise time. Consider the trapezoidal wave shown in Fig. 26.10. The shortest rise time (42 percent of shortest pulse width), shortest pulse time, and fastest repetition rate should yield the worst-case EMI in dBV. The actual measured EMI will be a few dBV better than the calculated dBV because the output driver frequency bandwidth does act as a low-pass filter [EMI below PWM (dBV < PWM)].

* CISPR/D/WG2 (Secretariat) 19 Sept 1989 Radiated Emissions Antenna & Probe Test Document has been generally interpreted by most RF engineers to specify a break point at 500 kHz of –60 dBV.

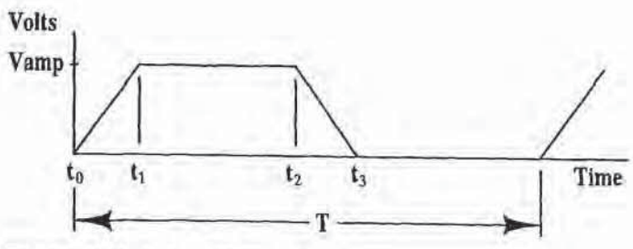


FIGURE 26.10 Trapezoidal wave shaping.

$$\omega_1 = \frac{2 \cdot \pi}{T}$$

$$\text{freq} = \frac{n}{T} \quad \text{where } n \text{ is an integer}$$

$$a = n \cdot \omega_1 \cdot t_1$$

$$b = n \cdot \omega_1 \cdot t_2$$

$$c = n \cdot \omega_1 \cdot t_3$$

$$\Re = \frac{-1}{t_1} + \frac{Cos(a)}{t_1} + \frac{Cos(b) - Cos(c)}{t_3 - t_2}$$

$$\Im = \frac{-Sin(a)}{t_1} + \frac{Sin(c) - Sin(b)}{t_3 - t_2}$$

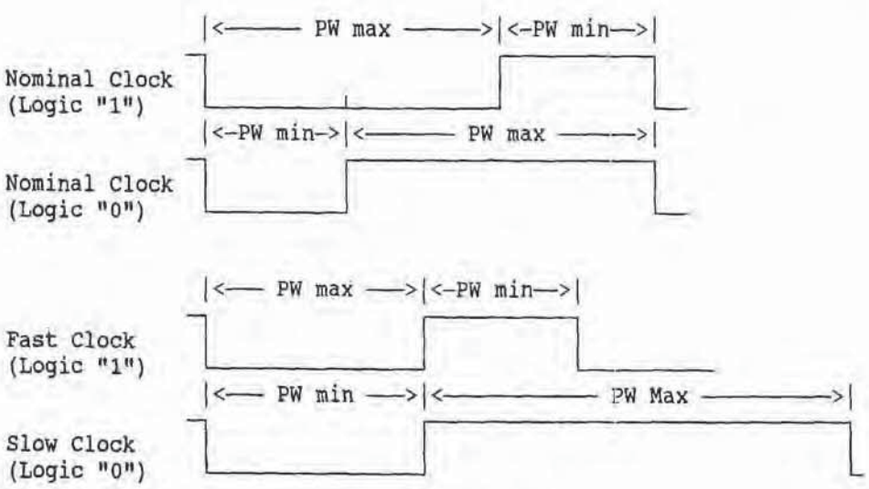
$$MAG = 20\log \frac{Vamp \cdot T}{(2 \cdot n \cdot \pi)^2} \sqrt{R^2 + F^2} \quad (26.1)$$

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There are a number of hardware constraints that affect network synchronization and *oscillator tolerance.* The values given in Table 26.2 are calculated without considering these constraints because they are not generally considered a factor for evaluating encoding techniques. For all encoding techniques, the same nominal bit rates or average bit rate, as in the case of VPWM, was used. The small decrease in data rates for 10-Bit NRZ, Bit-Stuf NRZ, and E-MAN, due to the added bits for synchronization, is normally neglected; i.e., Baud rate was used.

The technique used by the receiver to detect a synchronizing transition plays a role in determining oscillator tolerance. Many different sampling or integration techniques could be used for a comparison, but for the sake of obtaining a reasonable judgment, for the encoding techniques under consideration, a very simple pulse width counter technique was assumed. A 12.5 percent of minimum pulse width (PW min) was assumed for variability in integration time (IT). The maximum time for synchronization was either the maximum pulse width (nominal) or time (nominal) between synchronization transitions.

Equation (26.2) in Fig. 26.11 yields the natural oscillator tolerance for the encoding technique. Figure 26.11 illustrates the maximum fast clock and minimum slow clock that can determine the logic value, either a "1" or a "0", for the symbol decoded by the symbol decoder. The IT is the time of uncertainty in determining the pulse width. The example demonstrated is for PWM encoding technique. All the other encoding techniques follow the same method. The actual tolerance would be affected by the application and the specific hardware used in the network. The variabilities introduced by the specific hardware will be needed to adjust parameters in Eq. (26.2) in order to find the final node oscillator tolerance.



$$Tol\% = \frac{PW\,\max - PW\,\min - IT}{PW\,\max + PW\,\min} * 100 \qquad (26.2)$$

FIGURE 26.11 Example of oscillator tolerance calculations.

There are generally three types of oscillators used with vehicle multiplex circuits: quartz crystal for very tight oscillator tolerances; ceramic resonators for low-cost, tight tolerances and fast startup time; and RC oscillators for very low cost and very fast startup time at a very loose oscillator tolerance.

The noise filter used is usually a digital filter or some type of sampling process. RC filters are usually not used because they are not precise enough. For all of the encoding techniques, a 12.5 percent of minimum pulse width was used for IT in calculating the oscillator tolerance.

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In a single-wire network, ground offsets between nodes cause an added received pulse-width variability. This condition is especially acute when trapezoidal waveforms are used to reduce EMI. Figure 26.12 illustrates the pulse-width timing (T) variability introduced by ground offset. This pulse-width variability must be accounted for because it causes a reduction in minimum pulse width and an increase in maximum pulse width, thus having the effect of reducing oscillator tolerance.

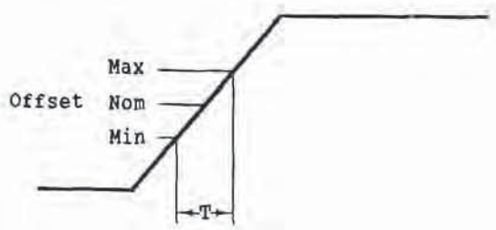


FIGURE 26.12 Ground offset on pulse-width timing.

The output drivers are the source of another pulse-width variability. The effect is the same as with ground offset only not nearly as acute. The problem is caused by line drivers used to permit arbitration having a longer delay time when going from the active to passive state than from a passive to active condition.

Data integrity is judged on a scale from poor, fair, good, superb, to perfect. Data integrity is generally considered to be affected by the EMI. The ambient levels of EMI in a vehicle are very low. This condition must remain in order to operate a communications receiver (consumer radio) in a vehicle. The problem is that very high levels of "bursty" noise for a short period at random intervals can completely disrupt multiplex communications for the duration of the noise. The only other effect of this bursty noise is a barely noticeable pop in the radio speaker. During these events, data integrity is compromised. The accepted practice for data communication (Class B) multiplexing is to simply detect this data corruption and throw out the full message rather than try to recover the data. This practice is acceptable because the amount of corrupted data compared to noncorrupted data is considered negligible, and/or can be retransmitted without causing bus bandwidth problems.

A thorough noise immunity study is very complex, and the criteria for judging would consider many factors. If something is known about the noise environment and the detector hardware, as is the case with the automotive situation, a study of data integrity may be useful. For the purpose of this discussion, assume that the criteria for judging which data-encoding method is acceptable is mainly dependent on its natural ability to detect corruption. Also, the corruption detection ability is often determined by the interface hardware capability and its message-handling protocol.

A number of validation tests can be performed on the message level. Bit-error algorithms such as a parity bit, checksum, or CRC are the most common test. Also, some protocols can perform message length by either message type or defining the message length in the data. These and other message level tests are independent of the bit-encoding method and should not influence data integrity of the bit-encoding technique.

The natural ability of the encoding technique to detect corruption is known as invalid bit detection. Usually three types of data integrity factors are considered for vehicle multiplexing because the effects of EMI environment are basically known:

1. *Low pass filtering.* For this factor, the data bit is passed through a low pass filter, i.e., an integrator; the longer the shortest pulse duration, the more effective the filtering.
2. The bursty noise detection test checks for a short duration of EMI.
3. Two independent data bit tests confirm valid data. PWM, for example, has two unique sample periods per bit and both periods must complement each other.

