rent sink. A logic one at the transmit data input must cause the bus "+" and bus "–" drivers to simultaneously provide a high impedance state.

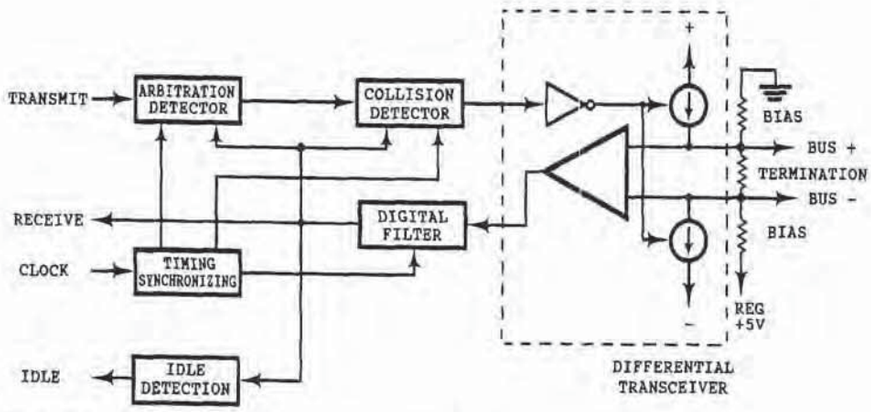


FIGURE 26.41 Simplified block diagram of network interface.

The wired OR action of the transmitting section allows more than one device to transmit at the same time, thus permitting data collisions. The nonsymmetrical action of the bus drivers will allow a transmission of a logic "0" from one device to overpower the transmission of a logic "1" from other devices. In this manner, two or more devices can simultaneously transmit and contend for the bus, each using a unique message ID byte. The winner is determined by the value or priority of the ID byte without losing bus time. A logic "0" bit in one message ID byte has priority over a logic "1" bit in another message ID byte.

The bus shall depend on external resistor and other components for bias and termination. Clamping diodes may be added to provide a high level of transient protection.

In addition to the transmission of data, the differential transceiver receives data at its bus "+" and bus "–" terminals. The received data is translated back into the standard digital logic levels by a differential amplifier. The microcomputer always receives the actual transmitted data and in this manner can test for loss of arbitration.

Bit Encoding. The bit encoding chosen is standard 10-bit NRZ, an asynchronous serial I/O. A start bit and a stop bit is added to provide data byte synchronization. Figure 26.42 illustrates this 10-bit NRZ waveform. The interface makes use of the available hardware that has this asynchronous I/O, e.g., the serial communications interface (SCI) available on many microcomputers.

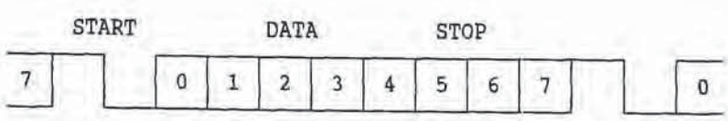


FIGURE 26.42 10-bit NRZ waveform (LSB first).

Network Access. The network access method of resolving contention is by nondestructive bit-by-bit arbitration.

Message Format. The message format shown in Fig. 26.43 will support a number of higher level protocols. Take note that idle periods, i.e., interbyte separations (IBS), are allowed between each byte of data. This permits the use of firmware control and direct connection to the host microcomputer's asynchronous serial I/O port.

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```
(SOM),(id 1),(id 2),(data 1),(data 2)···(data n),(EOM)

1.   SOM, defines start of message
2.   id 1, 8 bit firmware addressing scheme
3.   id 2, optional identifier
4.   Data, may take any form, i.e., data value, CRC, checksum, number of
     bytes in message, acknowledgment, etc.
5.   EOM, defines end of message (10 bits of Idle bus)
```

FIGURE 26.43 Frame format.

Handshaking. The IC utilizes a low-cost serial universal interface to most microcomputers by three modes of operation that are supported in one device: SCI, SPI, and buffered SPI.

The circuits of the interface IC used when connected to the microcomputer SCI are basic to the operation of all the other modes of serial communications. Therefore, this mode will be explained first. The components of the device (See Fig. 26.41) include the following: a contention permitting differential transceiver, a collision detector, an arbitration detector, a digital filter, a bus idle detector, and a timing and synchronizing circuit.

For a contention permitting differential transceiver, see the "Physical Interface" section for details. With a collision detector, data collision detection occurs because the transceiver output is reflected back into its input. The data collision detector samples the transmitted signal and the received signal. The timing of this sampling is determined by the timing circuit. When the collision detector determines that a logic "1" bit is being transmitted, but a logic "0" bit is being received, the collision detector blocks the transmitted signal. In this way, the data collision detector will permit only the interface with the highest priority to continue transmitting. The collision detector action of blocking transmission is also reset by detection of bus idle (10 consecutive idle bits).

The arbitration detector works in conjunction with the timing and synchronizing circuit to arbitrate between the start of data to be transmitted with the start of a received message from the bus. The arbitration detector blocks a transmission that could corrupt a message that is already in progress. It also allows the device that starts transmission first, after a bus idle, to pass its data through the interface and out onto the bus. In all other nontransmitting devices, the arbitration detector blocks transmission of data until the detection of a bus idle condition. When more than one device wants to transmit at about the same time, greater than ¼ bit time, the arbitration detector will allow transmission on a first-come first-served basis. If data transmission from more than one device on the bus is attempted in near synchronism—i.e., less than or equal ¼ bit time—the arbitration detector will allow the transmission. However, the data collision detector will permit only the one with the highest priority to continue transmission. The arbitration detector is also reset by the detection of a bus idle.

A low-pass digital filter is placed between the transceiver and the received data output. This circuit functions to filter out any received EMI from the desired digital data signal before being processed by the other circuits of the interface.

The function of the bus idle detector circuit is to detect when the bus is idle (not active) or busy (active) and then feed this information back to the microcomputer. It accomplishes idle detection by sensing a received stop bit followed by 10 bits of continuous idle or logic "1"s. Normally, an active or busy period follows an idle period. The sensing of an active or busy bus is accomplished by detecting a start bit. During unusual conditions such as node startup, any transition from a logic "1" to a logic "0" that is maintained for a period longer than ¼ bit time sets the active or busy flag.

The timing and synchronizing circuit uses an external clock and establishes the synchronizing and Baud rate timing signal. This generator circuit first synchronizes on the negative edge of a start bit and then generates a timing signal at the center (½ bit time) of each bit. This timing signal is used by the arbitration and collision detector circuit for sampling received data. This timing signal is also used by the idle detection circuit to determine an idle bus.

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Error Detection Management. The normal method used to detect message data error is a firmware checksum scheme. Also, the correct number of bytes in a frame is validated by the microcomputer firmware and, in some applications, data byte overrun flags are utilized by the microcomputer hardware.

Fault Tolerance. There is continued network operation when a node loses power or is disconnected from the bus.

Data Rate. A 7812.5 Baud rate is recommended.

Framing Overhead. The typical frame length is four bytes long. Framing consists of 4 start bits, 4 stop bits, 8 id bits, 8 checksum bits, and 10 end of message bits = 34 bits total framing, not including IBS. Data = 16 bits.

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

$$\frac{\text{OVERHEAD}}{\text{MESSAGE}} = \frac{34}{(34 + 16)} = 68\% \text{ not including IBS}$$

Latency. In a nondestructive bit-by-bit arbitration scheme, a node will experience varying amounts of latency based on the priority of the message to be transmitted. When more than one device wants to transmit at the same time—i.e., less than ¼ bit time—the arbitration detector will allow transmission on a priority basis. If more than one device wants to transmit at about the same time—i.e., greater than ¼ bit time—the arbitration detector will allow transmission on a first-come first-served basis.

Power Reduction Mode. This supports a "sleep state" under microcomputer control by a <10-μ source or sink from bus "+" or bus "–" of input leakage shutdown current.

26.3.5 Class B Data Communication Network Interface, SAE J1850 PWM

The SAE J1850 Standard[10] defines two versions of vehicle multiplex networks. This section covers the PWM encoded at 41.6 Kbps and the following section (26.3.6) discusses the VPWM data encoded at 10.4 Kbps version.

Application/Affiliation. The Society of Automotive Engineers (SAE) developed a vehicle data network for Class B data communications. The latest revision, MAY94, is in publication.

Transmission Media. The physical layer approach is a dual-wire voltage drive. The media for dual-wire is either a twisted or parallel wire pair.

Physical Interface. A representative circuit diagram for the receiver/transmitter is shown in Fig. 26.44.

Bit Encoding

Pulse-Width Modulation. A "1" bit and "0" bit are shown in Fig. 26.45. All bits are encoded in this manner except for a few unique symbols differentiated by the pulse timing. Some of the symbols include start of frame (SOF), end of data (EOD), and end of frame (EOF).

Network Access. Nondestructive prioritized bit-by-bit arbitration.

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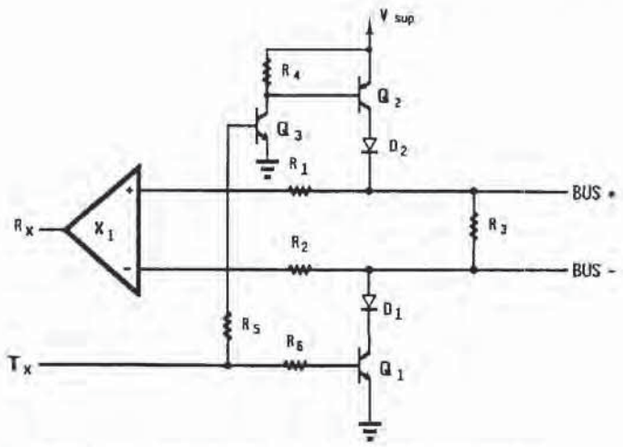
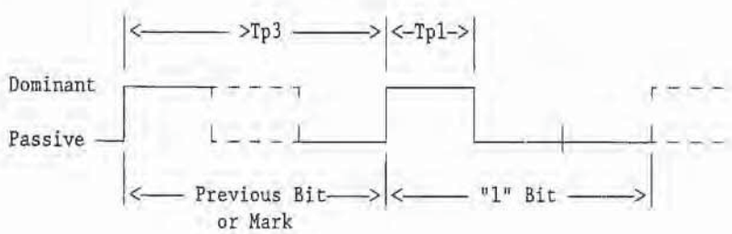
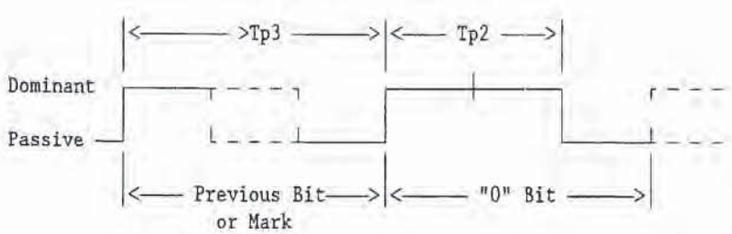


FIGURE 26.44 Representative diagram of PWM physical interface.



"1" Bit Definition



"0" Bit Definition

FIGURE 26.45 SAE J1850 PWM bit representation.

Message Format. The maximum length for a frame is 101 bit times. The error detection byte is included in the data field at the discretion of the designer. Another possible use of the data field could be a message/address identifier. The response byte is explained more fully in the handshaking section following. Interframe spacing is nominally 2 bit times. The message frame is shown in Fig. 26.46.

Handshaking. Acknowledgment is provided in the message frame using the response bytes. The response byte appears after the EOD. If an acknowledgment is not expected, a response byte will not be sent and the bus will remain in the passive state signifying an EOF. If the in-message acknowledge/response feature is active, then the response byte is an 8-bit acknowledge identifier or one or more response bytes followed by an ERR byte. One or more nodes may attempt to respond to the requesting node and arbitration will occur during the response time period.

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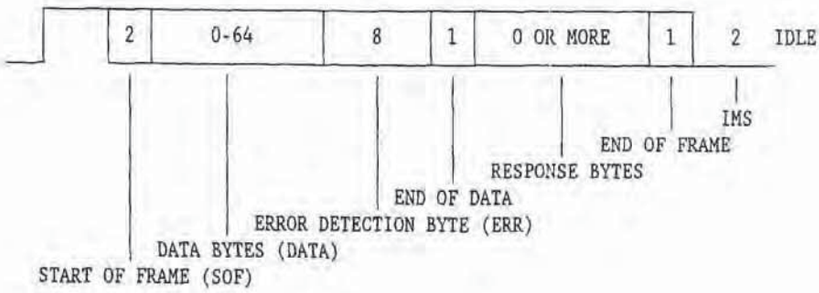


FIGURE 26.46 SAE J1850 PWM version message frame.

Error Detection Management. Includes detection of invalid bit value and invalid message structure. An invalid bit or an invalid message will cause the receive process to be terminated until the next SOF. The in-message error detection field (ERR) uses an 8-bit CRC based on the polynomial $x^8 + x^4 + x^3 + x^2 + 1$.

Fault Tolerance. Communications may be interrupted to/from a node when a node loses power, there is a bus short to ground, a bus short to battery, or a transceiver failure, but there shall be no damage to any other node. The remaining nodes are capable of communications when a node loses power, there is a transceiver failure, and for a loss of connection to network.

Data Rate. The bit rate specified is 41.6 Kbps.

Framing Overhead. The total length for the frame is 101 bit times and, for the overhead calculation, add two bits for IMS. The total length for the calculation becomes 103. The total allowed data is 80 bits for a one-byte form of header, a message identifier, and 64 bits for a three-byte form of header. The percentage of overhead is therefore $23/(80 + 23) = 22.3\%$ and $39/(64 + 39) = 37.9\%$.

Latency. In a nondestructive bit-by-bit arbitration scheme, the highest priority message/address will gain access to the bus. In a message priority scheme, a node will experience varying amounts of latency based on the average priority of messages to be transmitted. A node in an address priority system will experience a delay proportional to the priority level of its address and the activity on the bus. An example of such a delay is a low-priority node, which will experience higher than average latency during periods of high bus loading.

Power Reduction Mode. A node should enter a "sleep state" if the bus is idle for more than 500 ms. "Wake-up" occurs with any activity on the bus.

26.3.6 Class B Data Communication Network Interface, SAE J1850 VPWM

The SAE J1850 Standard[10] defines two versions of vehicle multiplex networks. This section covers the VPWM encoded data at 10.4 Kbps and the previous section (26.3.5) discusses the PWM encoded data at 41.6 Kbps version.

Application/Affiliation. The Society of Automotive Engineers (SAE) developed a vehicle data network for communications. The latest revision, MAY94, is in publication.

Transmission Media. The physical layer of the VPWM version defines a single-wire voltage drive. The media for single-wire is a single random lay wire.

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Physical Interface. The representative circuit diagram for the VPWM receiver/transmitter is shown in Fig. 26.47.

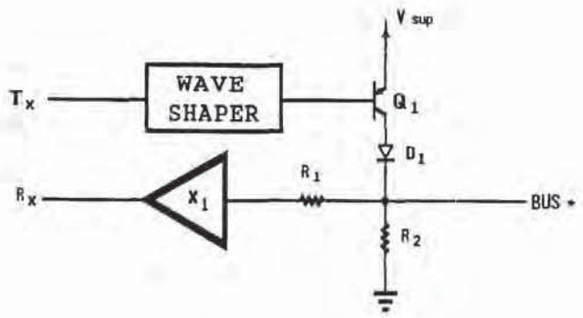


FIGURE 26.47 Representative diagram of a VPWM physical interface.

Bit Encoding. Each bit or symbol in variable pulse-width encoding (except break) is defined by the time between two consecutive transitions and the level of the bus, dominant or passive. Therefore, there is one symbol per transition and one transition per symbol. The end of the previous symbol starts the current symbol.

The "1" and "0" Bits. A "1" bit is either a long 128-μs passive pulse or a short 64-μs dominant pulse. Conversely, a "0" bit is either a short passive pulse or a long dominant pulse (see Fig. 26.48). The pulse widths change between passive and dominant bus states in order to accommodate the arbitration and priority requirements.

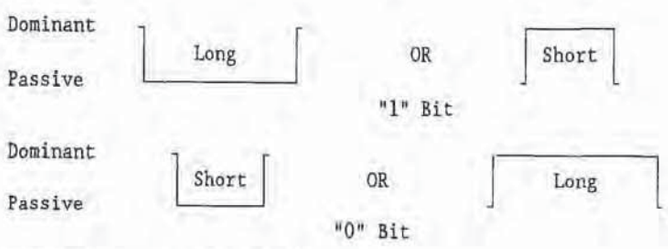


FIGURE 26.48 One and zero bit definitions.

The start of frame (SOF) is a dominant pulse, 200 μs in duration (see Fig. 26.49).

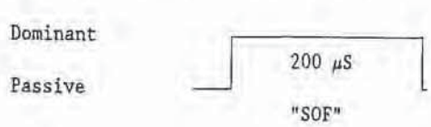


FIGURE 26.49 Start of frame (SOF) symbol.

The end of data (EOD) is a passive pulse, 200 μs in duration (see Fig. 26.50).

The end of frame (EOF) is a passive pulse, 280 μs in duration (see Fig. 26.51).

The In-Frame Response Byte(s)/Normalization Bit. The in-frame response is transmitted by the responder and begins after the



FIGURE 26.50 End of data (EOD) symbol.

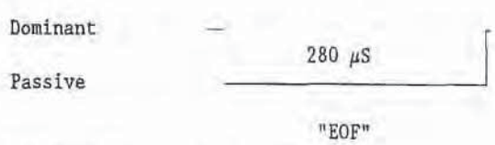


FIGURE 26.51 End of frame (EOF) symbol.

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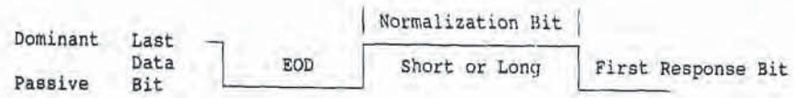


FIGURE 26.52 Normalization bit pulse-width modulation.

passive EOD symbol. For variable pulse-width modulation, the first bit of the in-frame response data is also passive. It is necessary to generate a normalization bit to follow the EOD symbol. The responding device generates the normalization bit prior to sending the IFR data. This normalization bit defines the start of the in-frame response and can take two forms. The first type is a dominant short period. The second type is a dominant long period and may be used to define an in-frame response with a CRC. Figure 26.52 illustrates the in-frame response using the normalization bit.

Network Access. Network access is by nondestructive prioritized bit-by-bit arbitration.

Message Format. The maximum length for a frame is 101 bit times. The error detection byte is included in the data field at the discretion of the designer. Another possible use of the data field could be a message/address identifier. The response byte is explained more fully in the handshaking section that follows. Interframe spacing is nominally 300 μs in duration bit times. The message frame is shown in Fig. 26.53.

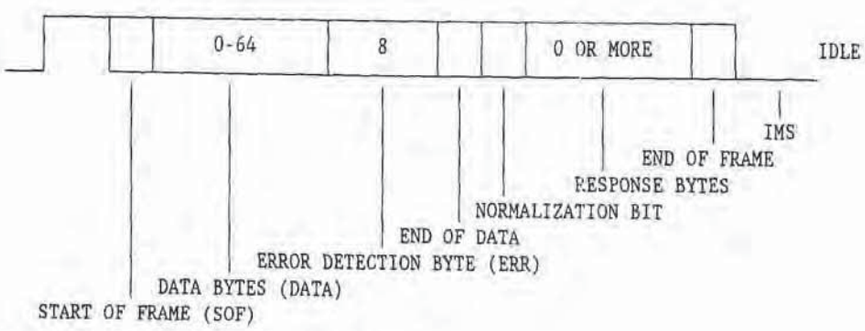


FIGURE 26.53 SAE J1850 VPWM message frame.

Handshaking. Acknowledgment is provided in the message frame using the response bytes. The response byte appears after the EOD. If an acknowledgment is not expected, a response byte will not be sent and the bus will remain in the passive state signifying an EOF. If the in-message acknowledge/response feature is active, then the response byte is an 8-bit acknowledge identifier or one or more response bytes followed by an ERR byte. One or more nodes may attempt to respond to the requesting node and arbitration will occur during the response time period.