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26.2.1 Pulse-Width Modulation (PWM)

The PWM encoding technique[6] is composed of two sample periods or phases (T_1 and T_2) per bit, as shown by Fig. 26.13. PWM encoding has the advantage that the time per bit remains constant, but has the disadvantage of generating more EMI because it has two transitions per bit. This time per phase of PWM also affects the generated EMI noise and, to minimize the EMI effect, one phase time is usually defined to be two times the other phase time in duration.

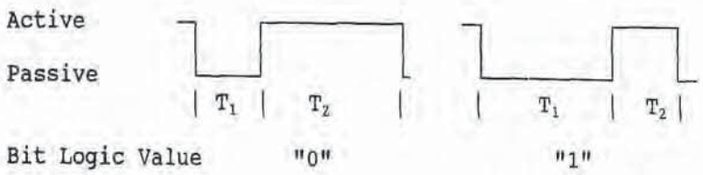


FIGURE 26.13 PWM encoded data.

Arbitration of PWM. PWM has the ability to perform bit-by-bit arbitration. Figure 26.14 illustrates that a "0" bit dominates and takes priority when bit-by-bit arbitrating over a logic "1".

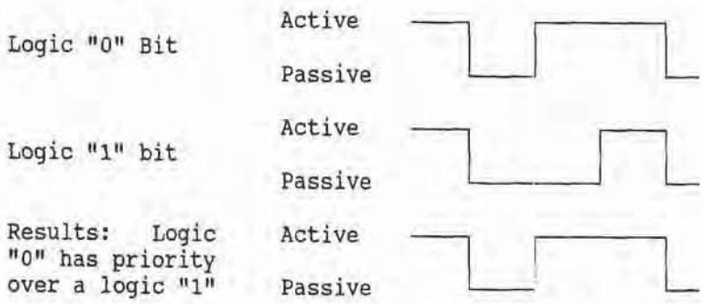
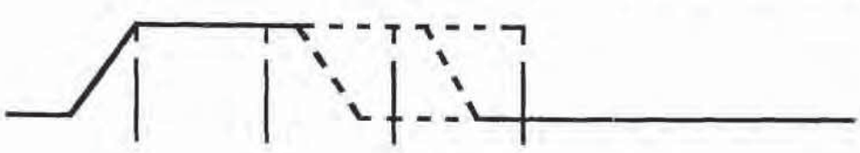


FIGURE 26.14 A logic "0" arbitrating with a logic "1".

Data Integrity of PWM. Consider a hardware sampler that has the capability of detecting (1) transition and (2) phase (ϕ) every sample window, as shown in Fig. 26.15. The sampler starts sampling at a transition, then sequentially samples window 1, window 2, and then window 3. If a transition is not detected by window 3, then data has been corrupted and the message is thrown out. When this type of sampler is used for PWM encoded data the sampler would sample five windows per bit and yield dual transition and phase information per bit. The transition and



Window	1	2	3
Error	$1 + \phi$	X	X
Short	0	$1 + \phi$	X
Long	0	0	$1 + \phi$

FIGURE 26.15 A three-window sampler.

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phase information must be consistent for a correct PWM encoded data or corruption would be assumed and the message will be thrown out. If at any time a transition of either phase is detected in sample window 1, the data has been corrupted and the message is thrown out.

PWM encoding is judged to have very good "perfect" invalid bit-testing capabilities even though the effectiveness of the low-pass filter is poor. Otherwise, it has two of the three (e.g., dual periods confirmation of data and burst noise) validation tests. PWM is "perfect" encoding technique used in vehicle multiplexing when data integrity has the highest priority. However, this encoding technique has multiple transitions per bit and would not allow operation at data rates near the natural EMI limits for single-wire or twisted pair transmission media.

26.2.2 Variable Pulse-Width Modulation (VPWM)

VPWM (sometimes referred to as VPW modulation) is a variation of PWM. Normal PWM has two phases per bit as shown by Fig. 26.16. T_1 is illustrated as a passive short and T_2 as an active long. This combination is defined as a logic "0" bit. Notice that a logic "0" bit takes priority when arbitrating over the opposite pattern of a passive long and an active short.

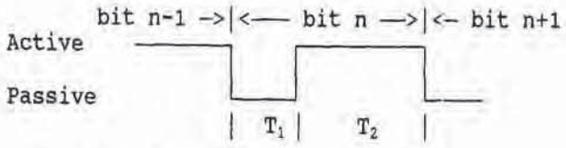


FIGURE 26.16 A PWM encoded logic "0" bit.

One of the most attractive features of VPWM is that the pulse-width variability introduced by factors such as ground offset and output driver timing variabilities can be added to the pulse-width timing without severely reducing the oscillator tolerance.

Arbitration of VPWM. VPWM encodes each phase as a data bit. Figure 26.17 illustrates a passive short arbitrating with a passive long. Figure 26.18 illustrates an active long arbitrating with an active short. In both cases, a logic "0" takes priority over a logic "1" bit. Therefore, arbitration using VPWM data encoding can be achieved.

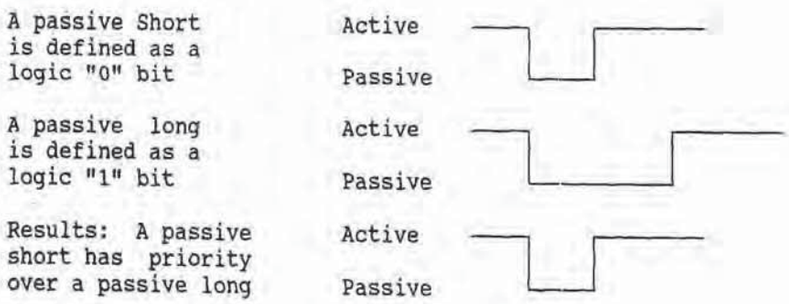


FIGURE 26.17 A passive short arbitrating with a passive long.

VPWM is utilized by SAE J1850; i.e., it uses a pulse width of 64 μs for a short and 128 μs for a long and approximates the same average data rate (10.4 Kbps) as regular PWM using a pulse width of 32 μs for a short and 64 μs for a long. The VPWM minimum pulse width for a short is 64 μs and permits a rise time of 16 μs for T as illustrated in Fig. 26.12. Compare this rise time to conventional PWM where a 32-μs short permits only an 8-μs rise time. The result of the proportionally longer rise time and wave shaping is an approximate 9-dBV improvement in EMI over PWM. The disadvantage of VPWM encoding is that the data rate per byte

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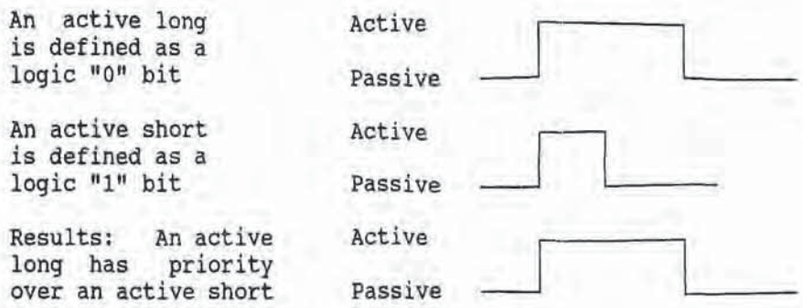


FIGURE 26.18 An active long arbitrating with an active short.

transmitted will vary in time depending on the data value. The microcomputer interfacing transmitter/receiver polling rate with VPWM is required to be less than ≈ 512 μs per byte, whereas with PWM, less than ≈ 768 μs per byte is required.

Data Integrity of VPWM. VPWM has good data integrity by sampling up to three times every pulse width as shown in Fig. 26.15. The sampler is designed to detect a transition and phase (ϕ) every sample window and have an average number of 2.5 samples per bit. If at any time a transition of either phase is detected in sample window 1, the data has been corrupted and the message is thrown out.

The sampling sequence is initiated by a transition of either phase. A short symbol is then sensed by not detecting a transition (0) in window 1 and detecting a transition ($1 + \phi$) and proper phase in window 2. Sampling in window 3 is a "don't care" (X), because sampling is terminated and the procedure is repeated. Window 3 is actually window 1 on the next sampling sequence.