Error Detection Management. Includes detection of bus out-of-range, invalid bit value, and invalid message structure. An invalid bit or an invalid message will cause the receive process to be terminated until the next SOF. The error detection field (ERR) uses an 8-bit CRC based on the polynomial: $x^8 + x^4 + x^3 + x^2 + 1$.

Fault Tolerance. Communications may be interrupted to/from a node when a node loses power, there is a bus short to ground, a bus short to battery, or a transceiver failure, but there shall be no damage to any other node. The remaining nodes are capable of communications when a node loses power, there is a transceiver failure, and for a loss of connection to network.

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Data Rate. The bit rate specified is 10.4 Kbps.

Framing Overhead. The total length for the frame is 101 bit times. For the overhead calculation, add 2 bits for IMS. The total length for the calculation becomes 103. The total allowed data is 80 bits for a one-byte form of Header (message identifier) and 64 bits for a three-byte form of header. The percentage of overhead is therefore $23/(80+23) = 22.3\%$ and $39/(64+39) = 37.9\%$.

Latency. In a nondestructive bit-by-bit arbitration scheme, the highest priority message/address will gain access to the bus. In a message priority scheme, a node will experience varying amounts of latency based on the average priority of messages to be transmitted. A node in an address priority system will experience a delay proportional to the priority level of its address and the activity on the bus. For example, a low-priority node will experience higher than average latency during periods of high bus loading.

Power Reduction Mode. A node should enter a sleep state if the bus is idle for more than 500ms. Wake-up occurs with any activity on the bus.

26.3.7 Chrysler Sensor and Control (CSC), SAE J2058

Application/Affiliation. A proprietary multiplexing technique,[11] the Chrysler Sensor and Control (CSC) bus, yields the flexibility in expansion to meet the future demands of automotive customers. The CSC bus components were developed to provide simple, yet reliable, communication between a host-master module and its sensors and actuators. The scheme chosen provides the ability to communicate in both polling mode and direct addressing modes. This form of multiplexing will permit smaller module connectors and reduce the number of wires crowding through the congested areas without introducing more modules. The (CSC) bus is a style of multiplexing that meets these objectives and allows the design of the base vehicle while attaching the complete cost of optional features to the option.

Two CSC components are available as of this publication: (1) CSC bus two-pin, CSC Bus Hall Effect Sensors, Allegro P/N A3054U, and (2) Driver/Receiver Master Interface, Cherry Semiconductor, Automotive IC Data Book, P/N CS-8425 Hall-Effect Sensor.

Transmission Media. The CSC network utilizes a single-wire random lay.

Physical Interface. The output waveform of the driver/receiver master interface must be wave-shaped to limit the rise and fall time. Empirical vehicle testing has confirmed acceptable EMI levels if the waveform transients exceed 20 μs at data rates of 1 Kbps. The susceptibility to EMI is of greater concern. (See Fig. 26.54).

The preferred solution is to reference the CSC sensor at the driver/receiver master interface ground. This solution virtually eliminates this longitudinal noise current and, at the same time, significantly reduces the effects of ground offset voltage. In a production vehicle, returning the CSC sensor references to the master module usually does not add a wire circuit because these sensors originally had an independent ground wire return to the body or chassis. Further improvement to EMI susceptibility can be achieved by placing a small bypass capacitor across the CSC bus at the sensor.

Bit Encoding. Continuous Polling Mode Sensor Multiplexing. Figure 26.55 contains the typical voltage waveform used to communicate with multiplexed sensors. As illustrated, the sensors use current to respond back to the master that generates the voltage waveform. In this scheme, each sensor has an internal preprogrammed address. The voltage begins at a reset (zero volt) level and climbs to 6 V. This initial 6-V level provides power to the sensors. During

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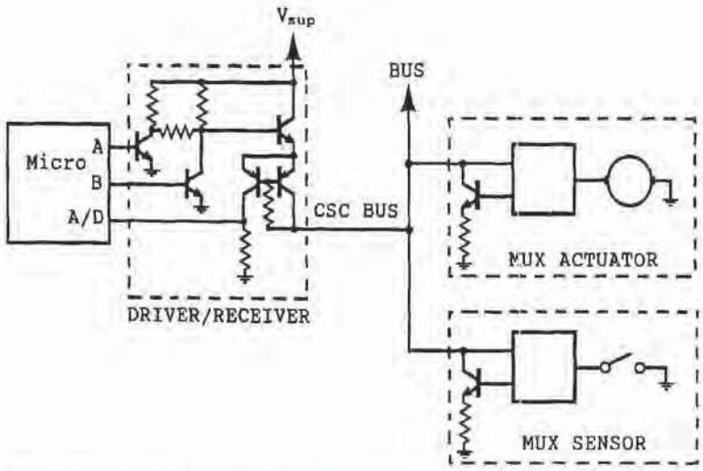
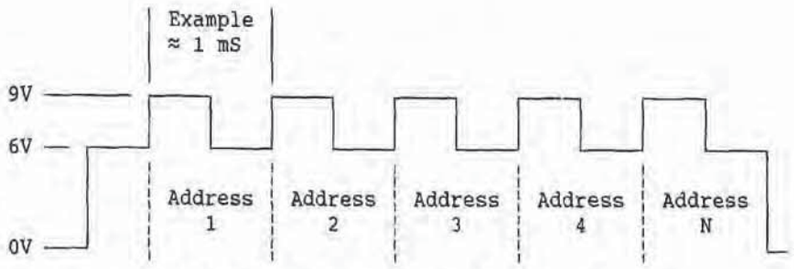
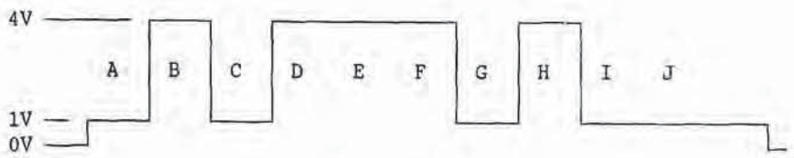


FIGURE 26.54 Representative diagram of a CSC sensor actuator bus.

this time, the master reads the amount of current required to keep the sensors powered. This current is called the sensor power current. At each change from 6 V to 9 V, a counter contained in the sensor is incremented. The sensors are addressed consecutively so this mode of CSC bus communication is called the *continuous polling mode.*



CSC Bus Sensor Polling Mode Voltage Waveform



Voltage Representing Current Drawn by the CSC Sensors

A: Sensor Power Current
B: Sensor Presence Current
C: Switch Open
D: Sensor Presence Current
E: Switch Closed
F: Sensor Presence Current
G: Switch Open
H: Sensor Presence Current
I: Switch Open
J: No Sensor Present

FIGURE 26.55 CSC bus sensor polling mode waveform.

While the voltage is at approximately 9 V, the sensors compare the value in their counter to their preprogrammed address. If a sensor detects a match between these two values, the sensor will increase the current drain on the CSC bus. This *response current* informs the mas-

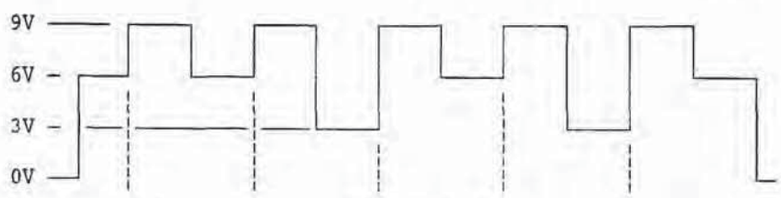
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ter that a sensor has recognized its address. This condition remains until the voltage falls to about 6 V.

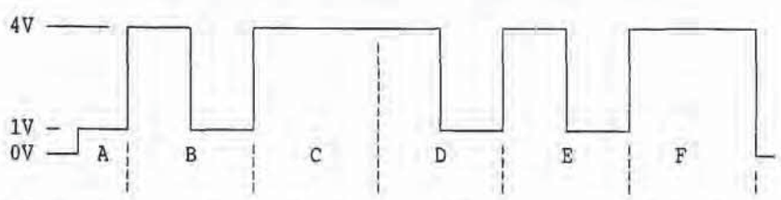
When the sensor being addressed detects that the voltage is below its threshold of about 7.5 V, it will determine the status of the sensing element, i.e., magnetic field detecting Hall effect sensor, optical sensor, or mechanical switch to ground. If the sensing element is active—i.e., a magnetic field is detected—light is detected, or a mechanical switch to ground is closed, the sensor continues to draw the response current so that the master can sense the sensor's status. If the sensing element is not active, response current will cease and only the sensor power current will be drawn.

Actuator Polling Multiplexing. This effort to control actuators utilizes the CSC bus multiplexing technique used as an extension of the sensor polling mode. A particular actuator is assigned an address, just as the sensor is assigned an address. Each actuator monitors the CSC bus to count the 6- to 9-V transitions in the same way as the sensor does. When the value in the counter of the actuator matches the actuator's address during the 6-V portion of the address, the actuator draws current to tell the master that the actuator is recognizing its address.

To activate an actuator output, the status must first be monitored by checking the current drawn during the second half of the address cycle. In contrast to the sensor polling scheme, which uses 6-V and 9-V levels only, the actuator multiplexing scheme adds a third 3-V level (see Fig. 26.56). During the second half of the address cycle, the level is driven to 3 V by the master when the output of the actuator is to be toggled. The actuator monitors the CSC bus during its address. If the actuator detects the 3-V level, a latch is set. The actuator does not change its output, because of noise considerations, after the first 3-V level is detected.



CSC Bus Actuator Polling Mode Voltage Waveform



Voltage Representing Current Drawn by Sensors and Actuators

A: Sensor Power Current
B: Sensor Present, Not Active
C: Actuator Toggled, High
D: Actuator Status Presently High
E: Actuator Toggled, Low
F: Sensor Present, Active

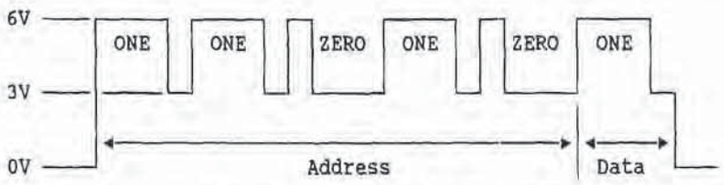
FIGURE 26.56 Continuous polling actuator multiplexing waveforms.

The actuator monitors the following polling cycle. If the second half of the actuator's address period in the very next polling cycle is 3 V then the actuator will toggle its output. Every subsequent polling cycle must contain the 6-V level during the actuator's address period for the output to remain constant. The current drawn by the actuator during this second half indicates the status of the output. When the output is to change state again, two consecutive polling cycles must contain 3-V levels during the second half of the actuator's address period.

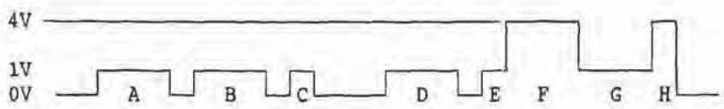
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Actuator Command Mode Multiplexing. In order to increase the flexibility of the communication scheme, the system designer has as an optional complementary actuator multiplexing capability. In order to provide all polling addresses to sensors and permit direct addressing of a particular actuator, a scheme was devised that complements the polling mode. This scheme has been called the *command mode, direct addressing,* or *control mode* of the CSC bus.

Instead of sequentially addressing the actuators as in the polled method, the master sends a 6-ms voltage signal to the actuators (Fig. 26.57). This waveform consists of transitions between 6 V and 3 V. The example 6-ms waveform is divided into six 1-ms bits and is called a 6-bit word. A 75%/25% pulse-width modulation technique is used to define the bit value. Each bit begins with a transition to 6 V. For example, a "1" bit is defined as 750 μs at 6 V and 250 μs at 3 V. A "0" bit is defined as 250 μs at 6 V and 750 μs at 3 V.



CSC Bus Command Mode Actuator Multiplexing Voltage Waveform



A, B, C, D, E, and G: Sensor Power Current
F: Actuator Response Current
H: Actuator Output Status High

Voltage Representing Current Drawn by Sensors and Actuators

FIGURE 26.57 CSC bus command mode actuator multiplexing waveform.

The first five bits of the 6-bit word are used to address the particular actuator and the sixth bit is used to control the state of the actuator's output. The master provides the voltage waveform. The CSC bus is initially at reset (≈0 V). From reset the voltage waveform is driven to 6 V. The waveform stays at 6 V for either 750 or 250 μs, depending on whether the bit is a "1" or a "0", respectively. The CSC bus then falls to 3 V for the remainder of the 1-ms bit period. During the 6-V portion of the first bit, the master monitors the current drawn by the components on the CSC bus. The master will use this current later as a reference to determine if an actuator has recognized its address.

All six bits are transmitted the same as just described. During the 3-V portion of the fifth and final address bit, the master can determine that an actuator has recognized its address by measuring the amount of current being drawn.

Network Access. The CSC bus utilizes a master-slave protocol. This protocol is appropriate because the master is usually the present major feature module and its associated sensors and actuators are the slaves. The feature module microcomputer is the host to the driver/receiver interface IC.

The CSC bus driver/receiver master interface integrated circuit contains the circuitry required to provide a DC offset square wave output. This output is controlled by two digital CMOS inputs: A and B. These two inputs are provided by a host microcomputer acting as the "brains" of the master control module. The IC is able to sense the CSC bus current and con-

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vert it to an analog voltage. This voltage is provided by the IC output for use by the microcomputer analog input.

Message Format. The network method for this communication system is a master-slave polling and/or direct address method. The master uses a voltage waveform to communicate to the sensors and actuators. A sensor is addressed through successive and ordered polling of each address (time slot or period) in ascending order.

```
<SOM>, Wake-Up Period, Addr 1, Addr 2, ..., Addr 32
```

An actuator may be controlled by either the polling mode shown or the direct address, command mode message below. The start of message (SOM) is defined as the rising edge from 0 to 6 V in the voltage waveform of Fig. 26.55.

```
<SOM>, <Five-Bit address>, <1 to N data bits>, (<parity bit>)
```

Handshaking. Both sensors and actuators respond to the master node when polled or directly addressed, with a response current informing the master that an address has been recognized.

Error Detection Management. Actuator data can be protected from unwanted actuation by a parity bit in the command message. The normal solution for eliminating EMI susceptibility that caused false sensor data is to software filter the data in the master control module.

In order to validate the proper addressing of a sensor or actuator in a noisy vehicle environment, the following procedure is suggested. If this current is not above the reference current measured, the sensor is not present or no actuator is listening. If two or more sensors or actuators are listening (determined by double the expected response current), the master can reset (output zero volts) the CSC bus. If the master detects that the sensor or actuator output is not in the correct state, the command can be repolled or resent.

Fault Tolerance. Handshaking between the master node and sensors allows operation and detection when sensors or actuators are removed from the network. The driver/receiver has a current limit that protects it from a bus short.

Data Rate. The data rate is determined by the master module software and need not be fixed. A rate of 1 Kbps is suggested.

Framing Overhead. The framing required time is equal to the data time therefore:

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

$$\frac{\text{OVERHEAD}}{\text{MESSAGE}} = \frac{1}{2} = 50\%$$

Latency. The master node is in control and can interrupt sensor or actuator polling to command an output to an actuator within a few milliseconds and 32 sensors can be polled within 32 ms, or a 1-Kbps rate.

Power Reduction Mode. The master node can control the power by not polling or addressing the network. The current draw will then be the sensor actuator standby power.

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26.3.8 Token Slot Protocol, SAE J2106

Application/Affiliation. General Motors developed protocol[12] for high-performance vehicle control and general information sharing.

Transmission Media. Not specified. Electrical twisted pair or fiber optic media are recommended. Fiber optic token slot networks operating at 1 Mbps have been demonstrated.

Physical Interface. Not specified. Multiple access to a logical common bus is required.

Bit Encoding. NRZ (nonreturn to zero) with opposite logic level bit insertion (stuffing) after five contiguous bits of the same state. Receiving nodes detect and remove inserted bits.

Network Access. The token passing bus network is open, peer-oriented, and multimaster. It is noncontention and uses a time slot token passing technique. See Fig. 26.58, 26.59, and 26.60.

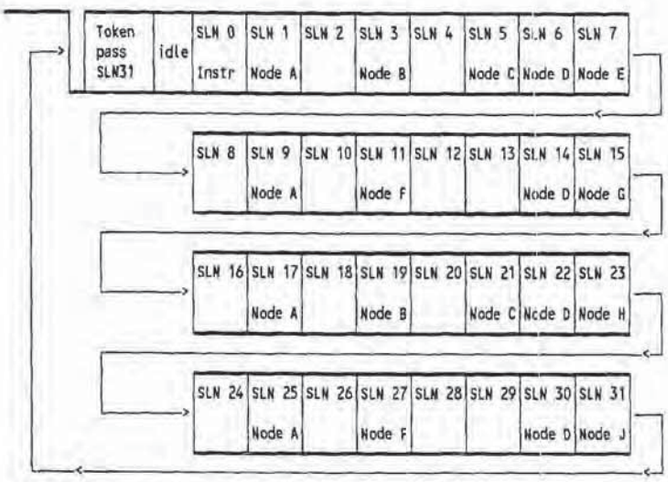


FIGURE 26.58 A typical token slot node assignment and slot sequence cycle pattern.

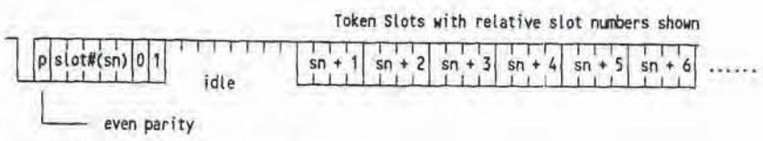


FIGURE 26.59 Token pass message format.

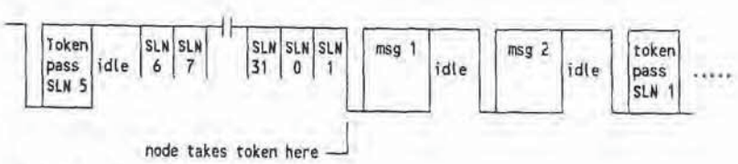


FIGURE 26.60 Typical token pass sequence.

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The intent of this bus access protocol is to guarantee periodic opportunities for message transmission by each node on the bus. It is to also ensure that the bus remains operational when devices are dynamically added or deleted and it must provide for quick recovery from error conditions.

After a node has completed sending its message traffic, a sequenced scan of short, equal time intervals (slots) offer bus transmit privileges to the node slot owners as follows (see Fig. 26.59): A token pass message or a *bus jam* instructs all nodes to begin the token slot timing mode. Each node is assigned one or more specific time slots and will activate its transmitter to send a message during its slot only if it is operational and has message traffic to send. Otherwise, the token slot interval is allowed to pass. When the transmitter is activated, all other nodes recognize that the token has been taken and they enter the receive mode.

The new token owner next proceeds to send its message traffic (see Fig. 26.60). Token hold times are individually assigned to each node and are strictly limited to assure a system maximum message latency limit. Individual message transmit priorities are determined by each node's application and are not restricted by the data communications network.

A node concludes a transmit session by sending the token pass message that contains the current slot number (see Fig. 26.60). In the ensuing token slot sequence, the node that owns the next sequential slot number may take the token or let it pass. When the maximum slot number is reached, the sequence wraps around to slot 0 and continues until the slot is picked up or until the original token passer sees its slot, at which time a new token pass message is generated and the cycle begins again.

Message Format. There are three basic message types which are distinguished by the 2-bit control field which is found in the first byte:

- *Token pass* (see Figs. 26.59 and 26.60). This is a single-byte message which contains the message control field (2 bits), the current slot number (5 bits), and a single parity (even bit). It is followed by an idle line (8 bits) delimiter.
- *Data* (see Figs. 26.61 and 26.62). This includes the message control field (2 bits), a message ID field (14 bits), up to 256 bytes of data, a 16-bit cyclic redundancy check (CRC) field, and a message delimiter bus idle line (8 bits). The message control field is used to request an "acknowledge" message response.

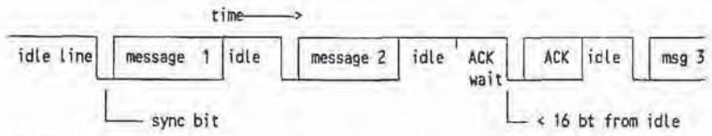


FIGURE 26.61 Token slot network general message framing.