A long symbol is likewise sensed by not detecting a transition (0) in window 1 or 2 and detecting a transition ($1 + \phi$) and proper phase in window 3.

The proper phase detection, when a transition is sensed, is used to ensure that the sequence does not get scrambled. It is also used to define which logic level, "1" or "0", has been received.

VPWM has been judged to have "good" data integrity because low-pass filtering of the data pulse width is good. Every transition is validated by an error-sampling window, and pulse duration measurements are validated by the proper phase test, i.e., two of the three invalid bit tests.

26.2.3 Standard 10-Bit NRZ

This is an asynchronous serial I/O (standard UART) 10 bits-per-byte of data. A start bit and a stop bit are added to provide data byte synchronization. The standard UART used in RS232 is bit-ordered least significant bit (LSB) first. Figure 26.19 illustrates this 10-bit NRZ waveform. Vehicle multiplex networks that use 10-bit NRZ make use of the available hardware that have this asynchronous I/O, i.e., the serial communications interface (SCI) available on many microcomputers.

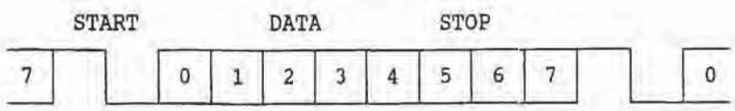


FIGURE 26.19 A 10-bit NRZ waveform (LSB first).

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Arbitration of 10-Bit NRZ. Figure 26.20 illustrates 28H from transmitter #1 arbitrating with 44H from transmitter #2. An active "0" is defined to win arbitration over a passive "1". Take note that bus has a 28H on it and, therefore, transmitter #2 shuts off its output when it tries to transmit bit #2. This loss of arbitration action is the usual method employed by all arbitrating protocols.

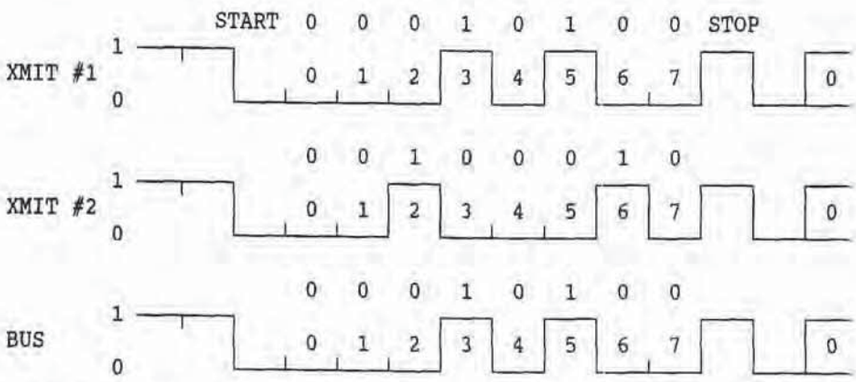


FIGURE 26.20 Arbitration of a 10-bit NRZ network.

Data Integrity of 10-Bit NRZ. The bit-synchronized sampling technique used for PWM and VPWM could be used for 10-bit NRZ encoded data, but it would be much more complex because it could be guaranteed to synchronize only on the stop-to-start transition. It would not sample only one bit, it may have to sample all eight. The normal technique is to use a start bit detector to sense a valid start bit and then sample all eight of the data bits sequentially.

As with all decoding techniques, the data is passed through a low-pass filter. However, filtering for NRZ is very effective because of the long data pulse duration. 10-bit NRZ encoding has been judged to have "fair" data integrity, mainly because the addition of a transition between the stop bit and start bit is not unique in the sequence and the detector hardware could get scrambled. Adding an invalid bit detection for bursty noise between data bits would improve the data integrity, but it could not validate every bit.

26.2.4 Bit-Stuf NRZ

Bit-stuffing is another way of synchronizing NRZ encoded data. The concept is to insert a bit (i.e., two transitions) after a specified number (X) of bits of contiguous "1" or "0" bits and if the X + 1 bit is the same logical value as the other contiguous bits. The proper number of contiguous bits is chosen as a compromise between the oscillator tolerance and the generated EMI. The higher the number of contiguous bits before inserting a stuff-bit, the better the synchronizing oscillator tolerance must be, but the lower the EMI. There is also a receiver decoding complexity consideration with bit-stuf NRZ. Figure 26.21 illustrates waveform used by CAN for X = 5.

The number of stuff-bits in a frame is dependent on the data value, and the transmission time for a data byte is a variable quantity depending on this data value. A number of the factors used to evaluate bit-stuf NRZ require a knowledge of the average number of data bytes per stuff-bit (see Fig. 26.22). This average number can be derived because the nature of a data bit in a message has equal probability of being a "1" or "0".

Arbitration of Bit-Stuf NRZ. As with all arbitrating encoding methods, the bit-stuf NRZ transmitter utilizes a driver that has an active state and a passive state, thereby supporting bit-by-bit arbitration.

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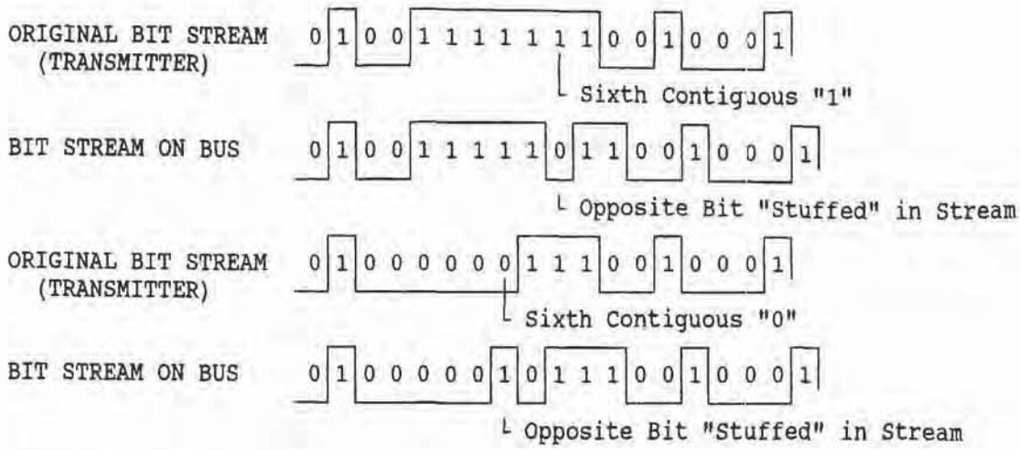


FIGURE 26.21 NRZ bit-stuffing.

The probability of there being a stuff-bit before B_i in the stuffing algorithm where X = 5 is as follows:

$$B_0,\ B_1 \cdots B_i \cdots B_{n-1}$$

$$p_i = \begin{cases} 0 & \text{when } i < 5 \\ 1/32 & \text{when } i = 5 \\ 1/64 & \text{when } i > 5 \end{cases}$$

$$F(N) = \text{No. of BYTES/STUF}$$

$$F(N) = \frac{N}{\sum_{i=0}^{n-1} p_i} \quad \text{where}$$

$$n = \text{No. of Bits}$$

$$N = \frac{n}{8} = \text{No. of Bytes}$$

$$\lim_{N \to \infty} F(N) = 8$$

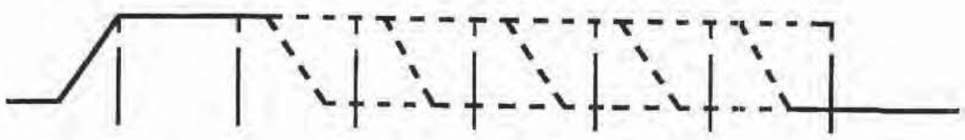
$$F(12) = 8.348$$

FIGURE 26.22 Derivation of average number of stuff-bits.

Data Integrity Bit-Stuf NRZ. The bit-synchronized six-window sampling technique illustrated in Fig. 26.23 could be used for bit-stuf NRZ encoded data and would be guaranteed to synchronize on the stuff-bit. It must accommodate sampling from one to five data bits sequentially. All bits of data prior to sampling a transition are assigned the same logic level as the level detected by transition and phase detector. If transition is detected in window #1, which is due to bursty noise, the message would be thrown out. This detector could somewhat improve the data integrity, but it could not validate every bit. As with all decoding techniques, the data is passed through a low-pass filter. However, filtering for NRZ is very effective because of the long data pulse duration.