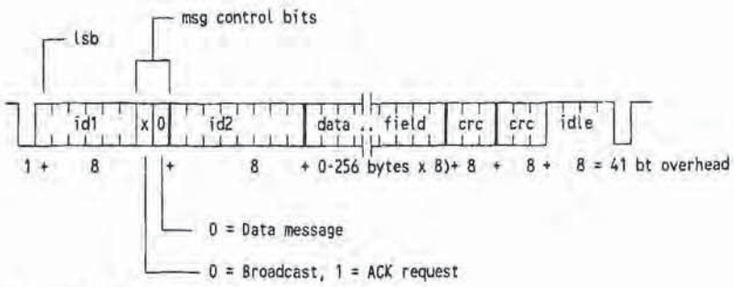


FIGURE 26.62 Token slot network data message format.

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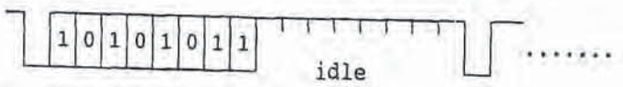


FIGURE 26.63 Token slot network acknowledge message format.

- *Acknowledge* (see Fig. 26.63). This is a fixed, single-byte (Hex D5) message plus an 8-bit idle line delimiter (16 total bits). It is initiated by the previous data message control field.

Handshaking. Any data message can be dynamically programmed to command an immediate returned acknowledge message from one receiving node. If after a short wait interval the requested acknowledge has not been received, the sender may retry and/or proceed to send other messages. Note that the responding node does not possess the token.

Error Detection Management. Both the receiving and the transmitting nodes independently monitor transmissions on the bus. The transmitting node checks messages for a 1:1 received to transmitted bit correspondence. All nodes check for correct timing, CRC, intermessage gaps, and, if requested, an acknowledge message. Receiving nodes do not acknowledge erroneous messages.

The 16-bit CRC conforms to the CCITT standard and detects all single-bit errors, all parity errors, and all burst errors less than 17 bits long. For burst errors longer than 16 bits, the CRC misses 0.0015 percent of errors.

A transmitter detected *bus time out* (BTO) error occurs when the bus is idle for more than a complete token slot sequence period. When a BTO is detected, all nodes start a new token pass slot sequence beginning at slot 0.

Bus errors or collisions cause the detecting node to generate a bus jam signal, a dominant line for 8-bit times, before the end-of-message idle line. This declares the current operation or message invalid and instructs all nodes to start a new token pass slot sequence beginning at slot 0.

Fault Tolerance. Each transmitting node monitors its own bus performance and fault history. Appropriate degraded mode operations are controlled by the node. The loss of any node or even a separated bus will not affect the continued bus operation by the remaining nodes.

Data Rate. Data rate limit is specified at 2 MHz. However, the data rate is only limited by bus media bandwidth and future data rate growth is possible.

Framing Overhead. The message framing overhead is summarized in Tables 26.3 and 26.4. See Fig. 26.64 for total message latency calculation methods.

TABLE 26.3 Token Passing Slot Overhead in Bit Times (bt)*

Slot width (assume xmtr ON aqt mid slot = 2 bit)	2
Token pass message	8
Delimiter gap	8
Token pass overhead per node	18 bit

* See Fig. 26.59 and Fig. 26.60

TABLE 26.4 Token Slot Data Message Overhead*

Synchronization bit	1
ID	16
Data (system determined limit, e.g., 0–256 bytes)	var
CRC	16
Intermessage delimiter gap	8
Acknowledge response (if requested) + gap	16
Per message overhead—with ACK	57 bits
or per message overhead—without ACK	41 bits

* See Fig. 26.61, 26.62, and 26.63

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Token Slot Message Overhead (in bit times = bt):

Synchronization bit	1
ID	16
Data (system determined limit - bytes)	(0-256 bytes)
CRC	16
Intermessage delimiter gap	8
Acknowledge response (if requested) + gap	16
Per message overhead - with ACK:	57 bt
or Per message overhead - without ACK:	41 bt

Token Passing Slot Overhead:

Slot width (assume xmtr on at mid slot = 1 bt)	1
Token Pass Message	8
Delimiter gap	8
Token pass overhead per node:	17 bt

Summary of Loop Time Calculations:

For P nodes sending an N message loop with M total message data bytes:

Total message overhead (no ACK)	41N
Total token overhead	17P
Total message data time (m x 8 bits)	8M
Unused slots = slot width x (max #slots - #usedslots) = 1(32-P)	
Total Loop Time	41N + 17P + 8M + 4(32-P)

Example Token Slot Timing Calculation

For 8 nodes sending a 16 message loop with 32 total message data bytes (2 msgs x 2 bytes per node x 8 nodes):

Total message overhead (no ACK)	41x16	=	656
Total token overhead	17x8	=	+ 136
			792
Total message data time (32 x 8 bits)		=	+ 256
Unused slot time	(1x24)	=	+ 24
Total Loop Time (bt)			1072

Data-to-total time overhead efficiency: 256/1072 = 24.0%

FIGURE 26.64 Determination of token slot message latencies.

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Latency. The protocol is noncontention and deterministic. As such, message latencies in the token slot network are both predictable and bounded, which is a requirement for feedback control systems.

Factors that affect message latency times are discussed in the following. See Fig. 26.64 for methods of latency calculation and prediction.

The token loop time determines the interval between opportunities to transmit a message. It is defined as the total elapsed time between token possessions by a particular node. It includes all message traffic, token pass slot times, and all token hold times.

Token slot time length is important during the token pass sequence when each time slot must provide sufficient time for worst-case signal propagation delays in order to allow nodes to detect that the token has been taken.

Token hold time is the maximum number of bit times that each node is allowed to hold the token. All message IDs, data fields, CRCs, intermessage gaps, message synchronization bits, NRZ5 bit insertions, acknowledge messages or acknowledge time outs, and token pass messages must not exceed this limit. Each node monitors and controls this time to stay within its assigned limit.

Power Reduction Mode. Not specified. Could be implemented.

26.3.9 Time Triggered Protocol (TTP)

Knowledge about the future (i.e., a priori knowledge) behavior of the TTP system is available to the system designer and is controlled by the progression of time.[13] For example, the point in time when a node is supposed to send a message can and must be determined by the real-time control algorithms and programmed into the module before release for production. The main advantage to TTP is to support high-speed distributed time-triggered real-time control of systems.

Application/Affiliation. TTP was developed by the Institute for Technical Information, Technical University Wien, Austria, and is an integrated communications protocol for Class C in-vehicle applications that provides all services required for the implementation of a distributed fault-tolerant high-speed real-time control system.

Transmission Media. A twisted pair or fiber optics is suggested for the transmission media.

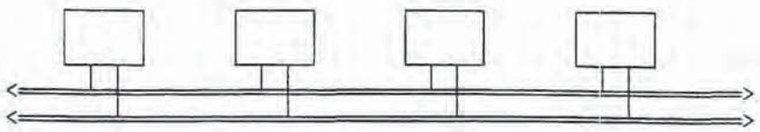
Physical Interface. The basic system I/O structure consists of nodes connected by two redundant physical interfaces to dual networks to protect for failures in cabling, contacts, connectors, etc. To tolerate a node failure, two nodes are connected in parallel. Four configurations are shown in Fig. 26.65.

Bit Encoding. The bit encoding is not specified. However, modified frequency modulation (MFM) is suggested as the encoding technique because it has fewer than one transition per bit.

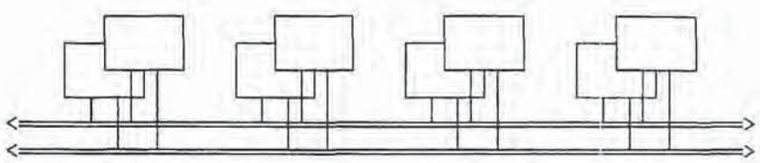
Network Access. The network access is accomplished using a time division multiple access (TDMA) controlled by a global time base generated by time triggered protocol (TTP). A TDMA round is defined to be a complete cycle during which each vehicle module has been granted at least one sending access.

Message Format. All information transmitted on a communications channel must be properly framed. A TTP frame consists of the following fields: start of frame (SOF), a control field, data field, and a CRC field. An interframe delimiter (IFD) exists between any two TTP frames. See Fig. 26.66.

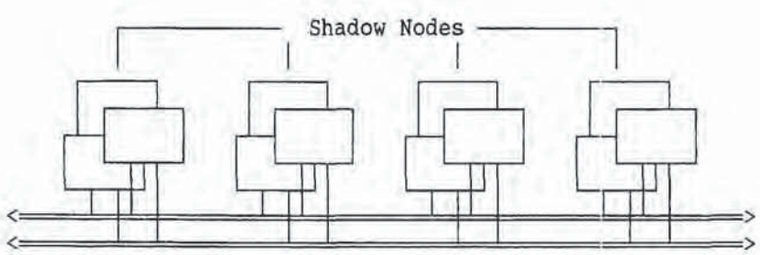
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Class I Configuration



Class II and Class III Configuration



Class IV Configuration

FIGURE 26.65 Fault-tolerant configurations.

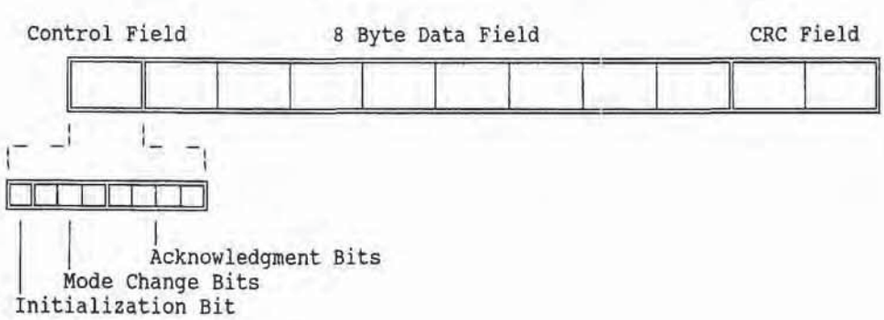


FIGURE 26.66 Typical frame format.

Start of Frame (SOF). This identifies the beginning of a new frame.

Control Field. The control field has three subfields.

Initialization Bit. This specifies an initialization frame (I-frame) or a normal frame (N-frame). I-frames are required to initialize a node. The state of the communications controller node (i.e., C-state) consists of three fields: a node field, a time field, and a membership field. Typically, each one of these fields will have a length of two bytes, or 16 bits. When a node is initialized, these three fields are filled from the data field. N-frames are normal data frames containing the application data in the data field.

Mode Change Bits (3 bits). If the initialization bit is unequal to zero, it allows the specification of seven successor modes to the current mode. Therefore, the protocol supports a rapid change from one mode to another mode, e.g., startup, normal operation, emergency, etc.

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Acknowledgment Bits (4 bits). These bits contain an acknowledgment for the frames sent by the preceding vehicle module. The question of which module is the preceding module depends on the current membership. The length of the acknowledgment field makes it possible to acknowledge each one of the four frames sent by a module in a class III or Class IV configuration.

Data Field. The data field consists of the concatenation of one or more messages containing application data. The length of each message is statically defined in the mode definition. It is not necessary to carry a name field in the frame since the message name can be inferred from the mode field and the point in time of sending.

Cyclic Redundancy Check (CRC) Field. The CRC field has a length of two bytes. For N-frames, the CRC is calculated over the C-state of the controller concatenated with the control field and the data field of the frame. A normal frame is only accepted if the sender and receiver have identical C-states, i.e., if they agree on mode, time, and membership. Since the receiver knows a priori the time of sending of each frame, it is not necessary to carry the value of the send time in the frame.

Interframe Delimiter (IFD). The interframe delimiter is required for proper bit synchronization of sender and receiver.

Handshaking. As shown in Fig. 26.65, two nodes are connected in parallel to tolerate a node failure in replicated vehicle communications channels. These replicated channels perform the same state changes at about the same time and are synchronized to within a known precision by TTP.

Error Detection Management. TTP is based on the assumption that the communications channels have only omission failures and the nodes support the fail-silent abstraction; i.e., they either deliver correct results or no results at all, which helps to enforce error confinement at the system level. A sender attaches a CRC to each frame and a receiver can detect when a frame has been mutilated and discard the corrupted frame.

For correct operation, the node must assure, by use of space or time redundancy, that all internal failures of a node are detected and the node is turned off before an erroneous output message is transmitted. Moreover, a membership service is required to detect omission failures of incoming and outgoing communications links. This membership service is part of the protocol.

Fault Tolerance. With dual duplex buses and redundant node communications channels, the fault tolerance capability is excellent. Table 26.5 shows the fault tolerance capability achieved with the four class configurations shown in Fig. 26.65. The recovery interval for a transient event depends on the length of the transient blackout period and the time TTP takes to detect, monitor, and recover from a blackout. This time for TTP is in the millisecond range.

TABLE 26.5 Fault Tolerance Capability

Tolerance of	Class I	Class II	Class III	Class IV
Permanent node failure	0	1	1	2
Permanent bus failure	1	1	1	1
Transient node failure	0	1 per event	1 per event	1 per TDM round
Transient bus failure	1 of 2	1 of 2	3 of 4	3 of 4

Data Rate. The data rate is not specified, but 1 Mbps is suggested.

Framing Overhead. The length of SOF and IFD depends on the bus propagation delay, the quality of the clock synchronization, and bit-encoding method. For transmission speeds below

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1 Mbit and a bus length below 20 m, the SOF = 1 and IFD = 3. The framing overhead is given by the following: OVERHEAD/MESSAGE = FRAMING/(FRAMING + DATA). For a message transmitting 4 bytes (32 bits) of data, using the formula: 28/(28 + 32) = 47%. For a message of 8 bytes (64 bits) of data, using the formula: 28/(28 + 64) = 30%. The total framing overhead is slightly higher to account for the periodic transmission of initialization frames.

Latency. Given a 1-Mbit channel for eight nodes sending a 16-message loop with 32 total message data bytes, the TDMA round of TTP is 0.48 ms in Class I or Class II configuration. This is also the worst-case delay for a node switch. If a Class III or Class IV configuration with four replicated messages is selected, the TDMA round is doubled, i.e., just below 1 ms.

Power Reduction Mode. The power reduction is not specified but could be specified as a mode of operation. The change to a power reduction could be done at any time.

26.3.10 Vehicle Area Network (VAN)

Application/Affiliation. VAN (vehicle area network) is a multiplex bus protocol proposal being considered by the ISO Technical Committee 22/SC3/WG1.[14]

Transmission Media. Twisted pair.

Physical Interface. Transmission is on differential pair using current sources. An optional analog filter is provided to increase noise immunity. See Fig. 26.67.

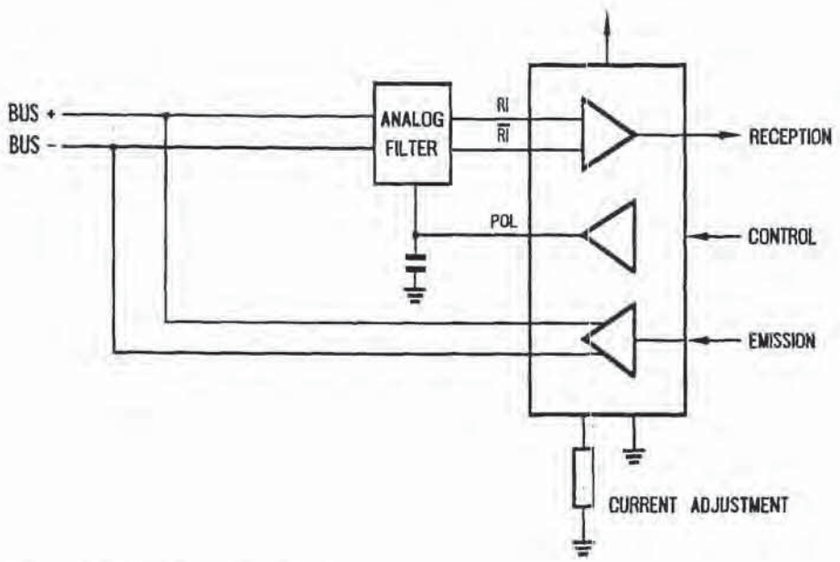


FIGURE 26.67 Fault-tolerant bus interface.

Bit Encoding. Two different bit representations are allowed: L-Manchester and E-Manchester. The bit representation is selected by the user. When L-Manchester is selected, all the bits in the frame are Manchester encoded. E-Manchester will be NRZ encoded except for the last bit of each nibble. With E-Manchester idle, IMS, and SOF are NRZ encoded, and ACK is Manchester encoded. See Fig. 26.68 for an example of E-Manchester encoding.

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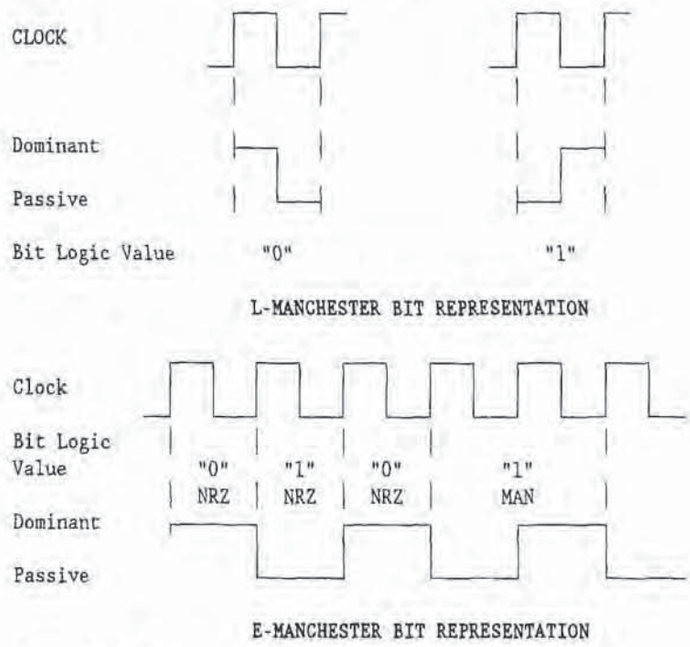


FIGURE 26.68 VAN bit encoding.

Network Access. Network access is by prioritized nondestructive bit-by-bit arbitration. Arbitration is resolved using the unique 12-bit identifier field at the start of the message. The format of this field is user-defined. VAN allows in-frame access based on a media access rank R. A node can access the frame, provided the previous R-1 bits of the arbitration field have been emitted and the previous time slot was recessive.

Message Format. The frame consists of eight fields. The start of frame (SOF) provides a common time reference that allows receiving nodes to correct their local clock. The start message bit initializes the frame. The two-byte frame identification field includes the unique 12-bit message identifier followed by three control bits and the remote transmission request bit (RTR). The RTR specifies if the frame includes data (0 bit) or if data is requested (1 bit). The RTR allows in-frame response immediately or later in a separate frame. The message frame is shown in Fig. 26.69.

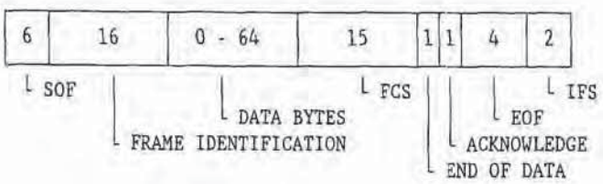


FIGURE 26.69 Single type frame format.

Handshaking. Message acknowledgment is achieved in one of two ways: no acknowledge or positive acknowledge, which means at least one station has received and accepted the message. If the receiving station cannot make an in-frame acknowledge, a separate acknowledge message must be sent later.

Error Detection Management. Methods of error detection include level monitoring, CRC, code violation detection, and frame check. Level monitoring is performed by the transmitting

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node. The transmitted bit levels are compared with the bit levels detected on the bus. Frame checking is performed through a 15-bit CRC code:

$$\frac{(x^8 + x^4 + x^3 + x^2 + 1)}{(x^7 + 1)}$$

Fault Tolerance. Single-wire operation is possible with the differential drive scheme due to the ac-coupling if the other wire is shorted to ground, shorted to V_{batt}, or open circuited.

Data Rate. The data rate is not specified.

Framing Overhead. The total frame size (including data) is 109 bits. The total frame size includes start, stop, and idle bits. The maximum amount of data allowed in a frame is 64 bits. The percentage of overhead is therefore 45/(45 + 64) = 41.3%.

Latency. As with all arbitration-based protocols, the latency amount varies depending on the priority of the message.

Power Reduction Mode. Not specified.