Bit-Stuf NRZ encoding has been judged to have "fair" data integrity, mainly because the addition of a synchronizing stuff bit is not unique in the sequence and the detector hardware could get scrambled.

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Window	1	2	3	4	5	6
Data		D_n	D_{n+1}	D_{n+2}	D_{n+3}	D_{n+4}
Error	$1+\phi$	X	X	X	X	X
Bit 1	0	$1+\phi$	X	X	X	X
Bit 2	0	0	$1+\phi$	X	X	X
Bit 3	0	0	0	$1+\phi$	X	X
Bit 4	0	0	0	0	$1+\phi$	X
Bit 5	0	0	0	0	0	$1+\phi$

FIGURE 26.23 A six-window sampler.

26.2.5 L-Manchester (L-MAN)

The L-MAN encoding technique is composed of two sample periods of opposite phases per bit, as shown by Fig. 26.24. L-MAN encoding has the advantage that the time per bit remains constant, but has the disadvantage of generating more EMI because it can have an average of one-and-a-half and maximum of two transitions per bit.

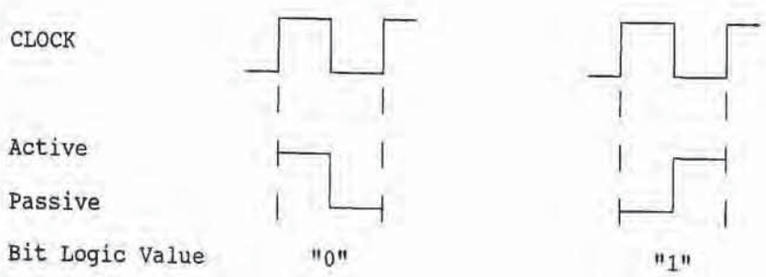


FIGURE 26.24 L-MAN encoded synchronizing bits.

A transition from active to passive level will be decoded as a logic "0" and a transition from passive to active level will be decoded as a logic "1". A synchronizing transition is always generated in the center of the bit period but may not be generated at the beginning of a bit period, depending on the data. As illustrated by Fig. 26.25, when there is a "0" to "1" or "1" to "0" data sequence the transition is not generated.

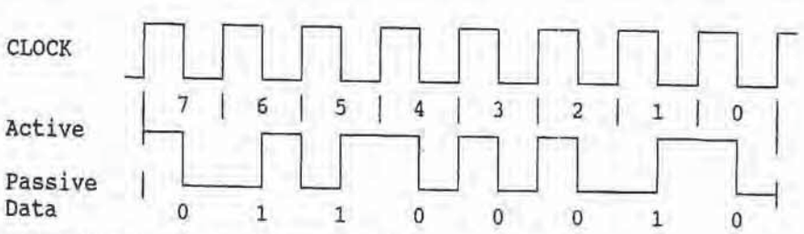


FIGURE 26.25 One byte of L-MAN encoded data.

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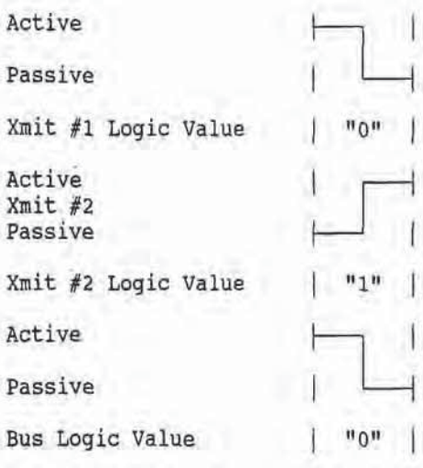


FIGURE 26.26 A logic "0" arbitrating with a logic "1".

Arbitration of L-MAN. Figure 26.26 illustrates how a logic "0" arbitrating with a logic "1" always wins arbitration. This situation is true because the active portion of the signal overrides the passive portion and also shuts off the output of the passive contender before it would become active.

Data Integrity of L-MAN. Consider a three-window sampler that has the capability of detecting a transition (1) and phase (ϕ) every sample window as shown in Fig. 26.15. The circuit starts sampling at a transition and then sequentially samples window 1, window 2, and then window 3. If a transition is not detected by window 3, then data has been corrupted and the message is thrown out. When this type of sampler is used for L-MAN encoded data, the sampler would sample four to five windows per bit and yield complementary transition and phase information per bit. If D_n and D_{n+1} have the same logic level—i.e., "1s" or "0s"—then a transition must not occur at the bit boundary or a corrupted data would be assumed and the message will be thrown out. If at any time a transition of either phase is detected in sample window 1, the data has been corrupted and the message is thrown out.

L-MAN encoding is judged to have very good "perfect" invalid bit-testing capabilities even though the effectiveness of the low-pass filter is poor. Otherwise, it has two of the three validation tests: dual validation of data by proper periods at the bit boundary and bursty noise test every bit. L-MAN has "perfect" encoding technique used in vehicle multiplexing when data integrity has the highest priority. However, this encoding technique has multiple transitions per bit and would not allow operation at data rates near the natural EMI limits for single-wire or twisted pair transmission media.

26.2.6 E-Manchester (E-MAN)

E-Manchester, or enhanced manchester, utilizes an L-Manchester encoded data bit for synchronization combined with three bits of NRZ encoded data bits. Figure 26.24 illustrates the L-Manchester synchronizing bit values and Fig. 26.27 is an illustration of four bits of E-MAN encoded data.

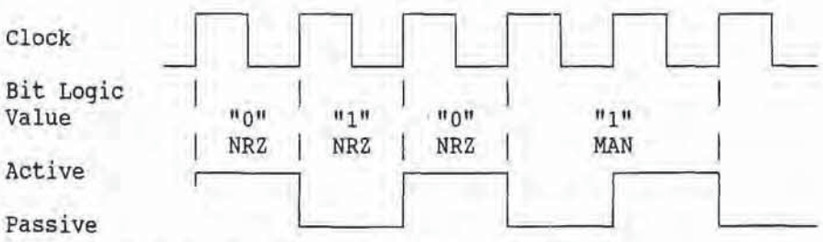


FIGURE 26.27 Four bits of E-MAN encoded data bits.

Arbitration of E-MAN. When arbitrating, an active (logic "0") takes priority over the opposite pattern (logic "1") for both the NRZ bits and the MAN encoded synchronization bit. This domination of a logic "0" over a logic "1" is easily understood for the NRZ encoded

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portion of an E-MAN encoded byte. The dominance of a logic "0" synchronization bit, which seems confusing, can be easily realized by considering the fact that the active portion of the signal overrides the passive portion and also shuts off the output of the passive contender before it would become active.

The main advantage of E-MAN over PWM or VPWM is that the shortest pulse width at 10.4 Kbps is ≈ 76.8 μs, and permits a 42 percent rise time of 32.3 μs compared to a 32 μs short and 13 μs rise time with conventional PWM. The result of the proportionally longer rise time and wave shaping is an approximate 11-dbV improvement in EMI over PWM. Another advantage of E-MAN over VPWM is that the data rate per byte transmitted is constant. The microcomputer transmitter/receiver polling rate with E-MAN is required to be a constant of less than ≈ 768 μs per byte.

Data Integrity of E-MAN. If the same sampling technique is used for E-MAN as was used for the bit-stuf NRZ case, it is capable of detecting (1) a transition and (2) a phase (ϕ) every sample window. The E-MAN sampling hardware can sample up to six times every pulse width as shown in Fig. 26.23.

The sampling sequence is initiated by a transition of either phase. If there is a transition (1 + ϕ) in window 2, then the value of D_n is determined by the logic level and phase.

If there is a transition (1 + ϕ) in window 3 in the sampling sequence, then $D_n = D_{n+1}$ and is determined by the logic level and phase. If there is a transition (1 + ϕ) in window 4 in the sampling sequence, then $D_n = D_{n+1} = D_{n+2}$ and is determined by the logic level and phase.

If there is a transition (1 + ϕ) in window 5 in the sampling sequence, then $D_n = D_{n+1} = D_{n+2}$ and is determined by the logic level and phase. The value of D_{n+3} is determined by the phase (ϕ) because it is the L-MAN encoded bit and will be confirmed by a transition (1 + ϕ) in window 2 on the following sampling sequence.

If there is a transition (1 + ϕ) in window 6 in the sampling sequence, then $D_n = D_{n+1} = D_{n+2}$ and is determined by the logic level and phase. The value of D_{n+3} is determined by the phase (ϕ) because it is the L-MAN encoded bit.