26.4 SUMMARY AND CONCLUSIONS

Throughout the 20th century the auto industry has seen many changes. The electrical components in the horseless carriage were essentially a magneto ignition system. In the 1920s, the electric starter became popular but the first real use of the semiconductor in the auto industry was in the 1960s, first in electronic voltage regulators and then in brakerless ignition systems. Toward the end of the 1970s, the full engine control computer was in production. Then by the 1980s, consumers were demanding electronically controlled turbo, electronically driven instrument clusters, antilock brake systems, and navigation and trip computers. The electronic content of passenger vehicles had doubled by the 1990s.

26.4.1 The Future of Automotive Electronics

In the future, electronics will play an even larger roll. The automotive electronics field is presently going through a number of noteworthy changes. Integration, diagnostics, design for manufacturability, and system engineering are the buzzwords of the 1990s. The past add-a-feature, add-a-module mode of operation is replaced by integration. For example, the common practice is to package many of the feature items such as intermittent wipers and automatic door locks into a single module. The manufacturer will have a built-in diagnostics technique that can computer-verify that the product is functioning properly at the time of construction. Also, the dealer will have the capability of accurately and economically determining the failed module. Integration, diagnostics, and systems engineering promise higher quality, better performance, and lower cost for the manufacturer and the consumer.

26.4.2 The Class B Data Communications Network

The Class B data network is the main enabler and driving force to module integration and service diagnostics. The data network interconnects these integrated systems, allows the modules to communicate with each other, and provides for quick service and maintenance. These inte-

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grated systems must be coordinated to make sure that everything functions together properly. The Class B data communications network is applicable because most of these features will not require real-time control processing.

Electronics and vehicle multiplexing means more than just new innovative gadgets in a car. This relatively new field of automotive engineering is a highly developed technology that has the potential for enormous benefits to the consumer in that it promotes safety and provides convenient and useful features in the automobile. The data network and electronics should make it easier and more economical to manufacture a car, drive a car, and service a car.

Even though the electronic content will have doubled, the car of the mid 90s will be significantly easier to manufacture because there will be half the number of modules, due to feature content integration. The data network that interconnects these modules will also reduce the size and number of interconnecting cables and cut the number of circuits by 25 percent.

The objective of the industry is to deliver a quality, defect-free product to the customer. As previously illustrated, integration plays a major role in reducing the number of modules that can fail, the number of parts that can break and the number of interconnecting circuits that can fail, thereby substantially improving the reliability. The data network and built-in diagnostics also play a key role in verifying that the product is manufactured properly. Proper diagnostics is also accomplished more perfectly by computer during manufacturing, and reduces or eliminates the arduous task of manual verification on the assembly line.

The computerized vehicles of the future need logically acute ergonomics for the driver. Safety, reliability, ease of use, buttons that are easy to reach, and gages or dials that are easy to see can all be characterized as "slickness." Our neoteric generation of customers is rightfully demanding these innovations and world competition makes it a top priority.

At the heart of these ease-of-driving innovations is the data network that allows the various integrated modules to coordinate their activity so that the buttons that control the displays can be placed at the best ergonomic locations. The display is then located for convenient viewing while operating the vehicle.

With the aid of market research, the integrated module may be chosen to contain just the mix of features the customer desires. The data network can significantly simplify delivery of the required data to that module. This gives the customer greater freedom than ever to pick and choose a personally designed content in his new vehicle, thus promoting customer personalization and satisfaction.

The auto industry designs for reliability, but when things fail, the objective is to economically fix it right the first time. Vehicle multiplexing again plays a major role in allowing the service technician to communicate with each of the modules using a diagnostic tool through a centrally located diagnostic connector. This method uses the power of the computer in the vehicle and the diagnostic tool to walk the technician through the diagnostic flowchart to deliver the solution to the problem in a language the service technician can understand.

26.4.3 Class A Multiplexing

With all these benefits why is multiplexing taking so long? Over the last two decades the automotive component manufacturers of electronic equipment have been touting the virtues of Class A vehicle multiplexing (low-speed body wiring and control functions). Previously, articles were illustrated with dramatic pictures of the amount of wire that could be saved by multiplexing. Other articles projected immense cost savings and technical benefits to be derived through the utilization of vehicle multiplexing. Now 20 years later, few, if any, of these predictions have become a reality. Thus, the domestic vehicle manufacturers have not generally endorsed these concepts.

For years it was postulated that vehicle multiplexing would be practical once a semiconductor device was developed that would replace the relay and have the capability of driving lights and electric motors. The recently developed MOS power driver has this multiplexing

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potential. The semiconductor industry hopes that this device is the real breakthrough that will make Class A vehicle multiplexing a reality. However, with this development, the industry is only closer to a solution. The real situation is that Class A multiplexing is still not cost effective. A closer examination of the problems of Class A multiplexing from a vehicle manufacturers' perspective is warranted. The effectiveness of multiplexing must consider the following factors:

- The ability to reduce the average vehicle system cost
- The ability to allocate the cost of the option to the option
- Wiring reductions such as number of circuits and bundle size
- The support of built-in diagnostics for manufacturing and service
- Bus throughput (capacity) and how well the network architecture handles time-critical messages.
- Reductions in weight and ease of assembly

26.4.4 Comparison of Class A and B Data Networks

Is the Class B multiplexing situation any different than the Class A? A careful system cost analysis for Class B vehicle multiplexing shows that the added cost of the multiplexing electronic components is not offset by the cost savings in vehicle wiring harnesses. The condition is very similar to Class A data network leading one to adopt the theory that vehicle multiplexing by itself is not cost effective. The higher the cost of the electronic multiplexer, the larger the problem of finding effective cost offsets. Therefore, if the Class A data network is too complex it may not be cost effective.

There are other driving forces, such as increased content, packaging, and wire bundle size, that have the potential of outweighing the cost disadvantage. The situation with the Class B data network is much different. Class B vehicle multiplexing is the enabler to other cost-offsetting methods that are not possible with Class A multiplexing. Cost reductions such as module integration and diagnostics can be effectively used to more than offset the cost of the electronic multiplexer.

26.4.5 The SAE J1850 Standard

The SAE J1850 is a standard for a Class B data communications network. The entire automotive industry will benefit from the development of this data network. In the past, development of proprietary data networks inefficiently used scarce industry resources. Standardization will save manpower and resources, in both the semiconductor and automotive industry, and make the resources previously dedicated to proprietary data networks available for concentration on more competitive electronic developments.

The transition to an industry standard data network will be difficult and will take several years to accomplish effectively. The first introduction of the full industry standard vehicle multiplex network will be found on only luxury vehicles and then only after the system economics warrant support. Economics will play a major role in determining when the average vehicle, manufactured domestically or abroad, will have an industry standard data network. It will take the dedication and talent of electronic engineers in both the automotive and the semiconductor industries to develop the components that will meet the economic requirements. The development of a family of components is required to support the economical use on more than just the more expensive and luxury type vehicles. The application for data networks varies between manufacturers' product lines and there will be a need for different levels of industry standard data network interfaces to meet the full application requirements.

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GLOSSARY

This glossary contains generally accepted terminology for automotive electronic application. The terms may have additional definitions depending on usage in other disciplines.

Arbitration The process of resolving which frame or in-frame response data continues to be transmitted when two or more nodes begin transmitting frames or in-frame response data simultaneously.

Arbitration detection Refers to a contention-based arbitration circuit, whereby the contention created by simultaneous access of multiple nodes on the network is resolved in a bit-by-bit arbitration circuit by means of collision detection where dominant bits in the arbitration field survive without destruction and all others discontinue transmission. (See **Bit-by-bit arbitration** and **Collision detection**.)

Architecture The organizational structure of a vehicle multiplex network, mainly referring to the application structure and communications protocol.

Balanced current I/O An input/output circuit configuration in which signals are transmitted as currents that travel down one conductor and return on the other, and these currents are balanced, i.e., of equal magnitude.

Baud rate A measurement or transfer rate; a number of discrete conditions or signal events per second.

Bipolar data Data that is driven both positively and negatively from a common point such as a reference voltage or ground (0) potential.

Bit-by-bit arbitration A contention-based arbitration, whereby the contention created by simultaneous access of multiple nodes on the network is resolved bit by bit. Bits may be represented as dominant or passive on the physical layer with dominant bits overriding passive ones in case of contention. The message with a dominant bit in the arbitration field survives without destruction and all others discontinue transmission. This procedure is repeated through all bits of the arbitration field.

Bit encoding The smallest unit of information in the binary system of notation.

Bit rate Bits per time during transmission, independent of bit representation.

Bit-stuf NRZ The insertion of extra bits into an NRZ data stream to avoid the appearance of unintended control sequences for synchronization.

Bit synchronized Transmission of a frame in which the data bits are transmitted with the transmitter and receiver bit transitions aligned in time (synchronized).

Broadcast type messages The transmission of information to more than one receiver as differentiated from node-to-node communications.

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Bus Topology of a communications network where all nodes are reached by links, which allow transmission in both directions.

Bursty noise Unwanted electromagnetic disturbances that are manifested as relatively short period barrages (bursts) at random or repetitive rates.

Checksum An error-detecting code based on a simple eight-bit summation series of all the bytes in the frame that are to be checked.

Class A system A multiplex system whereby vehicle wiring is reduced by the transmission and reception of multiple signals over the same signal bus between nodes that replaces the conventional wiring in vehicles. The nodes used to accomplish multiplexed body wiring typically did not exist in the same or similar form in a totally conventionally wired vehicle.

Class B system A multiplex system whereby data (e.g., parametric data values) is 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 system A multiplex system whereby 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.

Collision detection Collision detection and bit-by-bit arbitration are sometimes used interchangeably and they both refer to a contention-based arbitration, in which the contention created by simultaneous access of multiple nodes on the network is resolved on a bit-by-bit arbitration basis utilizing a collision detection means. (See **Bit-by-bit arbitration.**)

Command mode A mode of operation of a master-slave system in which the master node takes prompt control of the network to achieve the input and/or output function.

Common mode rejection ratio The ratio of the common mode input voltage to output voltage commonly expressed in dBV, i.e., the extent to which a differential amplifier rejects an output when the same signal is applied to both inputs.

Contention process A state of the bus in which data from two or more transmitters are simultaneously attempting to use a single shared network medium. A collision detection or arbitration process can be used to resolve the conflict.

Contiguous bits A condition where a string of data bits is continuous and without dead time between bits.

Control field A field in a frame which designates command information.

Control mode Control mode and command mode are used interchangeably and refer to a mode of operation of a master-slave system in which the master node takes prompt control of the network to perform the input and/or output function.

Cyclic redundancy check (CRC) An error-detecting code in which the code is defined to be the remainder resulting from dividing the bits to be checked in the frame by a predetermined binary number.

Data collision A state of the bus in which two or more transmitters are turned on simultaneously to conflicting states.

Data consistency A feature of communications in some multiplex wiring systems whereby it is determined and ensured that all required recipients of a message have received the message accurately before acting upon it simultaneously. This feature is desirable in, for example, ensuring that all four lamps are turned on at once or that all four brakes are energized simultaneously.

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Data decoding technique The process of retrieving a signal on the transmission medium that was encoded (e.g., NRZ, PWM, Manchester) back into the original logical, "1"s and "0"s bits.

Data encoding technique Data bit encoding defines the way in which the logical bits, "1"s and "0"s, are translated into signals on the transmission medium by the physical interface (e.g., NRZ, PWM, Manchester).

Data field Data (data field) are bytes between header bytes and error detection byte. Data and data field are sometimes used interchangeably and they both refer to a field within a frame that may include bytes with parameters pertaining to the message and/or secondary ID and/or extended addresses and/or test modes, which further define a particular message content being exchanged over the network.

Decibel volts (dBV) A measure of the relative strength of two signals where the value is 20 times the log of the ratio of the voltage of the two signals.

Deterministic A signal is said to be deterministic when the future behavior of the signal can be predicted precisely.

Differential receiver The node receiver that contains a differential input. (See **Balanced current I/O**.)

Direct addressing mode Direct addressing, control mode, and command mode are used interchangeably and they refer to a mode of operation of a master-slave system in which the master node takes prompt control of the network to perform the input and/or output function.

Dominant bit A bit which wins arbitration when contending for the bus. For SAE J1850, a logic "0" is the dominant bit.

Driver A solid state device used to transfer electrical power to the next stage, which may be another driver, an electrical load (power driver), a wire or cable (line driver), a display (display driver), etc.

Duplex bus A multiplex bus where both transmission and reception occur simultaneously on the same network media. Also referred to as "full duplex."

Dynamic range The difference between the overload level and the minimum acceptable signal level in a multiplex system, sometimes expressed in dBV.

Event-based The attribute of transmission of data on a manually triggered event or on change of parametric value.

Event-driven The attribute of an event-based network protocol.

Fault tolerance Ability of a system to survive a certain number of failures while performing its required functions, but possibly with some degraded characteristics.

Frame One complete transmission of information, which may or may not include an in-frame response. The frame is enclosed by the start of frame and end of frame symbols. For Class B networks, each frame contains of only one message. (See **Message** and **Message frame**.)

Framing overhead The framing overhead defines the amount of nondata overhead associated with the given protocol, i.e., framing overhead.

Functional addressing Functional addressing allows a message to be addressed or sent to one or more nodes on the network interested in that function. Functional addressing is intended for messages that may be of interest to more than a single node. For example, a vehicle speed message could be sent to all nodes requiring the vehicle speed using a functional address. Functional addressing is labeling of messages based on their operation code or data content.

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Functional superset A Class C multiplex network is defined as a functional superset of Class B and Class A multiplex network, networks that have both physical and functional properties. As a functional superset, the network must be capable of communications that would perform all of the functions of the networks in that set.

Gate A minimum cell composed of transistors which form a circuit to perform a logic function such as NAND or NOR, and typically is used as a size or complexity measure of a component.

Gateway A node used to connect networks that use different protocols, as differentiated from a bridge. A gateway acts as a protocol converter.

Global address The predefined address or ID used as a broadcast to all nodes on the network.

Global time base A clock or timing device relating to, or involving, the entire vehicle network and providing the time base for the time-triggered protocol.

Ground offset Difference in voltage at a ground point as compared to a reference ground point. (See **Longitudinal noise**.)

Handshaking Defines 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.

Header field The header or header field, often used interchangeably, is a one- or three-byte field within a frame which directly or implicitly contains information about the message priority, message source and target addressing, message type, and in-frame response type.

Hexadecimal (Hex) A four-bit digital numbering system using 0, 1, ... A, B, C, D, E, and F to represent all the possible values of a decimal equivalent 0 to 15.

Identifier (ID) The primary ID identifies the target for this functional message and is the primary discriminator used to group functions into main categories.

Idle detection The capability of a circuit to detect the condition of a nondata period.

In-frame acknowledgment The form of the acknowledgment that is expected within that frame.

In-frame response (IFR) The form of the response that is expected within that frame. (See **Response**.)

Initialization Parameterization and eventual configuration of a system during startup.

Interbyte separation (IBS) A condition under which data bytes of an asynchronous serial transmission within a frame are disjointed or separate with variable amounts of dead time between bytes.

Interframe delimiter (IFD) Interframe delimiter (IFD), interframe separation (IFS), and interframe spacing are used interchangeably and refer to a condition under which the frames of an asynchronous serial transmission on a multiplex network are disjointed or separate with variable amounts of dead time between messages as a result of system clock tolerances in order to support synchronization of frames.

Invalid bit A detector system that determines when a data bit has deviated outside the established requirements.

Invalid message structure A detector system that determines when the message frame composition has deviated outside the established requirements.

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Latency The time required to transfer a message from the transmitting node measured from the moment it is prepared to send the message until it is correctly received by the targeted receiver. It may include a retry strategy delay if the initial exchange is not successful.

Line driver A solid state device (driver) used to transfer electrical energy to a wire or cable communications medium (signal bus) performing the transmit portion of the transceiver function.

Local area network (LAN) A local multiplex network that can serve a variety of devices. Typically in automotive systems it is used for collecting data from sensors and controlling actuators for one host module.

Longitudinal noise Difference in voltage between two ground points as a result of ground offset electrical noise currents. (See **Ground offset**.)

Manchester (MAN) A digital signaling technique in which there is a transition in the middle of each bit time. A "1" is encoded with a high level during the first half of the bit time and a "0" is encoded with a low level during the second half of the bit time. Therefore, there is a maximum of two transitions per bit time.

Master (node or module) The master node and master module are used interchangeably and are defined as the device which controls the transfer of information on a multiplex network. (See **Master-slave**.)

Master-slave A type of system whereby one node, a module, acts as a master or central unit and controls the actions of the other nodes designated as slaves or remote units.

Media access The method used to award the communication network to one of the nodes for the transmission of a message, e.g., master slave, token passing, CSMA/CD.

Message All of the data bytes contained in a frame. The message is what is left after the frame symbols have been removed from the frame. As such, the message is the sequence of bytes contained in the frame.

Message frame A portion of a communication protocol within the message transfer specifying the arrangement and meaning of bits or bit fields in the sequence of transfer across the transmission medium. The message frame is what is left after the message has been removed from the frame.

Message latency The time required by a system to access the medium so as to begin the delivery of information. Message latency is measured from the time that a node is ready to send specific information to the time of the start of the transmission of this information, which will ultimately be successful. Thus, the total time required to successfully send a desired message will be the sum of the message latency and the message transmission time.

Message source An identifier that defines the physical origin of a frame of data.

Message transfer The portion of the protocol dealing with the organization, meaning, and timing associated with the bits of data. Message transfer deals with what bits must be sent and when they must be sent to accomplish the transmission of a message.

Message type A classification of the different categories or classes of messages, such as functional or physical.

Modified frequency modulation (MFM) An encoding technique that defines two symmetrically spaced phases, data and clock, to a synchronizing signal. Modulating data causes transitions at these phases depending on the logic level.

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Multiple-byte header protocol A protocol that utilizes a number of bytes in the header field within a frame which directly contains information about the message priority, message source and target addressing, message type, and in-frame response type.

Multiplex bus (signal bus) Multiplex bus and signal bus are sometimes used interchangeably and refer to the wiring serving all multiplex system nodes and includes the signal, power, and ground buses.

Multiplexing The process of combining several messages for transmission over the same signal path. There are two widely used methods of multiplexing: time division and frequency division.

Negative acknowledgment A control character on a communications network transmitted from a receiving point as a negative response to the reception of the message. The response signifies that the message was not received correctly.

Network A system capable of supporting communications by three or more nodes.

Network access Method used to award the communications network to one of the nodes for the transmission of a message.

Network topologies The layout of elements capable of supporting communications by three or more nodes.

Node Any subassembly of a multiplex system which communicates on the signal bus, i.e., a transceiver. In addition to modules, nodes may include other devices that contain the intelligence necessary to support these communications.

Nonreturn to zero (NRZ) A data bit format in which the voltage or current value, which is typically voltage, determines the data bit value, i.e., one or zero.

Nondestructive bit-by-bit arbitration Nondestructive bit-by-bit arbitration and bit-by-bit arbitration are used interchangeably and both refer to a contention-based arbitration, whereby the contention created by simultaneous access of multiple nodes on the network is resolved bit by bit. (See **Bit-by-bit arbitration.**)

Normalization bit A VPW modulation bit symbol that follows an end of data symbol used to initialize an in-frame response with the proper phase.

OSI model The open system interconnect (OSI) model defines a seven-layer model for a data communications network.

Parametric data values A parameter is the variable quantity included in some messages. The parameter value, scaling, offset, units, transfer function, etc., are unique to each particular message.

Parity (odd or even) The parity check bit is said to be odd or even when the simple sum of all the binary bits in the frame, including the check bit, is always odd or always even. (See **Parity bit.**)

Parity bit A check bit appended to a frame composed of binary bits to make the simple sum of all the binary bits, including the check bit, always odd or always even.

Parity error An error is determined when the locally calculated parity check bit disagrees with the parity check bit received in the frame.

Physical addressing Labeling of messages for the physical address location of their source and/or destination(s). This is independent of their geographic location, connector pin, and/or wire identification assignments. The information in these messages are only of relevance to particular nodes, so the other nodes on the bus should ignore the message.

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Physical layer The properties of the communications medium (signal bus) which can be determined by electrical measurements, such as voltages, currents, impedances, rise times, etc.