The L-MAN encoded bit is not unique in the sequence and the detector hardware must keep track of where the L-MAN bit should be, because if a transition (1 + ϕ) for the L-MAN encoded bit falls in a window other than window 6, then the value of D_{n+3} is determined by the phase (ϕ) of the transition.

E-MAN encoding has been judged to have "fair" data integrity, mainly because the L-MAN encoded bit is not unique in the sequence and the detector hardware could get scrambled. If a transition is detected in window 1, an invalid bit was detected, which helps data integrity but it could not validate every bit. As with all decoding techniques, the data is passed through a low-pass filter. However, filtering for E-MAN is very effective because of the long data pulse duration.

26.2.7 Modified Frequency Modulation (MFM)

Modified frequency modulation (MFM), a modulation technique developed during the latter 1960s, was used in disk drives and is adaptable to vehicle multiplexing. The advantage of using the MFM encoding technique is that it would be synchronous with an average of 0.75 and a maximum of 1 transition per bit. The encoding technique permits a transition rise time that can be maximized and wave-shaped to significantly reduce EMI. Disk drives have a similar requirement where the modulation technique allows pulses to be recorded on a disk at maximum density. The diagram shown in Fig. 26.28 demonstrates one method of applying MFM encoding technique to a data communication network.

The rule for encoding simply causes a transition at the data time when the data at that time slot is a logic "1". A transition is also generated at the clock time slot when the data before and after the time slot was a logic "0" (or two "0"s in a row).

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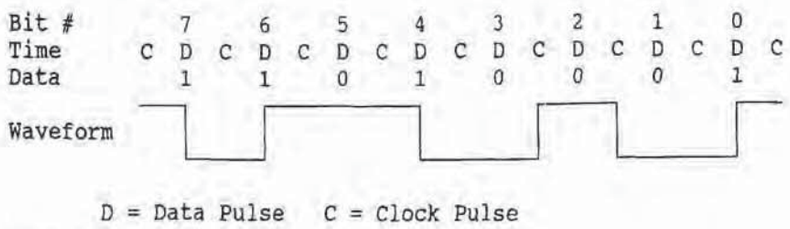


FIGURE 26.28 MFM encoded byte of data.

Arbitration of MFM. A requirement for vehicle multiplexing is that the data from one device shall bit-by-bit arbitrate with the data from another device. The arbitration bit-ordering is defined MSB first, and 00H has the highest priority. To support arbitration, the output driver is defined and designed to have an active state that has priority over a passive state. Figure 26.29 demonstrates the four encoding rules that can be used to generate a waveform "A" that always wins arbitration.

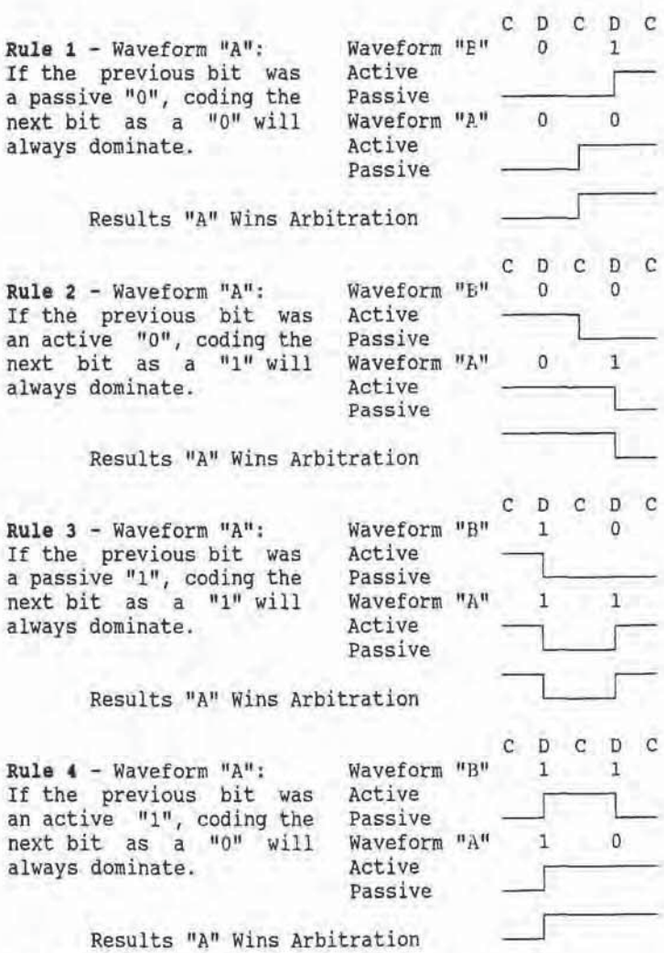


FIGURE 26.29 The four rules for winning arbitration.

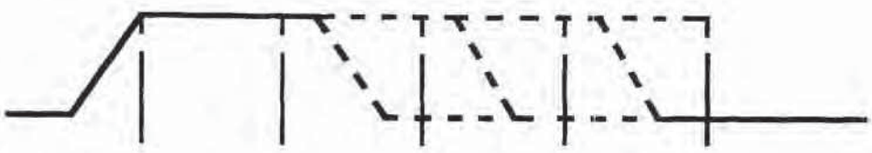
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Assume that the existence of four rules for winning arbitration demonstrates that it is possible to convert data into a form that will correctly arbitrate. This assumption means that data can be encoded into a different byte, which will have to be decoded back after arbitration. Applying the four rules, the process required to code a "0" in the original byte to win, and a "1" to lose, is: start with the MSB, move toward the LSB, i.e., left to right. When encoding, make sure all the "0s" encountered are of the type that will win arbitration, i.e., Rule 1 and 4. When a "1" is encountered make sure the type of "0" that will be following the previous bit will win arbitration over the "1" in the present bit, i.e., Rule 2 and 3. For each "1" encountered in a row, make sure the other byte that has the same bits up to that point, but now has a "0", will win arbitration with that "0".

Encoding and decoding of data into an MFM format can be accomplished by hardware in the interface circuit. A two-step process is required. First the data bytes to be transmitted must be translated into the correct form for arbitration using the rules illustrated by Fig. 26.28. The operation of the MFM encoder depends on a starting value of a dominant "1", which is provided by the start of frame (SOF).

After the data is translated into the correct form for arbitration, it can be encoded by the circuit. The data is then ready to be transmitted by the I/O. The received data requires the reverse sequence of first decoding by the circuit and then translation into the correct binary form. Translation can be accomplished by the circuit.

Data Integrity of MFM. The MFM encoding receiver samples up to four times every pulse width when starting at a data transition, and up to three times every pulse width when starting on a clock, as shown in Fig. 26.30.



Window	1	2	3	4
Clock	D_n	C	D_{n+1}	
Data	C	D_n	C	D_{n+1}
Error	$1+\phi$	X	X	X
Bit 1	0	$1+\phi$	X	X
Bit 1½	0	0	$1+\phi$	X
Bit 2	0	0	0	$1+\phi$

FIGURE 26.30 MFM data integrity capability.

The sampling sequence is initiated by a transition of either phase. The sampler can detect a transition $(1 + \phi)$ of either phase in every sample window. The following sequences begin with a transition in a data window:

1. If next $1 + \phi$ in data window 1, then an error has been detected.
2. If next $1 + \phi$ in data window 2, then the value of $D_n = 1$.
3. If next $1 + \phi$ in data window 3, then the value of $D_n = 0$ and $D_{n+1} = 0$.
4. If next $1 + \phi$ in data window 4, then the value of $D_n = 0$ and $D_{n+1} = 1$.

The following sequences begin with a transition in a clock window:

1. If next $1 + \phi$ in clock window 1, then an error has been detected.
2. If next $1 + \phi$ in clock window 2, then the value of $D_n = 0$ and $D_{n+1} = 0$.

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3. If next $1 + \phi$ in clock window 3, then the value of $D_n = 0$ and $D_{n+1} = 1$.
4. If next $1 + \phi$ in clock window 4, then an error has been detected.

MFM has been judged to have very good ("superb") data integrity because, as with VPWM encoding, every transition is validated by an error-sampling window and a proper phase test. Also, when transitions fall in windows 3 and 4 for data and in 2 and 3 for clock, the value of two data bits is sensed. One sampling confirms the previous, thus improving data integrity capability. With MFM decoding technique, the data is passed through a low-pass filter. However, filtering for MFM is very effective because of the long data pulse duration.