Poll The process by which a master device invites a slave device, such as a sensor or actuator, one at a time, to transmit data or to act on command.

Positive acknowledgment A control character on a communications network transmitted from a receiving point as a positive response to the reception of the message. The response signifies that the message was received correctly.

Priority Attribute of a message controlling its ranking during arbitration. A high priority increases the probability that a message wins the arbitration process.

Propagation delay The worst-case or maximum propagation time through a medium such as the circuits of an IC or a multiplex network.

Protocol A formal set of conventions or rules for the exchange of information between nodes, including the procedures for establishing and controlling transmissions on the multiplex signal bus (message administration) and the organization, meaning, and timing associated with the bits of data (message transfer).

Pulse-width variability The variations in pulse-width tolerances associated with variable pulse-width modulation caused by such things as ground offset and the bus driver.

Response A message or portion of a message initiated by a receiving node as a result of a message transmitted by a different node. A response can be an acknowledgment or response data, and it can be appended to the original message (immediate response) or a unique message (separate response).

Response current A system that utilizes change in current signal which is used to indicate whether a message has been received properly.

Response data A response to a message which provides the data or information requested in the message. This may be an in-frame response or a report to requested data.

Serial communications interface (SCI) A common microcomputer interface that provides a standard mark/space (NRZ) which produces one start bit, eight data bits, and one stop bit in a serial data format.

Shadow nodes A node in a time triggered protocol architecture which receives input messages but does not produce any output as long as the other two nodes of the network are operational. As soon as one of these other two nodes fails, the shadow node takes the time division multiple access (TDMA) slot from the failed node and produces output.

Single-byte header protocol A protocol that utilizes a single byte in the header field within a frame which implicitly contains information about the message priority, message source and target addressing, message type, and in-frame response type.

Single-wire random lay Refers to a transmission medium of a multiplex network that consists of a single conductor and a common return that is randomly placed in the wiring harness with all of the other vehicle circuits. The return conductor could be the vehicle chassis or a common ground conductor.

Sleep state (sleep mode) Sleep state and sleep mode are sometimes used interchangeably and refer to the behavior whereby a node is on a low-power consumption standby state waiting to be switched on by a frame or other activity. This is distinct from an off mode where there is no power consumption and it is disconnected from the power supply.

Start bit The bit encoded within an asynchronous transmission that synchronizes the receiver clock to terminate the end of that block or byte of data.

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Stop bit The bit encoded within an asynchronous transmission that synchronizes the receiver clock to the start of that block or byte of data.

Symbol The individual elements that compose the message frame such as start of frame (SOF), end of data (EOD), end of frame (EOF), and CRC.

Synchronization Procedure to ensure a desired timing for interrelated actions and/or processes.

System architecture The organization of a multiplex system including, but not necessarily limited to, the location and ranking of logic or decision-making elements and the types and methods of communications between these elements.

T-tap connection A splice in a wiring harness forming a "T" connection. This configuration is associated with an automated insulation displacement type connection at a connector.

Target address The address of the node for which the message is intended. This address is usually the physical address of a particular node.

10-bit NRZ A common microcomputer interface that provides a standard mark/space (NRZ) which produces a total of 10 bits, 1 start bit, 8 data bits, and 1 stop bit in a serial data format. [See **Serial communications interface (SCI)**]

Tightly looped distributed processing A control strategy that acts within the actual time the physical events take place and whereby control elements are physically located in several different places.

Time-critical message The attributes of a message that require action in a very short period of time bordering on real-time control requirements.

Time division multiple access (TDMA) A general classification of multiplexing that utilizes time division multiplex protocols.

Time division multiplex protocol A protocol in which the meaning of a piece of information on the signal bus is determined by its relationship, i.e., first, second, third, etc., to the start of the message or bitstream. In a time division multiplex protocol, data can be interleaved on a bit-by-bit, byte-by-byte, or block-by-block basis.

Time triggered media access Bus access is controlled by a global time base which opens slots to data depending on the network protocol.

Time triggered protocol (TTP) A real-time control system architecture where all system activities are triggered by the progression of real time. This distributed time triggered architecture requires clock synchronization by a global time base.

Token The symbol of authority passed between nodes in a token-passing protocol. Possession of this symbol identifies the node currently in control of the medium.

Token-passing protocol A node that has communicated passes the control of the bus, including the right to communicate to another node, at the end of the message via a token.

Token slot protocol A protocol where bus access is controlled by a time base which opens a time slot to a number of nodes that, in turn, take control of the network when there is data to communicate to another node.

Transceiver An electrical circuit which both transmits (line driver portion) and receives (line receiver portion).

Transitions (bit) The process of changing from one voltage level to another voltage level.

Translated The conversion from one binary number to another binary number in order to achieve correct bit-by-bit arbitration.

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Trapezoidal waveforms A sawtooth waveform superimposed onto a square wave.

Twisted pair A transmission line consisting of two similar conductors that are insulated from each other and are twisted around each other to form a communications channel. The purpose for twisting the conductors around each other is to reduce the electric and magnetic field interaction with other conductors.

Variable pulse-width (VPW) modulation (VPWM) A method of using both bus state and pulse width to encode bit information. This encoding technique is used to reduce the number of bus transitions for a given bit rate. One embodiment would define a "1" as a dominant short pulse or a passive long pulse while a "0" would be defined as a long dominant pulse or a short passive pulse. Since a message is composed of random "1"s and "0"s, general byte or message times cannot be predicted in advance.

Wake-up The process of activating a node that is in the sleep state.

Wave-shaped A technique of rounding the corners of a trapezoidal waveform in order to significantly minimize the EMI.

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CHAPTER 27
ELECTROMAGNETIC STANDARDS AND INTERFERENCE

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27.1 SAE AUTOMOTIVE EMC STANDARDS

27.1.1 Overview

The Society of Automotive Engineers (SAE) has been involved in writing electromagnetic compatibility standards since 1957 with SAE-J551. In its original form, SAE-J551 was intended to protect "roadside receivers," particularly television, from vehicle ignition noise. There have been several revisions to SAE-J551 and new electromagnetic compatibility standards due to the evolution of digital electronics. With the implementation of digital electronic systems on vehicles, a new set of radio noise problems prompted a new standard to be written in 1987.

This chapter will review the Society of Automotive Engineers (SAE) Electromagnetic Compatibility (EMC) standards on both vehicle system level and component-level test methods. The Electromagnetic Radiation (EMR) and Electromagnetic Interference (EMI) Standards Committees are working together to cover all aspects of the EMC field and to develop test methods and limits relating to vehicle and other motorized equipment. Each of the committees has representation from automotive corporations, truck and bus corporations, suppliers, consumers, test houses, and government.

Presently, the Society of Automotive Engineers EMC Standards Committees are revising SAE J1113 and SAE J551 to create documents made up of multiple parts, covering all aspects of component and vehicle testing. SAE EMC standards are being harmonized with those of the International Standards Organization (ISO). The vehicle-level EMC standard, SAE J551, is divided into emissions test parts numbered 2 through 10 (Table 27.1) and immunity test parts numbered 11 through 20 (Table 27.2). The component-level EMC standard, SAE J1113, is divided into immunity test parts numbered 2 through 40 (Table 27.3) and emissions test parts numbered above 40 (Table 27.4). Part 1 of both documents contains an introduction and definitions. The SAE standards are structured to be living documents to accept changes and additions without the need to revise or renumber parts.

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TABLE 27.1 EMC Emissions Tests for Vehicles—SAE J551

SAE J551 part	Bandwidth	Frequency range	Test distance	Comparable standard
2	Broadband	30 MHz—1 GHz	10 m	CISPR 12
3	Narrowband	10 kHz—1 GHz	3 m	CISPR TBD
4	Narrow & broad	150 kHz—1 GHz	1 m	CISPR TBD
5	Narrow & broad	20 kHz—1 GHz	10 m	CISPR TBD

TABLE 27.2 EMC Immunity Tests for Vehicles—SAE J551

SAE J551 part	Test type	Frequency range	Comparable standard
11	Off vehicle source	500 kHz—18 GHz	ISO 11451/2
12	On vehicle source	1.8 MHz—1.2 GHz	ISO 11451/3
13	Bulk current injection	1—400 MHz	ISO 11451/4
14	Reverberation chamber	200 MHz—18 GHz	None
15	Electrostatic discharge	N/A	ISO 10605
16	Transients	N/A	None
17	Power line magnetic field	60 Hz—30 kHz	None

TABLE 27.3 EMC Immunity Tests for Components—SAE J1113

SAE J1113 part	Test type	Frequency range	Comparable standard
2	Conducted immunity	30 Hz—250 kHz	None
3	Conducted immunity	100 kHz—400 MHz	ISO 11452/7
4	Bulk current injection	1—400 MHz	ISO 11452/4
11	Transients	N/A	ISO 7637-1
12	Coupled transients	N/A	ISO 7637-3
13	Electrostatic discharge	N/A	ISO 10605
21	Semi-anechoic chamber	30 MHz—18 GHz	ISO 11452/2
22	Power line magnetic	60 Hz—30kHz	None
23	RF stripline	10 kHz—1 GHz	ISO 11452/5
24	TEM cell	10 kHz—200 MHz	ISO 11452/3
25	Triplate	10 kHz—1 GHz	None
26	Power line E-field	60 Hz—30 kHz	None
27	Reverberation chamber	500 MHz—2 GHz	None

TABLE 27.4 EMC Emissions Tests for Components—SAE J1113

SAE J1113 part	Test type	Frequency range	Comparable standard
41	Narrowband	10 kHz—1 GHz	CISPR TBD
42	Transient	N/A	ISO 7637-1

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27.1.2 SAE J551

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SAE J551 combines all of the vehicle-level automotive-related EMC test methods for emissions and immunity tests into one document. The contents of the SAE J551 are as follows.

SAE J551/1 General and Definitions

Absorber lined chamber A shielded room with absorbing material on its internal reflective surfaces (floor absorber material optional).

Amplitude modulation (AM) The process by which the amplitude of a carrier wave is varied following a specific law. The result of that process is an AM signal.

Antenna correction factor The factor that is applied to the voltage measured at the input connector of the measuring receiver to give the field strength at the antenna.

Antenna matching unit A unit for matching the impedance of an antenna to that of the 50-ohm measuring receiver over the antenna measuring frequency range.

Artificial network (AN) A network inserted in the supply leads of an apparatus to be tested which provides, in a given frequency range, a specified load impedance for the measurement of disturbance voltages and which isolates the apparatus from the power supply in that frequency range.

Bandwidth The width of the frequency band over which a given characteristic of an equipment does not differ from its reference by more than a specified amount or ratio.

Broadband artificial network (BAN) A network that presents a controlled impedance to the device under test over a specified frequency range while allowing the device under test to be interfaced to its support system. It is used in power, signal, and control lines.

Broadband emission An emission which has a bandwidth greater than that of a particular measuring apparatus or receiver.

Bulk current Total amount of common mode current in a harness.

Bulk current injection probe A device for injecting current in a conductor without interrupting the conductor and without introducing significant impedance into the associated circuits.

Characteristic level The controlling (or dominant) emission level experienced in each frequency subband. The characteristic level is the maximum measurement obtained for both antenna polarizations and for all the specified measurement positions of the vehicle or device. Known ambient signals shall not be considered part of the characteristic level.

Class An arbitrary performance level agreed upon by the purchaser and the supplier and documented in the test plan.

Component continuous conducted emissions The noise voltages/currents of a continuous nature existing on the supply or other wires of a component/module which may cause interference to reception in an on-board receiver.

Compression point The input signal level at which the gain of the measuring system becomes nonlinear such that the indicated output deviates from an ideal receiving system's output by the specified increment in dB.

Coupling A means or a device transferring power between systems.

Current (measuring) probe A device for measuring the current in a conductor without interrupting the conductor and without introducing significant impedance into the associated circuits.

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Degradation (of performance) An undesired departure in the operational performance of any device, equipment, or system from its intended performance.

Device A machine equipped with an internal combustion engine but not self-propelled. Devices include, but are not limited to, chain saws, irrigation pumps, and air compressors.

Directional coupler A three- or four-port device consisting of two transmission lines coupled together in such a manner that a single traveling wave in any one transmission line will induce a single traveling wave in the other, the direction of propagation of the latter wave being dependent upon that of the former.

Disturbance suppression Action which reduces or eliminates electrical disturbance.

Disturbance voltage; interference voltage Voltage produced between two points on separate conductors by an electromagnetic disturbance, measured under specified conditions.

Electromagnetic compatibility (EMC) The ability of an equipment or system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbance to anything in that environment.

Electromagnetic disturbance Any electromagnetic phenomenon which may degrade the performance of a device, equipment, or system or adversely affect living or inert matter.

Electromagnetic immunity (to a disturbance) The ability of a device, equipment, or system to perform without degradation in the presence of an electromagnetic disturbance.

Electromagnetic interference (EMI) Degradation of the performance of an equipment, transmission channel or system caused by an electromagnetic disturbance.

Electromagnetic radiation The phenomena by which energy in the form of electromagnetic waves emanates from a source into space; energy transferred through space in the form of electromagnetic waves.

Forward power Power supplied by the output of an amplifier (or generator) traveling towards the load.

Ground (reference) plane A flat conductive surface whose potential is used as a common reference.

Ignition noise suppressor That part of a high-voltage ignition circuit intended to limit the emission of impulsive ignition noise.

Immunity level The maximum level of a given electromagnetic disturbance incident on a particular device, equipment, or system for which it remains capable of operating at a required degree of performance.

Impulse electric field strength The root-mean-square value of the sinusoidally varying radiated electric field producing the same peak response in a bandpass system, antenna, and bandpass filter, produced by the unknown impulse electric field.

Impulse noise Noise characterized by transient disturbances separated in time by quiescent intervals. The frequency spectrum of these disturbances must be substantially uniform over the useful pass band of the transmission system. The same source may produce impulse noise in one system and random noise in a different system (from ANSI/IEEE Std 100).

Impulsive ignition noise The unwanted emission of electromagnetic energy, predominantly impulsive in content, arising from the ignition system within a vehicle or device.

Interference suppression Action which reduces or eliminates electrical interference.

Measuring instrument impulse bandwidth The maximum value of the output response envelope divided by the spectrum amplitude of an applied impulse.

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Narrowband emission An emission which has a bandwidth less than that of a particular measuring apparatus or receiver.

Net power Forward power minus reflected power.

Peak detector A detector, the output voltage of which is the peak value of the applied signal.

Polarization (of a wave or field vector) The property of a sinusoidal electromagnetic wave or field vector defined at a fixed point in space by the direction of the electric field strength vector or of any field vector; when the direction varies with time, the property may be characterized by the locus described by the extremity of the considered field vector.

Quasi-peak detector A detector having specified electrical time constants which, when regularly repeated identical pulses are applied to it, delivers an output voltage which is a fraction of the peak value of the pulses, the fraction increasing toward unity as the pulse repetition rate is increased.

Receiver terminal voltage (antenna voltage) The voltage generated by a source of radio disturbance and measured in dB (μV) by a radio interference measuring receiver conforming to the requirements of CISPR Publications 16 or ANSI C63.2.

Reflected power Power traveling toward the generator reflected by the load due to impedance mismatch between the transmission line and the load.

Resistive distributor brush The resistive pick-up brush in an ignition distributor cap.

RF ambient (electromagnetic environment) The totality of electromagnetic phenomena existing at a given location.

Shall Used to express a command, i.e., conformance with the specific recommendation is mandatory and deviation is not permitted. The use of shall is not qualified by the fact that compliance with the standard is considered voluntary.

Shielded enclosure A mesh or sheet metallic housing designed for the purpose of separating the internal from external electromagnetic environment.

Standing wave ratio (SWR); voltage standing wave ratio (VSWR) The ratio, along a transmission line, of a maximum to an adjacent minimum magnitude of a particular field component of a standing wave.

Tracking generator A narrowband radio frequency source synchronized to the instantaneous receive frequency of a scanning receiver or spectrum analyzer.

Transmission line system (TLS) A transmission line system is a stripline or parallel plate or similar device to generate an E-field.

Vehicle A self-propelled machine (excluding aircraft, rail vehicles, and boats over 10 m in length). Vehicles may be propelled by an internal combustion engine, electrical means, or both. Vehicles include, but are not limited to, mopeds, automobiles, trucks, agricultural tractors, snowmobiles, and small motorboats.

SAE J551/2 Performance Levels and Methods of Measurement of Electromagnetic Radiation from Vehicles and Devices, Broadband, 30 to 1000 MHz. This document provides test procedures and recommended levels to assist engineers in the measurement of broadband electromagnetic radiation and control of radio interference.

SAE J551/3 Performance Levels and Methods of Measurement of Electromagnetic Radiation from Vehicles and Devices, Narrowband, 10 kHz to 1000 MHz. This document covers methods of measuring incidental narrowband radiation from vehicles and devices and establishes performance levels intended to protect nearby communication and broadcast receivers.

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SAE J551/4 Test Limits and Methods of Measurement of Radio Disturbance Characteristics from Vehicles and Devices, Narrowband, 150 kHz to 1000 MHz. This document provides measurement techniques and test limits intended to protect radio receivers installed in a vehicle from disturbances produced by components/modules in the same vehicle.

SAE J551/5 Performance Levels and Methods of Measurement of Electromagnetic Radiation from Electric Vehicles, Broadband and Narrowband, 9 kHz to 1000 MHz. This document provides electric vehicle test procedures and performance levels for the measurement of both radiated magnetic and electric field strengths.

SAE J551/11 Vehicle Electromagnetic Immunity—Off-Vehicle Source. This document adopts ISO CD11451-2: Road Vehicles—Electrical Disturbances by Narrowband Radiated Electromagnetic Energy—Vehicle Test Methods—Part 2: Off-vehicle Radiation Source.

SAE J551/12 Vehicle Electromagnetic Immunity—On-board Transmitter Simulation. This document adopts ISO CD11451-3: Road Vehicles—Electrical Disturbances by Narrowband Radiated Electromagnetic Energy—Vehicle Test Methods—Part 3: On-board Transmitter Simulation.

SAE J551/13 Vehicle Electromagnetic Immunity—Bulk Current Injection (BCI). This document adopts ISO CD11451-4: Road Vehicles—Electrical Disturbances by Narrowband Radiated Electromagnetic Energy—Vehicle Test Methods—Part 4: Bulk Current Injection.

SAE J551/15 Vehicle Electromagnetic Immunity—Electrostatic Discharge (ESD). This document adopts the portions of ISO TR10605 which pertain to ESD calibration and vehicle ESD testing.

27.1.3 SAE J1113

Note: This section contains portions reprinted with permission from Draft SAE J1113 ©1993 Society of Automotive Engineers, Inc.

SAE J1113 combines all of the module-level automotive-related EMC test methods for emissions and immunity tests into one document. The contents of the SAE J1113 are as follows.

SAE J1113/1 General and Definitions

Ambient Level Those levels of radiated and conducted signal and noise existing at a specified test location and time when the test sample is not in operation. Atmospherics, interference from other sources, and circuit noise or other interference generated within the measuring set compose the ambient level.

Conducted emission Desired or undesired electromagnetic energy which is propagated along a conductor.

Device under test (DUT) The device whose immunity is being checked.

Electromagnetic compatibility (EMC) The condition that enables equipment, subsystems, and systems (electronic, chemical, biological, etc.) to function without degradation from electromagnetic sources and without degrading the electromagnetic environment; i.e., it is the condition which allows the coexistence of different electromagnetic sources without significant change in performance of any one in the presence of any or all the other.

Emission Electromagnetic energy propagated from a source by radiation or conduction.

Equipment under test (EUT) The device or system whose immunity is being checked. Synonymous with DUT.

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Field decay (voltage) The exponentially decaying negative voltage transient such as developed by an automotive alternator when the field excitation is suddenly removed, as when the ignition switch is turned off.

Field strength The term *field strength* shall be applied to either the electric or the magnetic component of the field, and may be expressed as V/m or A/m. When measurements are made in the far field and in free space, the power density in W/cm^2 may be obtained from field strengths approximately as (V/m)/377 or (A/m) × 377. When measurements are made in the near field and in free space, both the complex electric and magnetic vector components of the field must be fully defined. Power density may then be obtained by use of the Poynting vector.

Ground plane A metal sheet or plate used as a common unipotential reference point for circuit returns and electrical or signal potential.

Immunity A measure of electronic module or system tolerance to external electromagnetic fields. decaying posit

Load dump (voltage) The exponentially live voltage transient developed by an automotive alternator, when disconnected suddenly from its load, while operating without a storage battery or with a discharged storage battery. Removal of the load, the resulting transient, or both in combination are commonly referred to as alternator load dump.

Radiated emission Radiation- and induction-field components in space. (For the purpose of this document, induction fields are classed together with radiation fields.)

Spurious emission Any unintentional electromagnetic emission from a device.

Susceptibility The characteristic of an object that results in undesirable responses when subjected to electromagnetic energy.

Test plan The specific document that details all tests and limits for the particular device in question.

SAE J1113/2 Conducted Immunity (30 Hz to 250 kHz). This document provides the requirements for determining the immunity characteristics of automotive electronic equipment, subsystems, and systems to EM energy injected onto all leads over the frequency range of 30 Hz to 250 kHz. The method is applicable to all input, output, and power leads.

SAE J1113/3 Conducted Immunity (100 kHz to 400 MHz). This document provides the requirements for determining the immunity characteristics of automotive electronic equipment, subsystems, and systems to electromagnetic energy injected onto all leads, including signal and power, over the frequency range 100 kHz to 400 MHz.

SAE J1113/4 Immunity to Radiated Electric Fields—Bulk Current Injection Method (1 to 400 MHz). This document provides a test method for evaluating the immunity of automotive electrical/electronic devices to radiated electromagnetic fields coupled to the vehicle wiring harness. Bulk current injection (BCI) uses a current probe to inject RF current from 1 to 400 MHz into the wiring harness of automotive devices.

SAE J1113/11 Immunity to Conducted Transients on Power Leads. This document provides the methods and apparatus to evaluate electronic devices for immunity to potential interference from conducted transients along battery feed or switched ignition inputs. The test apparatus specifications outlined in this procedure were developed for 12-V passenger cars and light trucks, 12-V heavy-duty trucks, and vehicles with 24-V systems.

SAE J1113/12 Electrical Interference by Conduction and Coupling—Coupling Clamp. This document provides a common basis for the evaluation of devices and equipment in vehicles

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against transient transmission by coupling via lines other than the power supply lines. The test demonstrates the immunity of the instrument, device, or equipment to coupled fast transient disturbances, such as those caused by switching of inductive loads, relay contact bouncing, etc.

SAE J1113/13 Immunity to Electrostatic Discharge (ESD). This document provides the test methods and procedures necessary to evaluate electrical components intended for automotive use to the threat of electrostatic discharges.

SAE J1113/21 Radiated Immunity Using an Absorber Lined Chamber—Far Field. This document provides the test methods and procedures for testing electromagnetic immunity (off vehicle radiation sources) of electronic components for passenger cars and commercial vehicles. To perform this test method, the electronic module, along with the wiring harness (prototype or standard test harness) and peripheral devices, will be subjected to the electromagnetic disturbance generated inside an absorber-lined chamber.

SAE J1113/22 Immunity to Radiated Magnetic Fields from Power Lines. This document provides the testing technique for determining the immunity of automotive electronic devices to magnetic fields generated by power transmission lines and generating stations.

SAE J1113/23 Radiated Immunity—Stripline Method. This document provides recommended testing techniques for the determination of electric field immunity of an automotive electronic device when the device equipment harness is exposed to an interference RF field. This technique uses a stripline coupler from 10 kHz to 1 GHz and is limited to harnesses (and/or samples) which have a maximum height of equal to or less than one-third the stripline height.

SAE J1113/24 Radiated Immunity—Transverse Electromagnetic Mode (TEM) Cell. This SAE document adopts ISO CD11452-3: Road Vehicles—Electrical Disturbances by Narrowband Electromagnetic Energy—Component Test Methods—Part 3: TEM Cell. It provides test methods and procedures for testing electromagnetic immunity of electronic components for passenger cars and commercial vehicles. The electromagnetic disturbance, considered in this part of ISO CD11452, will be limited to continuous narrowband electromagnetic fields.

SAE J1113/25 Radiated Immunity—Triplate Line Method. This document provides testing techniques for the determination of electric field immunity of an automotive electronic device when the device equipment harness is exposed to an interference RF field. This technique uses a Tri-Plate Line (TPL) from 10 kHz to 1 GHz and is limited to components which have a maximum height of equal to or less than one-third the height between the driven element and the outer, grounded plates.

SAE J1113/26 Radiated Immunity—60 Hz E-field. This document provides testing techniques using a parallel plate antenna and a low-current, high-voltage generator for the determination of electric field immunity of an automotive electronic device when the device and its equipment harness are exposed to a 60-Hz electric field.

SAE J1113/27 Immunity to Radiated Electromagnetic Fields (Reverberation) Method. This document provides the reverberation test method to evaluate the immunity of electronic devices in the frequency range of 500 MHz to 2.0 GHz. The reverberation test data correlates with vehicle-level radiated immunity test data in the anechoic chamber and mobile transmitter sites.

SAE J1113/41 Test Limits and Methods of Measurement of Radio Disturbance Characteristics from Vehicle Components and Modules, Narrowband, 150 kHz to 1000 MHz. This document provides test limits and procedures for the measurement of radio disturbances produced by components/modules in the same vehicle.

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SAE J1113/42 Conducted Transient Emissions. This document provides a component-level test procedure to evaluate the automotive electrical and electronic components for conducted emissions of transients, and for other electromagnetic disturbances. The test apparatus specifications in this procedure were developed for components installed in 12-V passenger cars and light trucks.

27.2 IEEE STANDARDS RELATED TO EMC

Although some of the following standards were not developed in the EMC Society (EMCS), they were developed with EMCS input and coordination. (Following each item, the letters in parentheses are the initials of the developing society, and the numbers in square brackets are IEEE order numbers.)

27.2.1 IEEE Standard 139-1988

IEEE Recommended Practice for the Measurement of Radio Frequency Emission from Industrial, Scientific, and Medical (ISM) Equipment Installed on User's Premises. (EMCS) [SH12377]

27.2.2 IEEE Standard 140-1990

IEEE Recommended Practice for Minimization of Interference from Radio-Frequency Heating Equipment. (EMCS) [SH13581]

27.2.3 IEEE Standard 187-1990

IEEE Standard of Radio Receivers: Open Field Method of Measurement of Spurious Radiation from FM and Television Broadcast Receivers. (EMCS) [SH13698]

27.2.4 ANSI/IEEE Standard 211-1990

IEEE Standard Definitions of Terms for Radio Wave Propagation. (APS) [SH13904]

27.2.5 ANSI/IEEE Standard 213-1987

IEEE Standard Procedure for Measuring Conducted Emissions in the Range of 300 kHz to 25 MHz from Television and FM Broadcast Receivers to Power Lines. (EMCS) [SH12047]

27.2.6 IEEE Standard 291-1969 (Reaff 1981)

IEEE Standards Report on Measuring Field Strength in Radio Wave Propagation. (APS) [SH01800]

27.2.7 IEEE Standard 299-1991

IEEE Standard Method for Measuring the Effectiveness of Electromagnetic Shielding Enclosures. (EMCS) [SH14134]

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27.2.8 IEEE Standard 368-1977

IEEE Recommended Practice for Measurement of Electrical Noise and Harmonic Filter Performance of High-Voltage Direct-Current Systems. (COMSOC) [SH07021]

27.2.9 ANSI/IEEE Standard 376-1975 (Reaff 1980)

IEEE Standard for the Measurement of Impulse Strength and Impulse Bandwidth. (EMCS) [SH03764]

27.2.10 ANSI/IEEE Standard 377-1980 (Reaff 1986)

IEEE Recommended Practice for Measurement of Spurious Emission from Land-Mobile Communication Transmitters. (EMCS) [SH07898]

27.2.11 ANSI/IEEE Standard 430-1986

IEEE Standard Procedures for the Measurement of Radio Noise from Overhead Power Lines and Substations. (PES) [SH10801]

27.2.12 ANSI/IEEE Standard 469-1988

IEEE Recommended Practice for Voice-Frequency Electrical-Noise Tests of Distribution Transformers. (COMSOC) [SH12328]

27.2.13 ANSI/IEEE Standard 473-1985

IEEE Recommended Practice for an Electromagnetic Site Survey (10 kHz to 10 GHz). (EMCS) [SH09134]

27.2.14 ANSI/IEEE Standard 475-1983

IEEE Measurement Procedure for Field Disturbance Sensors (RF Intrusion Alarm). (EMCS) [SH08433]

27.2.15 ANSI/IEEE Standard 518-1982 (Reaff 1990)

IEEE Guide for the Installation of Electrical Equipment to Minimize Noise Inputs to Controllers from External Sources. (IAS) [SH08813]

27.2.16 ANSI/IEEE Standard 539-1979

IEEE Standard Definitions and Terms Relating to Overhead Power Lines Corona and Radio Noise. (PES) [SH06882]

27.2.17 ANSI/IEEE Standard 539a-1984

Supplement to IEEE Standard 539-1979. (PES) [SH09530]

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27.2.18 ANSI/IEEE Standard 644-1987

IEEE Standard Procedures for Measurement of Power Frequency Electric and Magnetic Fields from AC Power Lines. (PES) [SH10892]

27.2.19 ANSI/IEEE Standard 776-1987

IEEE Guide for Inductive Coordination of Electric Supply and Communication Lines. (COMSOC) [SH11239]

27.2.20 IEEE Standard 1027-1984

Draft Trial-Use Standard Method for Measuring the Magnetic Field Intensity Around a Telephone Receiver. (COMSOC) [SH09497]

27.3 THE ELECTROMAGNETIC ENVIRONMENT OF AN AUTOMOBILE ELECTRONIC SYSTEM

Note: Parts of this section were taken from the article of the same name by J. P. Muccioli and S. S. Awad published in the *IEEE Transactions on Electromagnetic Compatibility,* Aug. 1987.

This work was performed to study the electromagnetic environmental conditions in a typical midsize automobile with a high-power frequency modulation (FM) transmitter installed inside the vehicle. Different antenna locations were used to radiate the electromagnetic waves that were studied. The data obtained from the experimental results is presented and discussed.

27.3.1 Test Methodology

The levels of the electric field strength inside the vehicle depend on a number of factors. One basic factor is the size of the automobile. In this case, a midsize automobile was used for experimentation. The electromagnetic source was selected to be a 100-W FM transmitter operating on five frequencies: 25.04, 35.04, 39.04, 51.20, and 144.50 MHz. The transmitting antenna was placed at four different locations on the outer surface of the vehicle as shown in Fig. 27.1. The transmitter was placed on the passenger seat and was connected to the radiating antenna through a coaxial cable. The electromagnetic environment was mapped inside the vehicle with both doors closed, engine running at idle, and the driver seated in the left front seat. The electric field strength measurements were taken at 15 different locations inside the vehicle, as shown in Fig. 27.2. At each location, the electric field strength was measured once in a direction parallel to the transmitting antenna and once orthogonal to it.

An important factor that can influence the magnitude of the electric field strength is that of ground plane. For this test, the vehicle was placed outside in the open, on dry ground, and away from any other building or vehicles which could affect the electromagnetic environment inside.

27.3.2 Test Instrumentation

1. Field strength meter—IFI, EFS-1, frequency range 10 kHz to 220 MHz
2. Motorola Transmitter 90/100-W power amplifier
   a. Frequency 25.04 MHz @ 100 W
   b. Frequency 35.04 MHz @ 100 W

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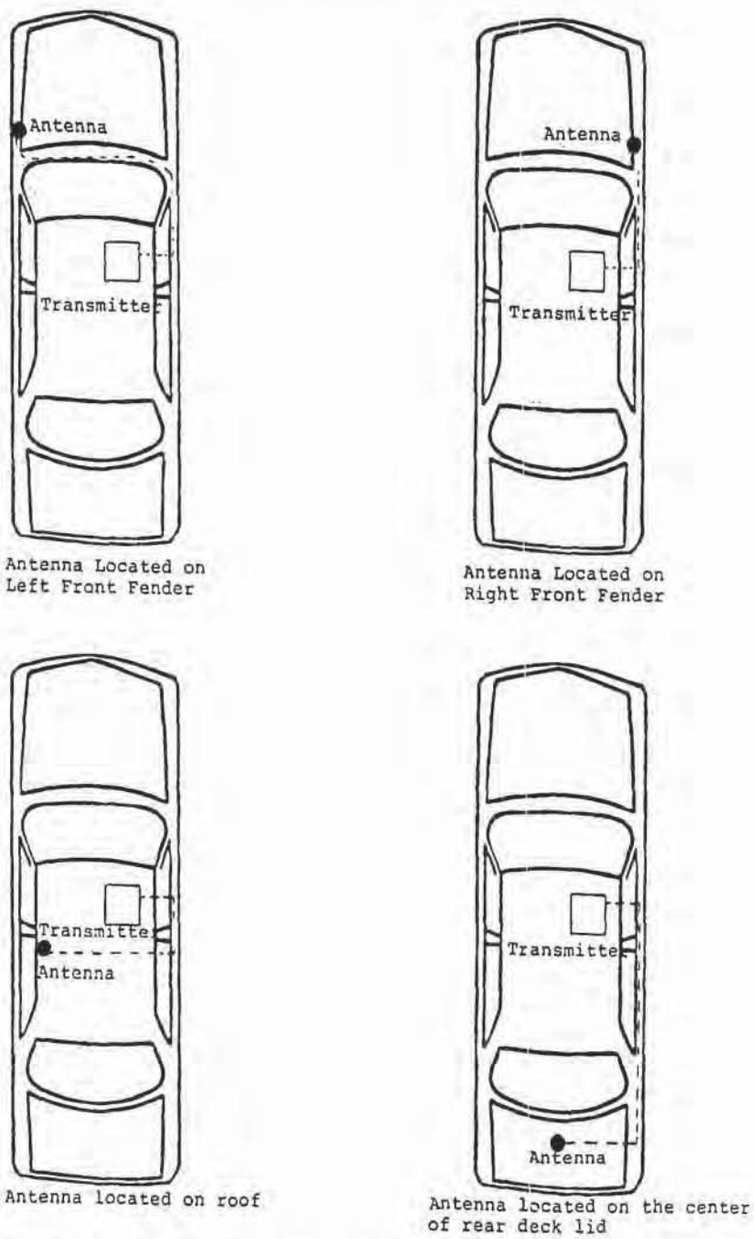


FIGURE 27.1 Antenna locations and coaxial cable routing.

c. Frequency 39.04 MHz @ 100 W

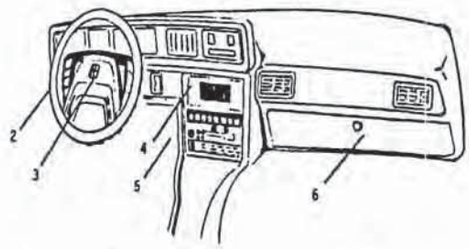
d. Frequency 51.20 Mhz @ 100 W

3. Drake UV-3 FM transceiver, 160 W RF power amplifier, frequency 144.50 MHz @ 100 W

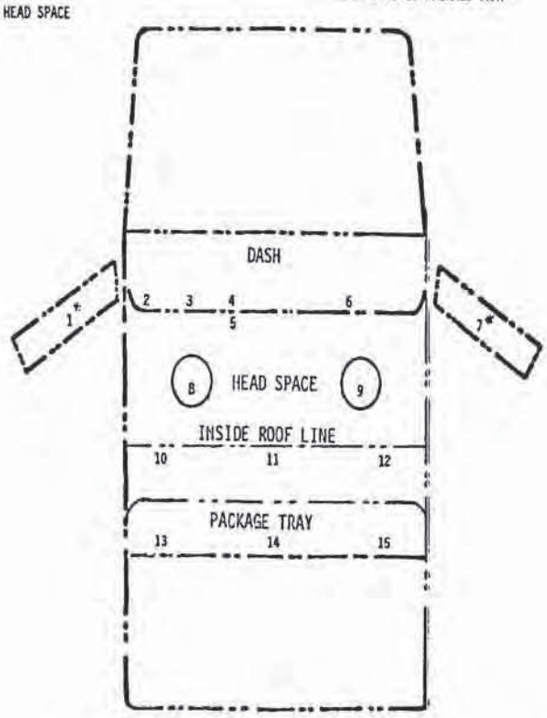
27.3.3 Summary

The results of the electric field measurements are shown in Table 27.5. For each of the four antenna locations, the electric field strength components (parallel and orthogonal to the

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1. LEFT DOOR TRIM PANEL AT DOOR HANDLE
2. LOWER LEFT SIDE OF DASH PANEL
3. STEERING WHEEL
4. CENTER OF DASH PANEL
5. LOWER CENTER OF DASH PANEL
6. GLOVE COMPARTMENT
7. RIGHT DOOR TRIM PANEL AT DOOR HANDLE
8. DRIVER HEAD SPACE
9. PASSENGER HEAD SPACE
10. LEFT INSIDE ROOF LINE BEHIND SUN ROOF
11. CENTER INSIDE ROOF LINE BEHIND SUN ROOF
12. RIGHT INSIDE ROOF LINE BEHIND SUN ROOF
13. LEFT SIDE OF PACKAGE TRAY
14. CENTER OF PACKAGE TRAY
15. RIGHT SIDE OF PACKAGE TRAY



* NOTE: DOOR MEASUREMENTS WERE MADE AT ARM REST ABOVE DOOR HANDLE

FIGURE 27.2 Fifteen metered locations inside the vehicle.