26.3 PROTOCOLS

Table 26.2 describes the protocol sections.[7] These descriptions appear in the order in which they are discussed for each protocol.

The following describes the *intent* of the various sections of the protocol characteristics.

The *application* section briefly identifies the applications for which the protocol was designed to serve: military, aircraft, industrial, land vehicles, and trucks. The *affiliation* section identifies the organization(s) that originally developed the protocol, specified the protocol, or which now endorse the protocol.

The *transmission media* section describes the physical medium generally associated or required by the given protocol: single-wire, dual-(parallel) wire, twisted pair, twisted pair with shield, dual twisted pair, and fiber optics.

The *physical interface* section describes the basic circuitry used to connect the nodes to the network. In some cases, the schematic of a typical interface may be shown. In others, a reference to a generally known interface technique may be made. This section may also include additional data about aspects of the interface not readily shown. An example would be that receiver nodes synchronize to the signal from a transmitting node, or that receiver nodes adjust their receiver clock to the received data signal.

The *bit encoding* section describes the way in which the logical bits, "1"s and "0"s, are translated into signals on the transmission medium by the physical interface (NRZ, PWM, and MANCHESTER).

The *network access* section describes the method used to award the communication network to one of the nodes for the transmission of a message: master/slave, token passing, and CSMA/CD.

The *message format* section describes the fields that make up the basic message(s) used in the protocol. This includes the order, name, and size of the fields.

The *handshaking* section describes the interaction of nodes within a network in order to effect a transfer of data. This may include such things as negative and positive acknowledgment, and in-message acknowledgment.

The *error detection management* section describes the types of errors the protocol detects and the recovery techniques it uses: wrong message length and CRC.

The *fault tolerance* section describes the ability of the protocol to continue operation, possibly at a degraded level, when various parts of the physical layer or medium of the network on which the protocol is operating fails (i.e., node connections are broken, bus wires are opened, bus wires are shorted to ground or to vehicle battery voltage).

The *data rate* section identifies the maximum data rate supported by the protocol.

The *framing overhead* section briefly shows the amount of nondata overhead, i.e., framing overhead, associated with the given protocol. If possible, the calculation of overhead is shown. Because some protocols offer significantly different message formats and/or message sizes, several overhead calculations may be necessary to give an accurate picture of the range of the protocol's overhead requirements.

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TABLE 26.2 Protocol Descriptions

	A-BUS	CAN	D2B	SAE J1567 C^2D	SAE J1850 PWM	SAE J1850 VPWM	SAE J2058 CSC	SAE J2106 token slot	TTP	VAN
SAE class		Class B & C		Class B	Class B	Class B	Class A	Class C	Class C	
Affiliation	VW	Proposed ISO Bosch	Philips	Chrysler	SAE RP Ford	SAE RP Chrysler, GM	Chrysler	GM	University Wien Austria	Proposed ISO
Application	Auto in-vehicle	Auto in-vehicle	Audio/video	Auto in-vehicle	Auto in-vehicle	Auto in-vehicle	Auto in-vehicle	Auto in-vehicle	Auto in-vehicle	Auto in-vehicle
Transmission media	Single-wire	Twisted pair/ fiber optic	Twisted pair	Twisted pair	Twisted pair	Single-wire	Single-wire	Twisted pair/ fiber optic	Twisted pair/ fiber optic	Twisted pair
Bit-encoding	NRZ	NRZ with bit-stuffing	PWM	10-bit NRZ	PWM	VPWM	Analog, NRZ, & PWM	NRZ with bit-stuffing	MFM	L-MAN E-MAN
Media access	Contention	Contention	Contention	Contention	Contention	Contention	Master/slave	Token slot	Time-triggered	Contention
Error detection	Bit only	CRC	Parity	Checksum	CRC	CRC	Parity	CRC	CRC	CRC
Data field length	2 bytes	0–8 bytes	2–128 bytes	1–6 bytes	0–8 bytes	0–8 bytes	1–32 bits	0–256 bytes	2–8 bytes	0–8 bytes
In-message acknowledge		Yes			Yes	Yes	Yes	Yes	Yes	
Maximum bit rate	500 Kbps	1 Mbps	100 Kbps	7.812 Kbps	41.6 Kbps	10.4 Kbps	1 Kbps	2 Mbps	1 Mbps	User definable
Maximum bus length	Not specified typical 30 m	Not specified typical >40 m	150 m	Not specified typical >30 m	40 m	40 m	Not specified typical >40 m	Not specified typical 30 m	Not specified typical 20 m	20 m
Maximum number of nodes	Not specified typical 32	Not specified typical >16	50	Not specified	Not specified	Not specified	Not specified	32 (transmit capability)	Not specified	16
Hardware available	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	Yes

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The *latency* section describes the factors that affect the delay between the availability of a message to be transmitted and the beginning of the reception of that message by the intended receiver.

The *power reduction* section has general information about any modes of operation that require less power than normal operation. As a minimum, this section identifies the lower power level(s). It also includes a brief description of the criteria used in transitioning to the lower power mode(s) and to return to normal power mode. Some of this information may be device-version-specific and will be so identified.

26.3.1 Automotive Bit-Serial Universal Interface System (A-BUS)

Application/Affiliation. Designed for automotive applications by Volkswagen AG.

Transmission Media. Not specified. Single-wire suggested.

Physical Interface. Not specified.

Bit Encoding. NRZ with eight samples/bit, which means each sample is ⅛th the length of the bit. A valid bit has to have either four or six complementary samples (see Fig. 26.31). This choice of either 4 or 6 matching samples is a user selectable function.

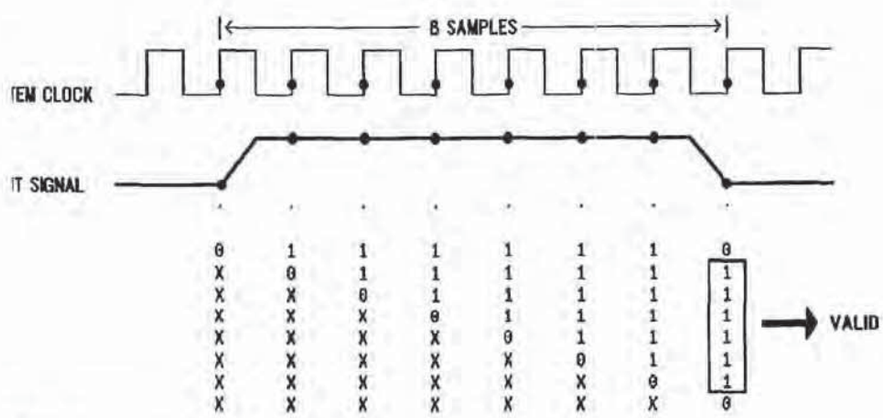


FIGURE 26.31 NRZ with eight samples/bit.

Network Access. Network access is achieved by a contention process that occurs through the end of the identifier field using a nondestructive bit-by-bit arbitration operation.

Message Format. Message length is constant and consists of 1 start bit, 1 bit (NC/DAT) indicating whether it is a data message or a command message, an 11-bit identifier, 16 bits of data, and 2 stop bits (STP0, STP1). Further detail is provided in Fig. 26.32. Two different types of messages are possible: the data message and the command message. Command messages may be used to ensure that a following command will not be accepted on the bus until the receiver has read the command. The ABUS IC can be programmed in a way that every following command will not be accepted on the bus until the master controller unit has read the command last received. In this case, no commands are lost.

Handshaking. Negative acknowledgment by receiver after error is detected. Any receiving device that notices a protocol error notifies all other bus members by pulling down the STP1

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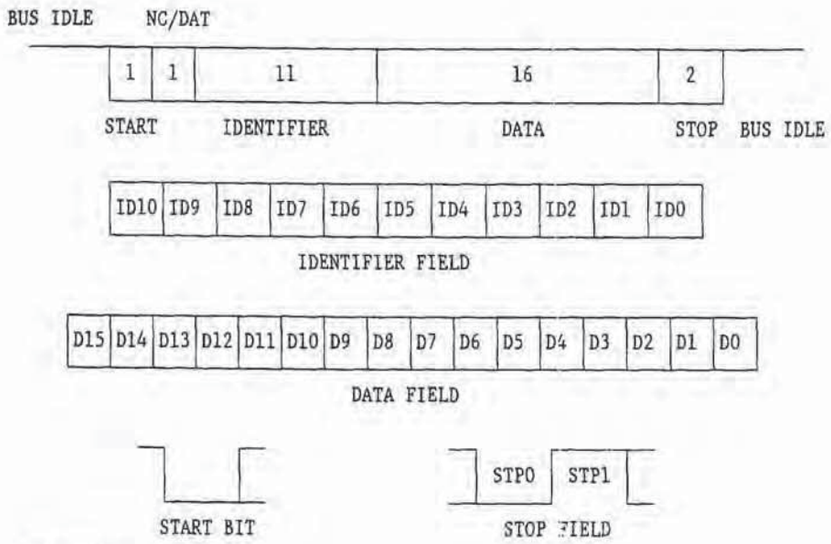


FIGURE 26.32 Message format.

bit. If the STP1 bit is low, the message is regarded as invalid by all members. There is no required or dedicated positive acknowledgment.