antenna) are listed for the 15 different meter locations at various transmitting frequencies. From Table 27.5, the electric field environment inside the vehicle could be divided into three different groups:

1. Locations of electric field strengths greater than 150 V/m
   - **a.** Left door trim panel at door handle
   - **b.** Left inside roof line behind sunroof
   - **c.** Right inside roof line behind sunroof
   - **d.** Steering wheel

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TABLE 27.5 Field Strength Data at Various Meter Locations

Antenna location on vehicle: left front fender (driver side)

	Frequency of transmitter 25.04 MHz @ 100 W		Frequency of transmitter 35.04 MHz @ 100 W		Frequency of transmitter 39.04 MHz @ 100 W		Frequency of transmitter 51.2 MHz @ 100 W		Frequency of transmitter 144.5 MHz @ 100 W	
Meter location	Field strength parallel to antenna	Field strength orthogonal to antenna	Field strength parallel to antenna	Field strength orthogonal to antenna	Field strength parallel to antenna	Field strength orthogonal to antenna	Field strength parallel to antenna	Field strength orthogonal to antenna	Field strength parallel to antenna	Field strength orthogonal to antenna
1	30 V/M	130 V/M	8 V/M	29 V/M	5 V/M	95 V/M	10 V/M	100 V/M	0 V/M	0 V/M
2	20 V/M	35 V/M	18 V/M	30 V/M	15 VLM	25 V/M	45 V/M	70 V/M	27 V/M	21 V/M
3	22 V/M	220 V/M	13 V/M	58 V/M	19 V/M	160 V/M	24 V/M	175 V/M	13 V/M	15 V/M
4	28 V/M	29 V/M	30 V/M	60 V/M	17 V/M	29 V/M	31 V/M	30 V/M	10 V/M	10 V/M
5	27 V/M	24 V/M	28 V/M	11 V/M	18 V/M	13 V/M	25 V/M	10 V/M	11 V/M	10 V/M
6	28 V/M	20 V/M	48 V/M	60 V/M	17 V/M	14 V/M	20 V/M	35 V/M	21 V/M	28 V/M
7	55 V/M	260 V/M	20 V/M	130 V/M	30 V/M	100 V/M	26 V/M	100 V/M	11 V/M	40 V/M
8	29 V/M	13 V/M	8 V/M	12 V/M	30 V/M	20 V/M	35 V/M	50 V/M	10 V/M	19 V/M
9	17 V/M	29 V/M	0 V/M	5 V/M	30 V/M	35 V/M	30 V/M	12 V/M	10 V/M	10 V/M
10	40 V/M	17 V/M	28 V/M	5 V/M	120 V/M	35 V/M	85 V/M	22 V/M	12 V/M	0 V/M
11	40 V/M	15 V/M	35 V/M	5 V/M	110 V/M	30 V/M	100 V/M	27 V/M	9 V/M	0 V/M
12	35 V/M	14 V/M	40 V/M	2 V/M	90 V/M	30 V/M	81 V/M	25 V/M	15 V/M	1 V/M
13	0 V/M	0 V/M	0 V/M	0 V/M	4 V/M	5 V/M	17 V/M	24 V/M	27 V/M	3 V/M
14	0 V/M	0 V/M	0 V/M	0 V/M	5 V/M	2 V/M	20 V/M	8 V/M	30 V/M	3 V/M
15	0 V/M	0 V/M	0 V/M	0 V/M	5 V/M	2 V/M	21 V/M	13 V/M	20 V/M	3 V/M

Antenna location on vehicle: right front fender

	Frequency of transmitter 25.04 MHz @ 100 W		Frequency of transmitter 35.04 MHz @ 100 W		Frequency of transmitter 39.04 MHz @ 100 W		Frequency of transmitter 51.2 MHz @ 100 W		Frequency of transmitter 144.5 MHz @ 100 W	
Meter location	Field strength parallel to antenna	Field strength orthogonal to antenna	Field strength parallel to antenna	Field strength orthogonal to antenna	Field strength parallel to antenna	Field strength orthogonal to antenna	Field strength parallel to antenna	Field strength orthogonal to antenna	Field strength parallel to antenna	Field strength orthogonal to antenna
1	5 V/M	70 V/M	1 V/M	30 V/M	2 V/M	32 V/M	12 V/M	58 V/M	0 V/M	5 V/M
2	2 V/M	5 V/M	18 V/M	19 V/M	14 V/M	17 V/M	90 V/M	85 V/M	5 V/M	10 V/M
3	0 V/M	18 V/M	5 V/M	70 V/M	15 V/M	90 V/M	55 V/M	115 V/M	5 V/M	2 V/M
4	10 V/M	11 V/M	15 V/M	28 V/M	14 V/M	40 V/M	8 V/M	73 V/M	15 V/M	52 V/M
5	5 V/M	5 V/M	19 V/M	18 V/M	16 V/M	13 V/M	8 V/M	10 V/M	12 V/M	12 V/M
6	13 V/M	30 V/M	52 V/M	55 V/M	30 V/M	35 V/M	11 V/M	15 V/M	10 V/M	18 V/M
7	12 V/M	180 V/M	14 V/M	140 V/M	5 V/M	50 V/M	18 V/M	220 V/M	5 V/M	11 V/M
8	2 V/M	0 V/M	11 V/M	11 V/M	35 V/M	13 V/M	20 V/M	8 V/M	20 V/M	5 V/M
9	1 V/M	10 V/M	16 V/M	20 V/M	30 V/M	24 V/M	35 V/M	8 V/M	11 V/M	11 V/M
10	14 V/M	1 V/M	110 V/M	27 V/M	80 V/M	26 V/M	48 V/M	16 V/M	20 V/M	5 V/M
11	17 V/M	2 V/M	100 V/M	16 V/M	80 V/M	30 V/M	53 V/M	11 V/M	18 V/M	5 V/M
12	18 V/M	8 V/M	100 V/M	23 V/M	75 V/M	23 V/M	62 V/M	13 V/M	17 V/M	5 V/M
13	8 V/M	8 V/M	5 V/M	5 V/M	3 V/M	3 V/M	10 V/M	8 V/M	24 V/M	10 V/M
14	8 V/M	8 V/M	5 V/M	5 V/M	5 V/M	1 V/M	10 V/M	3 V/M	30 V/M	3 V/M
15	10 V/M	35 V/M	5 V/M	5 V/M	3 V/M	2 V/M	8 V/M	5 V/M	14 V/M	5 V/M

2. Locations of electric field strengths between 50 and 150 V/m
   a. Center of dash panel
   b. Center of package tray
   c. Driver head space
   d. Glove compartment
   e. Lower center of dash panel

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TABLE 27.5 Field Strength Data at Various Meter Locations (*Continued*)

Antenna location on vehicle: roof

Meter location	Frequency of transmitter 25.04 MHz @ 100 W		Frequency of transmitter 35.04 MHz @ 100 W		Frequency of transmitter 39.04 MHz @ 100 W		Frequency of transmitter 51.2 MHz @ 100 W		Frequency of transmitter 144.5 MHz @ 100 W	
	Field strength parallel to antenna	Field strength orthogonal to antenna	Field strength parallel to antenna	Field strength orthogonal to antenna	Field strength parallel to antenna	Field strength orthogonal to antenna	Field strength parallel to antenna	Field strength orthogonal to antenna	Field strength parallel to antenna	Field strength orthogonal to antenna
1	18 V/M	55 V/M	2 V/M	200 V/M	8 V/M	80 V/M	15 V/M	170 V/M	0 V/M	2 V/M
2	11 V/M	17 V/M	11 V/M	26 V/M	2 V/M	16 V/M	35 V/M	99 V/M	17 V/M	19 V/M
3	16 V/M	50 V/M	25 V/M	20 V/M	13 V/M	60 V/M	21 V/M	125 V/M	0 V/M	13 V/M
4	13 V/M	17 V/M	17 V/M	14 V/M	11 V/M	21 V/M	40 V/M	35 V/M	2 V/M	30 V/M
5	14 V/M	15 V/M	15 V/M	14 V/M	12 V/M	12 V/M	38 V/M	30 V/M	12 V/M	5 V/M
6	31 V/M	28 V/M	26 V/M	30 V/M	55 V/M	27 V/M	30 V/M	80 V/M	5 V/M	13 V/M
7	70 V/M	280 V/M	30 V/M	290 V/M	11 V/M	52 V/M	60 V/M	280 V/M	2 V/M	28 V/M
8	48 V/M	22 V/M	92 V/M	70 V/M	100 V/M	55 V/M	75 V/M	40 V/M	20 V/M	10 V/M
9	2 V/M	25 V/M	43 V/M	32 V/M	42 V/M	45 V/M	90 V/M	25 V/M	17 V/M	26 V/M
10	210 V/M	40 V/M	210 V/M	45 V/M	270 V/M	48 V/M	210 V/M	65 V/M	30 V/M	5 V/M
11	230 V/M	30 V/M	240 V/M	48 V/M	220 V/M	52 V/M	210 V/M	30 V/M	35 V/M	2 V/M
12	170 V/M	30 V/M	205 V/M	65 V/M	180 V/M	35 V/M	230 V/M	35 V/M	18 V/M	5 V/M
13	5 V/M	2 V/M	10 V/M	5 V/M	14 V/M	10 V/M	28 V/M	13 V/M	17 V/M	5 V/M
14	0 V/M	0 V/M	11 V/M	2 V/M	14 V/M	8 V/M	30 V/M	10 V/M	28 V/M	10 V/M
15	0 V/M	0 V/M	10 V/M	3 V/M	10 V/M	8 V/M	30 V/M	15 V/M	17 V/M	10 V/M

Antenna location on vehicle: center of rear deck lid

Meter location	Frequency of transmitter 25.04 MHz @ 100 W		Frequency of transmitter 35.04 MHz @ 100 W		Frequency of transmitter 39.04 MHz @ 100 W		Frequency of transmitter 51.2 MHz @ 100 W		Frequency of transmitter 144.5 MHz @ 100 W	
	Field strength parallel to antenna	Field strength orthogonal to antenna	Field strength parallel to antenna	Field strength orthogonal to antenna	Field strength parallel to antenna	Field strength orthogonal to antenna	Field strength parallel to antenna	Field strength orthogonal to antenna	Field strength parallel to antenna	Field strength orthogonal to antenna
1	2 V/M	31 V/M	0 V/M	45 V/M	15 V/M	100 V/M	10 V/M	180 V/M	0 V/M	2 V/M
2	2 V/M	5 V/M	24 V/M	40 V/M	30 V/M	75 V/M	45 V/M	55 V/M	0 V/M	13 V/M
3	5 V/M	45 V/M	22 V/M	110 V/M	14 V/M	150 V/M	20 V/M	280 V/M	2 V/M	18 V/M
4	2 V/M	5 V/M	43 V/M	40 V/M	10 V/M	24 V/M	30 V/M	15 V/M	5 V/M	30 V/M
5	2 V/M	0 V/M	30 V/M	30 V/M	5 V/M	16 V/M	50 V/M	30 V/M	2 V/M	2 V/M
6	20 V/M	30 V/M	5 V/M	1 V/M	100 V/M	78 V/M	10 V/M	12 V/M	1 V/M	1 V/M
7	21 V/M	200 V/M	55 V/M	300 V/M	150 V/M	>300 V/M	28 V/M	>300 V/M	5 V/M	35 V/M
8	22 V/M	11 V/M	0 V/M	11 V/M	50 V/M	18 V/M	58 V/M	27 V/M	2 V/M	11 V/M
9	14 V/M	68 V/M	22 V/M	2 V/M	92 V/M	52 V/M	68 V/M	52 V/M	2 V/M	10 V/M
10	100 V/M	21 V/M	5 V/M	13 V/M	150 V/M	20 V/M	150 V/M	45 V/M	40 V/M	13 V/M
11	110 V/M	18 V/M	5 V/M	18 V/M	180 V/M	27 V/M	130 V/M	30 V/M	38 V/M	8 V/M
12	140 V/M	24 V/M	10 V/M	16 V/M	175 V/M	26 V/M	160 V/M	30 V/M	28 V/M	10 V/M
13	12 V/M	5 V/M	27 V/M	2 V/M	23 V/M	5 V/M	35 V/M	11 V/M	45 V/M	9 V/M
14	23 V/M	8 V/M	40 V/M	3 V/M	40 V/M	5 V/M	45 V/M	12 V/M	60 V/M	20 V/M
15	10 V/M	5 V/M	24 V/M	0 V/M	25 V/M	5 V/M	25 V/M	18 V/M	30 V/M	28 V/M

f. Lower left side of dash panel

g. Passenger head space

3. Locations of electric field strengths less than 50 V/m

a. Left side of package tray

b. Right side of package tray

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ABOUT THE AUTHOR

James P. Muccioli has extensive experience in EMC design, analysis, and testing. His background includes 13 years of specialized EMC systems experience at Chrysler Corporation and United Technologies. He served on the faculty of Lawrence Technological University, teaching an undergraduate course on noise reduction techniques and a continuing education seminar on electronic system noise reduction. He teaches EMC seminars through his own consulting firm JASTECH and has authored several symposium papers on EMC and is a NARTE Certified EMC Engineer. He is an active member of SAE-J1113 and J-551 EMC committees (1984–present) and is chairperson of the SAE Integrated Circuit EMC Task Force (1991–present). He is an IEEE-Electromagnetic Compatibility Society Board of Directors member.

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CHAPTER 28
ELECTROMAGNETIC COMPATIBILITY

James P. Muccioli
EMC Consultant, JASTECH

28.1 NOISE PROPAGATION MODES

28.1.1 Introduction

Before an engineer can design for EMC, he must first understand the paths where electromagnetic interference can affect electronic modules and how electromagnetic emissions from his module will affect other electronic modules. Noise propagation can be defined as conducted mode propagation and/or radiated emissions propagation.

28.1.2 Conducted Mode Propagation

Conducted mode propagation occurs when electromagnetic interference travels on the wiring harness connecting the noise source to the device affected, as shown in Fig. 28.1.

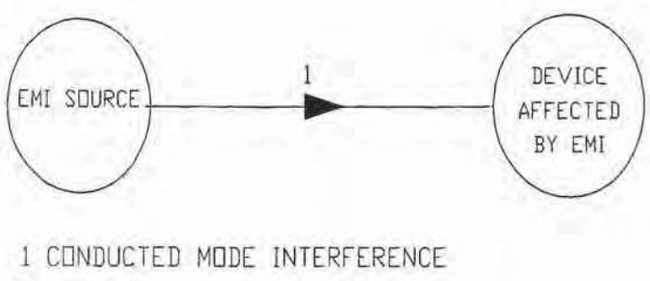


FIGURE 28.1 Conducted mode propagation.

28.1.3 Radiated Emissions Propagation

Radiated emissions propagation occurs when the electromagnetic interference travels through free space (air) from a noise source to the device affected, as shown in Fig. 28.2.

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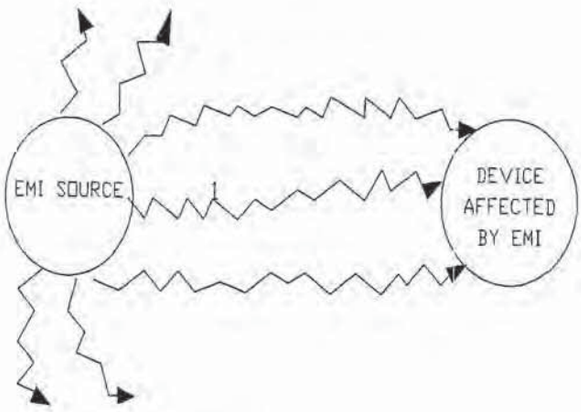


FIGURE 28.2 Radiated emissions propagation.

28.1.4 Conducted and Radiated Propagation

Conducted and radiated propagation occurs when the electromagnetic interference travels on and radiates from the wiring harness connecting the noise source to the device affected, as shown in Fig. 28.3.

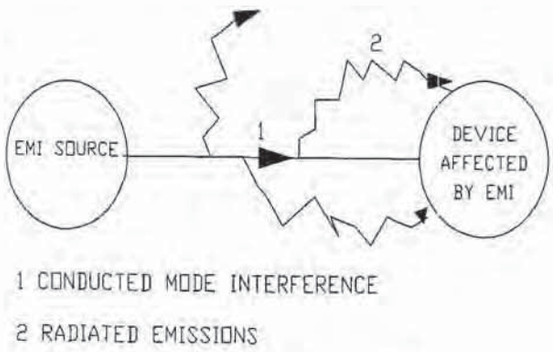


FIGURE 28.3 Conducted and radiated propagation.

28.1.5 Radiated and Conducted Propagation

Radiated and conducted propagation occurs when the electromagnetic interference travels through free space (air) from a noise source to the wiring harness of the device affected, as shown in Figure 28.4.

28.2 CABLING

28.2.1 Introduction

The use of wiring harnesses (transmission lines) in the presence of electromagnetic fields can cause unwanted noise energy to be induced onto signal-carrying conductors. Typical wiring

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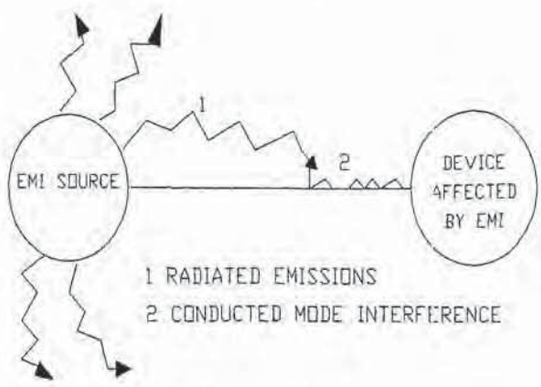


FIGURE 28.4 Radiated and conducted propagation.

harnesses in today's automobiles are made up of single, twisted pair, and coaxial type conductors. One of the biggest problems associated with using twisted pair and coaxial cables is an inappropriate method of termination. A test was performed to determine how termination affects them, and how they reject radiated interference.

28.2.2 Test Methodology

Using a stripline antenna, an E-field intensity of 50 V/m was maintained throughout the entire frequency range of the test. Figure 28.5 shows the test setup of the stripline antenna with relation to the cable under test and the ground plane. All cables used were 2 m in length and terminated with the same resistances. The cables were swept through a frequency range of 10 KHz to 100 MHz. Data points were selected at multiple decades of frequency.

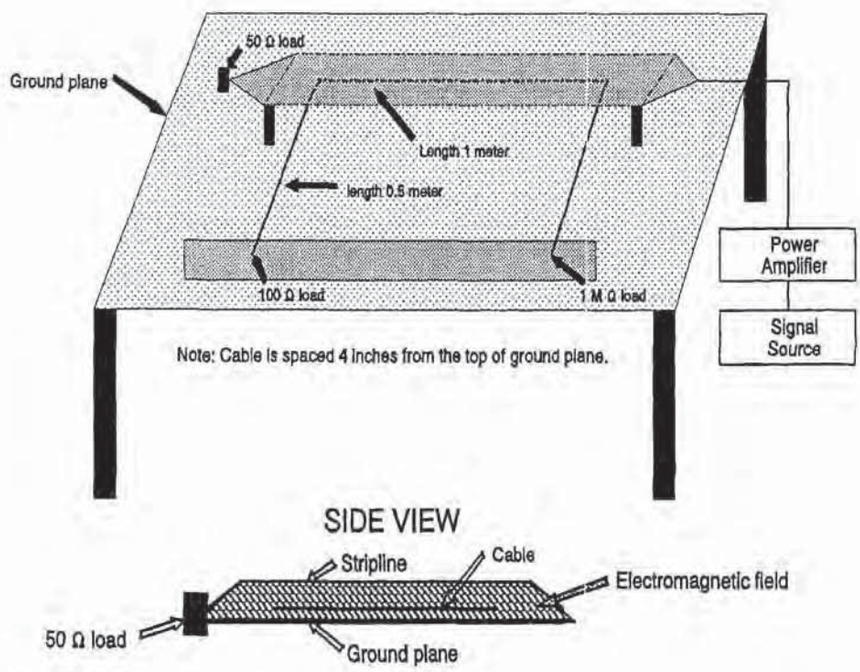


FIGURE 28.5 Stripline test setup.

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28.2.3 Summary

Figure 28.6 shows the various cable configurations. Configurations A through F have both ends grounded, while configurations G through K have only one end grounded. The attenuation values for each cable configuration are shown in Table 28.1. Overall, cables with single-ended grounding offered more attenuation than cables with dual-ended grounding. This data should be used to get a feel for the different types of cable configurations. When the cable termination and load resistors are known, a test should be performed to verify the attenuation expected

TABLE 28.1 Attenuation in dB of Cable Configurations

Letter	10 kHz	50 kHz	100 kHz	1 MHz	10 MHz	100 MHz
A	0	0	0	0	0	0
B	0	0	0	0	0	–20
C	15	25	30	40	38	10
D	11	15	15	17	15	–10
E	8	8	7	13	10	20
F	8	12	15	27	28	20
G	40	44	46	56	38	51
H	20	15	15	15	10	–10
I	26	36	41	46	30	0
J	15	30	30	35	32	18
K	15	35	42	45	30	0

28.3 COMPONENTS

28.3.1 Capacitor

Capacitor Model. A high-frequency capacitor model is needed for analyzing the effects due to electromagnetic compatibility. Figure 28.7 shows one way to model a high-frequency capacitor.

Capacitor EMC Guidelines. Consider the frequency range, voltage rating, stability, temperature coefficient, and tolerance when choosing the dielectric type for the capacitance. The type of dielectric used in the capacitor will dictate the frequency range over which the capacitor will be most effective for filtering. Table 28.2 includes the relative losses (leakage) of dielectric types.

TABLE 28.2 Relative Losses of Dielectric Types

Dielectric type	Frequency range	Relative losses
Aluminum electrolytic	1 Hz–10 KHz	High
Tantalum electrolytic	1 Hz–10 KHz	High
Paper/mylar	100 Hz–5 MHz	Medium
High K-ceramic	1 KHz–100 MHz	Low
Plastic films	1 KHz–9 GHz	Low
Mica/glass/low-loss ceramic	5 KHz–10 GHz	Low

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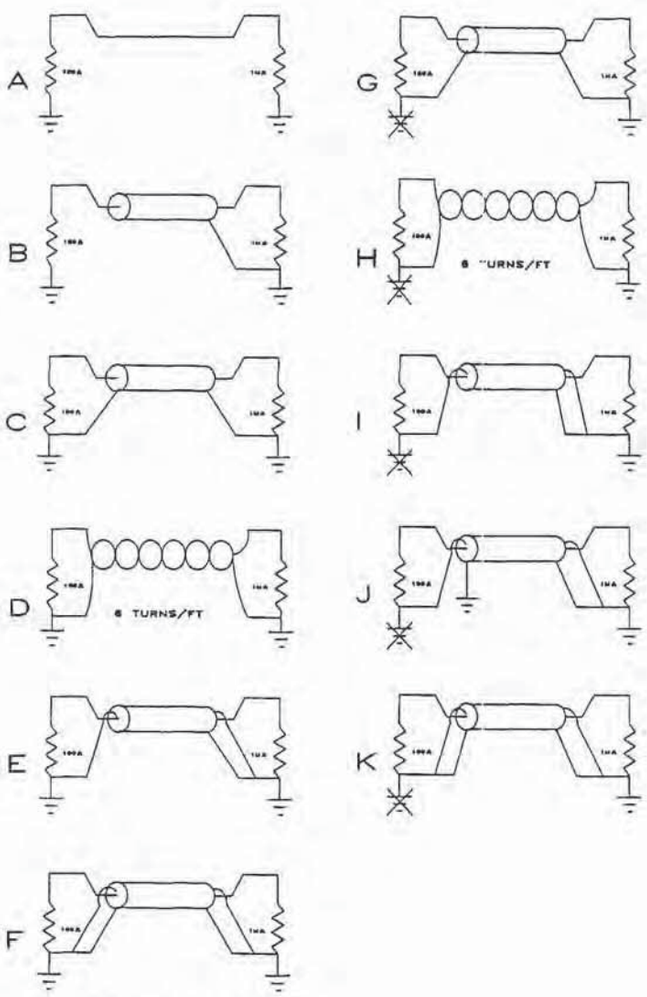
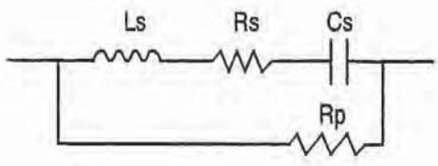


FIGURE 28.6 Cable configurations.