Error Detection Management. The transmitter and receiver monitor the bus for errors. The transmitter reads its own message back from the bus and compares it with the message that it intended to send. The receiver detects four different types of code errors by sampling the bus and when it has not been possible to compare the samples.

Start-Bit Error. This occurs when it has not been possible to generate a start bit at the beginning of the transmission process.

Transmit Error. A transmit error is monitored when, during a message transmission, the value read back was not equal to the value sent out a total of *Y* times* consecutively between the arbitration and STP1 bit.

Receive Error. A receive error is monitored when, during a message reception, an error has been detected a total of *X* times* consecutively prior to the STP1 bit.

Short Circuit. This occurs when no logical "1" has been read for a period of 256 clock pulses after a high to low transition.

Fault Tolerance. Not specified.

Data Rate. Maximum specified bit rate = 500 Kbps.

Framing Overhead. The message length is 31 bits; 16 of these are data. To transmit four bytes of data, two messages must be sent. Using the formula:

$$\frac{\text{OVERHEAD}}{\text{MESSAGE}} = \frac{\text{FRAMING}}{(\text{FRAMING} + \text{DATA})}$$

Approximate framing overhead/message calculated is: $(15+15)/((15+16)+(15+16)) = 48\%$.

* *X* and *Y* are programmable values (to 8, 16, and 32). In the present implementation, these error occurrences are stored in a status register and cause an interrupt. The sender tries to send a message for 8 to 32 times before it is recognized as an error.

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Latency. The ABUS protocol uses nondestructive bit-by-bit arbitration in contention to determine bus access. In the case of two or more nodes beginning transmission simultaneously, the message with the highest priority will win the arbitration and continue transmission. As a result, the maximum latency for the highest priority message is the number of bits in the maximum length message multiplied by the time per bit. A 31-bit message will require 64 μs at 500 Kbps. Lower priority messages may encounter additional delay in the event that they lose arbitration. Their latency may be determined based on a statistical analysis of the system, bus load, priority, and other.

Power Reduction Mode. The power consumption of the ABUS IC can be reduced by using the sleep mode. In this mode, the oscillator is turned off and the power consumption is reduced to 10 to 100 μA. The sleep mode is initiated by the host microprocessor. The IC will wake up either by a reset or by bus activity, but will go through a reset in either case. After the reset it will take about 50 ms for the oscillator to work properly; e.g., the first message works as an "alarm clock," which implies it is not received completely.

26.3.2 Controller Area Network (CAN)

Application/Affiliation. Both standard (S) and extended (E) message formats are intended for automotive in-vehicle applications. An ISO draft standard and an SAE Information Report[8] have been published.

Transmission Media. Not specified. Most of the announced production-intent systems use a wire-shielded or unshielded bus. Fiber optic systems using CAN have been demonstrated.

Physical Interface. User defined. One specific implementation is defined in Bosch presentations and documents to ISO.

Bit Encoding. NRZ (Nonreturn to Zero) with bit-stuffing (see Fig. 26.33). Logic level is constant for entire bit field, i.e., either "1" or "0", and bit of opposite state is inserted into bitstream by a transmitter if five contiguous bits of the same state are seen. Receivers remove the inserted bit from the bitstream, resulting in restoration of the original data stream. Implementations are programmable to allow either three or one samples per bit and specify the location of samples within a bit.

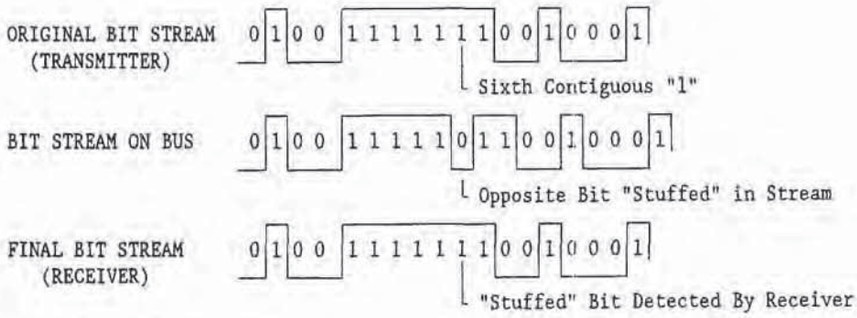


FIGURE 26.33 NRZ bit-stuffing.

Network Access. Contention using nondestructive bit-by-bit arbitration. Any node may transmit if the bus is idle. In the case of simultaneous transmissions, arbitration is resolved through the value in the identifier field. The message priority is defined in the identifier. Each message has a unique identifier, and, as a result, a unique priority. These identifiers/priorities are defined by the user, i.e., the system designer.

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Message Format. There are primarily three message types: data frame (see Fig. 26.34), remote frame (see Fig. 26.35), error frame (see Fig. 26.36), and overload frame (used in events where individual node has not had complete time to store message, see Fig. 26.37).

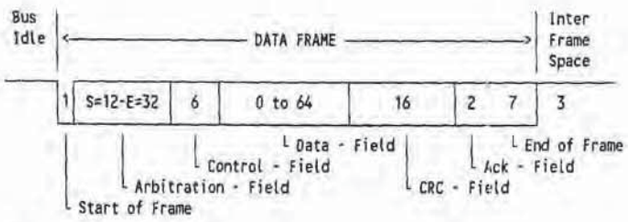


FIGURE 26.34 Data frame.

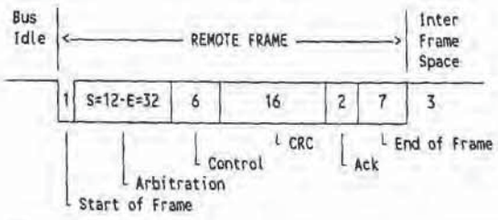


FIGURE 26.35 Remote frame.

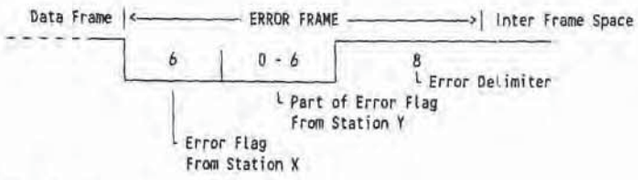


FIGURE 26.36 Error frame.

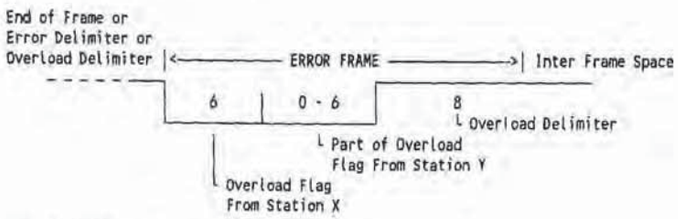


FIGURE 26.37 Overload frame.

Handshaking. Handshaking is provided within the message via either positive or negative acknowledgment. Positive acknowledgment is provided by a dedicated two-bit field in the message frame; one bit for acknowledgment and one bit for delimiter. All nontransmitting nodes will confirm uncorrupted message reception by transmitting a "dominant" bit in this dedicated field. As a result, the transmitting node receives confirmation that the message was received uncorrupted and does not have independent acknowledgments from individual nodes. Negative acknowledgment is provided through the error frame. See Fig. 26.34 for additional detail.

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Error Detection Management. All nodes monitor all messages. If an error is detected within a message, then the node(s) detecting that error destroy that message by transmitting an error frame. The result of this error frame is that all nodes (including the transmitting node) know that an error has been detected within the present message. The transmitter will retransmit the message at its next opportunity through normal bus access arbitration. Error-checking is provided on CRC, message length, message format, and bit level and timing. The message length is specified in the control field.

Fault Tolerance. Protocol is intended to treat all node address faults in the same manner. Fault confinement is provided by each node constantly monitoring its performance with regard to successful and unsuccessful message transactions. Each node will act on its own bus status based on its individual history. As a result, graceful degradation allows a node transmitter to disconnect itself from the bus. If the bus media is severed or shorted, the ability to continue communications is dependent upon the condition and the physical interface used.

Data Rate. Bit rate of up to 1 Mbit/s.

Framing Overhead. Maximum message length, which is the maximum time between messages, is 111 bit times for standard format and 131 bit times for extended format, i.e., 111 and 131 μs at 1 Mbps. For the highest priority message, if a message has just begun and the message in question is queued up, the latency will be 111/131 μs, and 222/262 μs maximum until its transmission is complete.

The maximum time between messages with four bytes data is 79 bits for standard format and 99 bits for extended format. Please note that this includes interframe space. For a message transmitting four bytes of data, using the formula OVERHEAD/MESSAGE = FRAMING/(FRAMING + DATA), the approximate framing overhead/message calculated for standard format is 47/(47 + 32) = 59%. For eight data bytes, the approximate framing overhead/message calculated is 47/(47 + 64) = 42%. For extended format, it is 67/(67 + 32) = 68% and 67/(67 + 64) = 51%, and does not include bit-stuffing.

Latency. The CAN protocol uses nondestructive bit-by-bit arbitration in contention to determine bus access. In the case of two or more nodes beginning transmission simultaneously, the message with the highest priority will win the arbitration and continue transmission. As a result, the maximum latency for the highest priority message is the number of bits in the maximum length message multiplied by the time per bit. In other words, it will have 111 bit times or 111 μs at 1 Mbit/s for standard format and 131 bit times or 131 μs at 1 Mbit/s for extended format. In the event that they lose arbitration, lower priority messages may encounter additional delay. Their latency may be determined based on a statistical analysis of the system, i.e., bus load, priority, and other.

Power Reduction Mode. Not specified.

26.3.3 Digital Data Bus (D2B)

Application/Affiliation. Digital data bus is a product of Philips for use in audio/video communications, computer peripherals, and automotive.

Transmission Media

Twisted pair

Physical interface

Differential floating pair (see Fig. 26.38)

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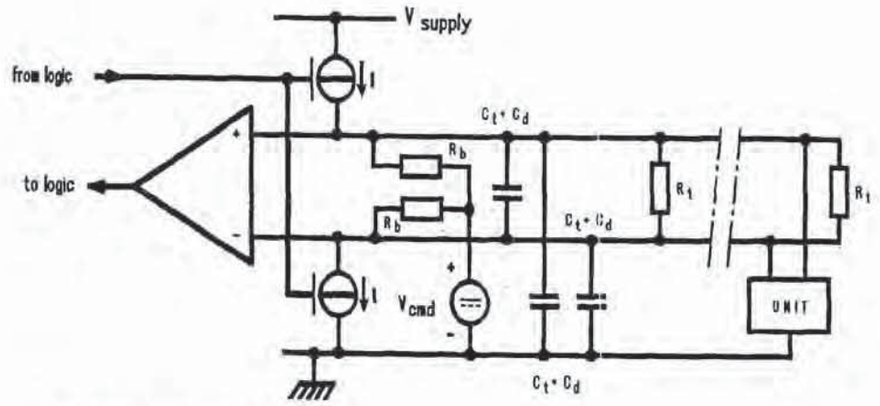


FIGURE 26.38 D2B physical interface.

Bit Encoding

Pulse-Width Modulation (PWM). The general bit format is composed of four sections: the preparation period, the sync period, the data period, and the stop period. The duration of the periods and the bit is dependent on the speed of the bus and the type of the bit. The speed of the bus is determined during contention. Low speed is dominant. There are three speeds possible. The general bit format is shown in Fig. 26.39.

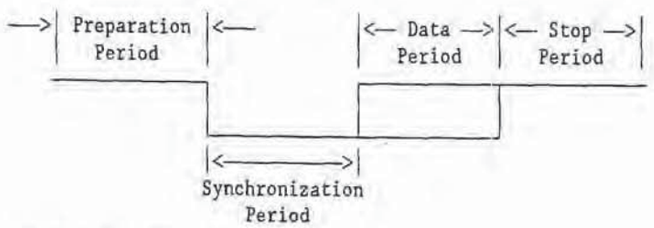


FIGURE 26.39 Pulse-width modulation bit format.

Network Access. Access is achieved by contention using nondestructive prioritized bit-by-bit arbitration. Competing nodes arbitrate first on the mode in which the node will operate in a three-bit field, where low mode is dominant. All nodes in a common mode then arbitrate based on the unique address bits of the competing masters. Low address is dominant. The mode designates the speed at which the bus will operate during the message transfer. A unit may use the bus for one time slot. The amount of data transferred in the time slot depends on the speed mode determined during arbitration.

Message Format. The frame consists of six fields. A parity bit follows the master, slave, control, and data fields. An acknowledge bit follows the slave field, control field, and the data field. An end-of-data bit follows each data byte. The total length of the frame is 47 bits. See Fig. 26.40 for the frame.

Handshaking. Handshaking is accomplished with positive acknowledgment in the transfer message. No reply from the slave is interpreted as a negative acknowledgment. The master can retry the message provided time remains in the slot. During every transfer, there are three different acknowledge bits: after the slave address, after the control bits, and after each data byte.

A master has the ability to lock a slave node to its address, having the effect of disabling the node from communicating with any other master on the network. This is done when a data

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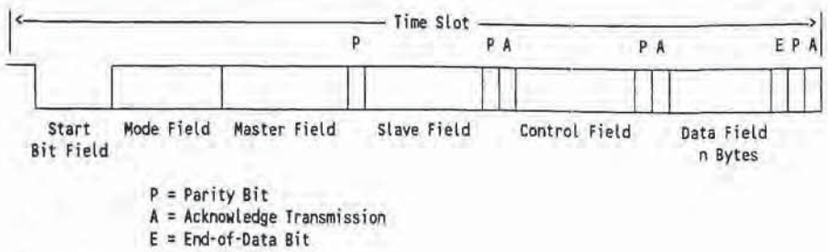


FIGURE 26.40 Six-field message format.

transfer exceeds the time slot and the master must arbitrate again for the bus to complete the data transfer.

Error Detection Management. Error checking is performed through odd parity on the slave address, control field, and after each data byte. The acknowledge bit in the transfer message will not be transmitted by the addressed slave if there is a parity error, the speed mode is too high, there is a timing error, slave locked to another master, or the receive buffer is full.

Fault Tolerance. Fault tolerance for nodes is not specified.

Data Rate. The maximum bit rate is 1Mbps. Three different transmission speeds are allowed.

Framing Overhead. The total frame size is 34 bits including interframe separation. In speed mode 1, 32 data bytes can be transferred from master to slave. Therefore, the percentage of overhead is $34/(34 + 256) = 11.7\%$.

Latency. D2B allows for three different speed modes for transmission and arbitrates on the address of the competing nodes once in a speed mode. Therefore, a low-priority node may experience high latency times vs. the average. Latency is also affected by the ability of a master to lock a slave node; a locked node will not respond to any messages. In certain situations, this could degrade the overall performance of the system.

Power Reduction Modes. Power reduction modes are available for the bus controllers.

26.3.4 Chrysler Collision Detection (C^2D), SAE J1567

Application/Affiliation. The serial communications network and bus interface special function integrated circuit[9] was developed by Chrysler Corporation and is supplied commercially by Harris Corporation. The interface IC was intended to provide a simple, yet reliable, data communications network between members of a distributed processing vehicle multiplex system. The communications protocol chosen minimizes the software support overhead requirement of the modules on the multiplex bus.

Transmission Media. Conventional 120-ohm automotive dual twisted pair >1 twist/in.

Physical Interface. The differential transceiver is a serial interface device which accepts digital signals and translates this information for transmission on a two-wire differential bus. The transmitter section, when transmitting, shall provide matched constant current sources to the bus "+" and bus "–" drivers (Refer to Fig. 26.41) sourcing and sinking current, respectively. When a logic "0" is supplied to the "transmit data" input, the differential amplifier shall cause the bus "+" driver to provide source current and the bus "–" driver to provide a matched cur-

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