Cs = Series capacitance

Ls = Inductance due to lead length and capacitor structure

Rs = Effective series resistance and dissipation factor

Rp = Parallel leakage and volume resistivity of dielectric

FIGURE 28.7 Equivalent circuit for a capacitor.

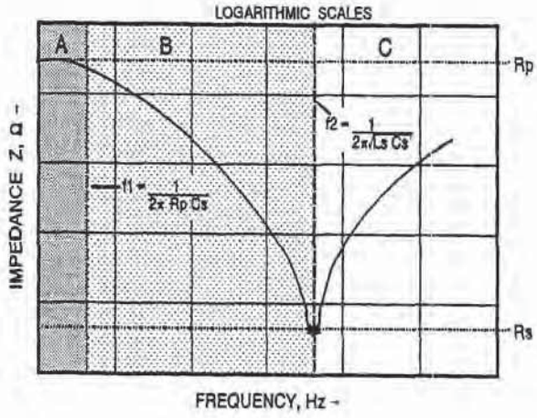
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Capacitor Quality Q Factor. Quality factor Q of a capacitor is the ratio of the resonant frequency to the bandwidth between the frequencies on opposite sides of the resonance. The Q of a simple resonant circuit composed of a capacitance and inductances is given by the following equation:

$$Q = \frac{(Q_C \times Q_L)}{(Q_C + Q_L)}$$

where Q_C = the magnitude of the ratio of the capacitor susceptance to its effective shunt conductance at a specified frequency, and Q_L = the magnitude of the ratio of the inductor reactance to its effective series resistance at a specified frequency.

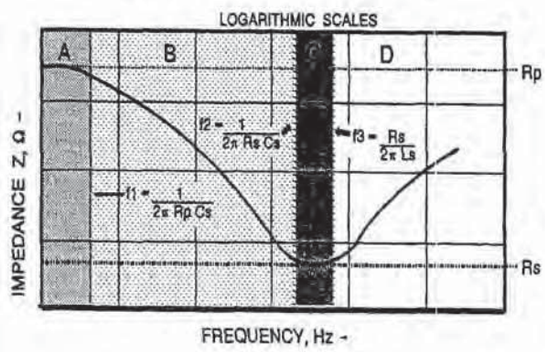
When Q is greater than 1, the capacitor impedance-versus-frequency model is as shown in Fig. 28.8. When Q is less than 1, the capacitor impedance-versus-frequency model is as shown in Fig. 28.9.



REGION

- A Capacitor impedance is primarily determined by parallel leakage and volume resistivity of the dielectric (Rp).
- B Capacitance (Cs) becomes the dominant with the impedance decreasing at -6 dB/octave.
- ★ Series resonance develops between Cs and Ls.
- C Series inductance (Ls) becomes dominant.

FIGURE 28.8 Capacitor impedance versus frequency when $Q > 1$.



REGION

- A Capacitor impedance is primarily determined by parallel leakage and volume resistivity of the dielectric (Rp).
- B Capacitance (Cs) becomes the dominant with the impedance decreasing at -6 dB/octave.
- C Series resistance (Rs) causes the relatively flat characteristic between f2 and f3.
- D Series inductance (Ls) becomes dominant.

FIGURE 28.9 Capacitor impedance versus frequency when $Q < 1$.

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The capacitor will self-resonate at some frequency dependent mainly upon the capacitive and inductive values of the capacitor itself, as shown in Figs. 28.8 and 28.9. Lead length is mainly responsible for the inductive element as depicted in the models. Excess length can reduce the resonant frequency significantly, hence reducing the operating frequency range.

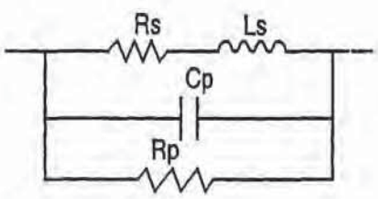
Using a network analyzer, data in Table 28.3 was gathered on ceramic capacitors. The lower the value of the capacitor, the greater the effect the leac length will have on the self-resonate frequency.

TABLE 28.3 Capacitors Measured at Self-Resonate Frequencies

Capacitance	Self-resonate frequency at ¼" leads	Self-resonate frequency at ½" leads
1000 pF	35 MHz	32 MHz
500 pF	70 MHz	65 MHz
100 pF	150 MHz	120 MHz
50 pF	220 MHz	200 MHz
10 pF	500 MHz	350 MHz

28.3.2 Inductor

Inductor Model. A high-frequency inductor model is needed for analyzing the effects due to electromagnetic compatibility. Figure 28.10 shows one way to model a high-frequency inductor.



Ls = Series inductance

Rs = Series resistance from wire used in winding

Cp = Distributed capacitance between the windings

Rp = Core and winding resistance losses (including skin effect) at the resonant frequency

FIGURE 28.10 Equivalent circuit for an inductor.

Inductor EMC Guidelines. EMC considerations for inductors include magnetic losses, mechanical stability, temperature coefficients, flux leakage, and dielectric losses. The shape of an inductor will determine some of its properties. An open core inductor, such as a cylinder, will have a large external magnetic field. A closed core inductor will confine most of the magnetic field. The toroid-shaped inductor has the maximum inductance per unit volume and low flux leakage. This is due to the fact that the toroid provides a closed circular path for magnetic flux, hence the external flux levels are very low. Figure 28.11 shows air core versus magnetic core inductors.

Inductor Quality Q Factor. Quality factor Q of an inductor is the ratio of the resonant frequency to the bandwidth between the frequencies on opposite sides of the resonance. The Q of a simple resonant circuit composed of a capacitance and inductances is given by the following equation:

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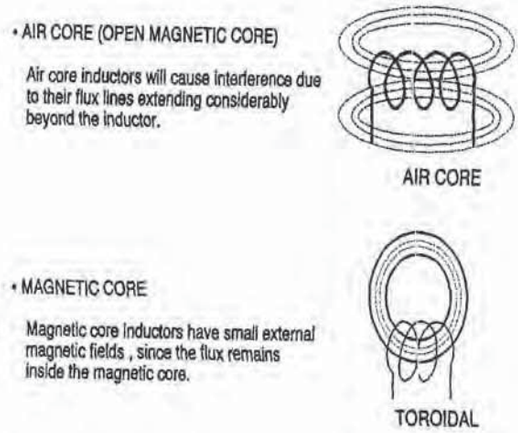


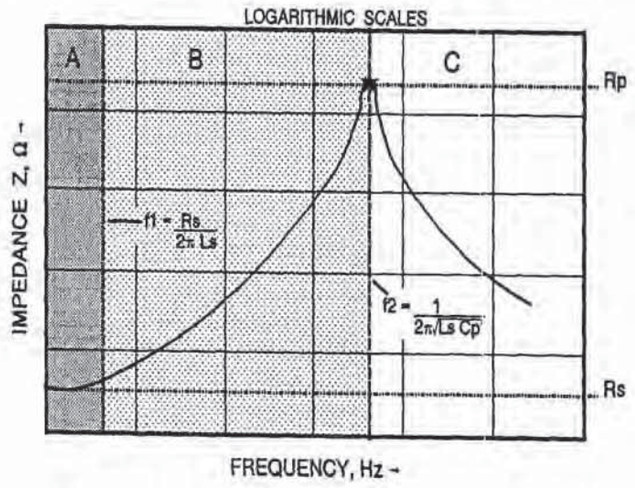
FIGURE 28.11 Air core versus magnetic core inductors.

$$Q = \frac{(Q_L \times Q_C)}{(Q_L + Q_C)}$$

where Q_L = the magnitude of the ratio of the inductor reactance to its effective series resistance at a specified frequency

Q_C = the magnitude of the ratio of the capacitor susceptance to its effective shunt conductance at a specified frequency

Figure 28.12 shows the inductor impedance versus frequency. An inductor has capacitance between each turn of the windings and leads. At some frequency, the inductor will become self-resonant, as shown in Fig. 28.12, due to its winding capacitance.



REGION

A Inductor impedance is primarily determined by the winding dc resistance (Rs).

B Inductance (Ls) becomes the dominant with the impedance increasing at +6 dB/octave.

★ Parallel resonance develops between Ls and Cp.

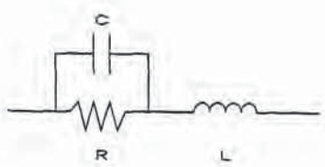
C Parallel capacitance (Cp) becomes dominant.

FIGURE 28.12 Inductor impedance versus frequency.

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28.3.3 Resistor

Resistor Model. A high-frequency resistor model is needed for analyzing the effects due to electromagnetic compatibility. In Fig. 28.13, one way to model a high-frequency resistor is shown.



C = SHUNT CAPACITANCE WHICH IS TYPICALLY 0.1 — 0.5pF

L = LEAD INDUCTANCE, EXCEPT FOR WIREWOUND RESISTORS

FIGURE 28.13 Equivalent circuit for a resistor.

Resistor EMC Guidelines. Consider the construction of the resistor before determining the transient handling capability and frequency characteristics. The resistor construction types are defined as carbon composition, chip (surface mount and leaded), film (thin and thick), and wirewound.

Transient Dissipation. Carbon composition resistors are capable of handling large transients without degradation to the resistor value. Chip-type resistors are capable of handling moderate (less than 40 V) transients, making them suitable for most printed circuit board applications. Film-type resistors should be *avoided* for lines which encounter transients of significant power, since the film degrades after many transients and the resistor value will become lower. Wirewound resistors can dissipate repetitive, high-power, and high-peak transients without failure. The larger the diameter of the wire windings, the more effectively the transient can be dissipated

Resistor Noise. In general, composition-type resistors produce the most electrical noise and wirewound resistors produce the least. Electrical noise in resistors manifests due to the thermal properties present in their construction. If a high-power and a low-power composition-type resistor are put in identical circuit conditions, the higher power resistor will produce less electrical noise. Because the noise produced by film-type resistors is less than that of composition types, they are used in small-signal or high-gain applications.

28.4 PRINTED CIRCUIT BOARD EMC CHECKLIST

1. Reduce radiated emissions and susceptibility by selecting the slowest possible switching speed (bandwidth) for the electronic devices.
2. Partition the PC-board.
   a. Bypass ground plane at I/O connector.
   b. Group regulators/power supplies near I/O connector.
   c. Place crystals/RC clock circuit directly next to ICs.
   d. Group same family of electronic devices together (interface, analog, low/medium/high-speed logic circuitry).

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3. Single point the different types of ground circuits to I/O ground.
4. Bypass all lines at I/O connector.
   a. Reduce RF entering the PC-board by filtering at entrance.
   b. Reduce RF leaving the PC-board by filtering at exit.
5. Lay out the power distribution system.
   a. Low impedance power distribution system limits EMI.
   b. Power feed and return lines *must* be as close as possible to minimize impedance and loop sizes.
6. Decouple active components and power supply lines.
   a. Minimize instantaneous current draw on the power bus by placing a capacitor from the IC power to the IC ground.
   b. Calculate the size of capacitor required.
   c. Bulk decoupling capacitor (electrolytic typical 10–100 μF) is required at power entrance point.
7. Ground all unused IC input pins where possible.
   a. Reduce IC noise by lowering the ground impedance and eliminate unused IC pins from acting like antennas.
8. Design reverse voltage protection where needed.
   a. Diodes can be used to protect against reverse voltage damage.
9. Design clock line routing.
   a. Minimize clock line loop size.
   b. Clock line return path must be next to clock line.
10. Design PC-board jumper cables to minimize loop area by having return paths for all types of signal and power lines.
11. Autoroute the PC-board one partition group at a time with signal lines last.
12. Design metal housings to act as shields.

28.5 INTEGRATED CIRCUIT DECOUPLING—A KEY AUTOMOTIVE EMI CONCERN

Note: Parts of this section were taken from the paper of the same name presented by James P. Muccioli at the EMC/ESD International Conference in April 1992.

28.5.1 Abstract

Since the development of the first solid state engine control for automobiles, microcircuit technology has evolved with greater complexity, faster clock speeds, and smaller package size. Electromagnetic compatibility (EMC) has become a high priority in the design of electronic automotive modules. At the same time, the die size of CMOS technology has decreased from 9-micron process size (50-ns rise/fall time) to 0.8-micron process size (1.5-ns rise/fall time) in high-speed CMOS integrated circuits. To minimize the effect of EMC due to the faster rise/fall time, the design engineer must analyze the integrated circuit (IC) package and associated decoupling capacitor. This section will concentrate on how to analyze the decoupling capacitor requirements.

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28.5.2 Introduction

Automotive electromagnetic emissions requirements and extreme cost constraints require the design engineer to be very innovative in addressing his EMI concerns. All components on the printed circuit board must be analyzed for effects and emissions contributed to the total radiated emissions from the electronic module. One source of noise on the printed circuit board is the integrated circuit. Choosing the right decoupling capacitor will limit the amount of electromagnetic emissions radiated from the integrated circuits on the printed circuit board. The decoupling capacitor, if not properly chosen for each integrated circuit, will contaminate the input/output lines in the form of ringing, overshooting, and/or undershooting.

28.5.3 Decoupling Capacitor Value

The decoupling capacitor supplies the instantaneous power required to the integrated circuit when switching from one of its transition states to another. When calculating the value for the decoupling capacitor, the following items must be considered:

1. Transient current of integrated circuit
2. Switching time of transition state
3. Allowable transient voltage drop in the supply voltage
4. Decoupling capacitor inductance due to lead length and capacitor structure
5. Printed circuit board trace inductance

Before the decoupling capacitor value can be determined, the design engineer must measure the rise/fall times of the various types of integrated circuits used on the printed circuit board. If the printed circuit board is using dual-source integrated circuits for production, the second source integrated circuits must also be measured and taken into account. After gathering this data, the switching frequency generated by the integrated circuit rise/fall time can be calculated by the formula:

$$f = \left[\frac{1}{\pi} \times t_r\right] \text{Hz} \tag{28.1}$$

where t_r = rise time/fall time in seconds

The value of the decoupling capacitor must satisfy two requirements:

1. The value of the decoupling capacitor must equal or exceed the minimum decoupling capacitor value required to supply enough power to meet the allowable transient voltage drop on the supply voltage.
2. The decoupling capacitor at this value must avoid self-resonance when instantaneous power is required for the integrated circuit.

The minimum value of the decoupling capacitor referred to in the first requirement (preceding) can be calculated by the formula:

$$C = \frac{(dI \times dt)}{dV} \tag{28.2}$$

where dI = current of transient (amps)
dt = switching time of transient (seconds)
dV = the transient voltage drop in the supply voltage (volts)

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The self-resonant circuit referred to in the second requirement (see Fig. 28.14) is the combination of the capacitance and inductance between the decoupling capacitor and integrated circuit, resonating at the switching frequency generated by the integrated circuit. The inductance in the self-resonant circuit is the combination of inductances of the capacitor (L_C), the printed circuit board trace (L_{PCB}), and the integrated circuit lead frame (L_{IC}). The capacitance used for calculating the self-resonant circuit is the value of the capacitor C only (the capacitance value for the printed circuit board trace and the integrated circuit lead frame can be neglected because their values are negligible when compared to the decoupling capacitor value). The frequency of the self-resonant circuit can be calculated by the following formula:

$$f_c = \frac{1}{2\pi\sqrt{(L_{PCB} + L_{IC} + L_C)(C)}} \text{ Hz} \tag{28.3}$$

where L_{PCB} = inductance of printed circuit board trace (henrys)
L_{IC} = inductance of integrated circuit lead frame (henrys)
L_C = inductance of capacitor (henrys)
C = capacitance value (farads)

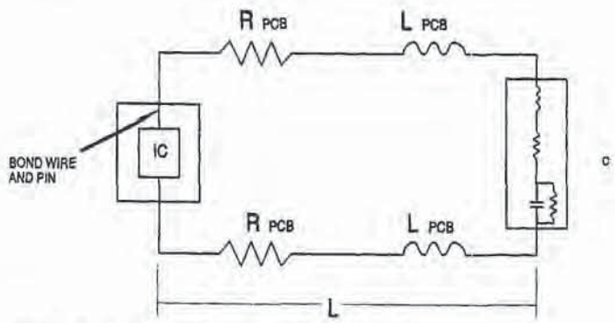


FIGURE 28.14 Self-resonant circuit.

If the second requirement is not met (the circuit becomes self-resonant), there will not be enough power to maintain the desired transient voltage drop.

When the design engineer analyzes the data from the three formulas and tries to meet the two requirements for a decoupling capacitor, the data will not always yield a solution.

The design engineer must also look at the decoupling capacitor placement (Fig. 28.15) and the various integrated circuit packages to determine if there are any differences in power and ground lead frame inductances.

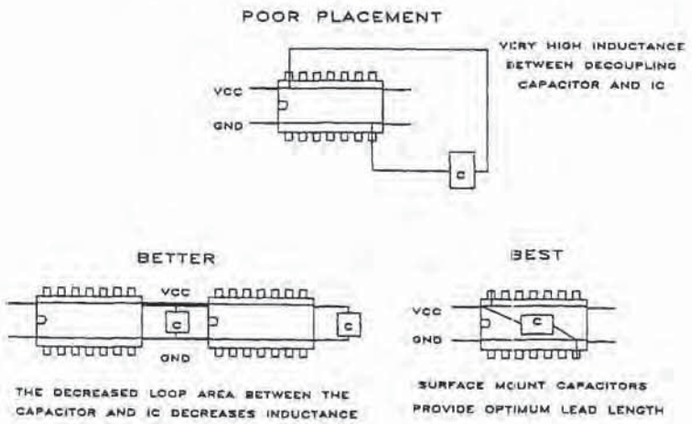


FIGURE 28.15 Decoupling capacitor placement.

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The longest copper lead frame trace inductance values of various integrated circuits are not easily available. With the help of Mike Catherwood from Motorola, the following chart was created:

Package type	L_{max} (nH)
14 lead SOIC	1.81
16 lead SOIC	1.69
14 lead PDIP	3.93
16 lead PDIP	4.33
28 lead PDIP	8.72
20 lead PLCC	1.79
24 lead PLCC	2.45
44 lead PLCC	3.94
52 lead PLCC	4.06
68 lead PLCC	6.58
32 lead R-PLCC	1.89

This information is necessary for picking the lowest lead frame inductance for a specific IC package.

Sample Problem. Find the decoupling capacitor value for a 74HCO4 14 lead PDIP hex inverter when assuming the following:

1. Supply voltage drop = 250 mV
2. Current of transient = 50 mA
3. Switching time of transient = rise/fall time of IC = 10 ns

Note: The smaller value of t_{TLH} or t_{THL}, taken from the IC specification sheet, can be used for t_r

4. Printed circuit board trace = 5 nH/cm
5. Printed circuit board trace length = 2 cm
6. Capacitor inductance = 1 nH

Solution. The switching frequency generated by the IC rise/fall time can be calculated using Eq. (28.1):

$$\begin{aligned} f &= [1/\pi \times t_r]\ \text{Hz} \\ &= 1/[\pi \times (1.0 \times 10^{-8})]\ \text{Hz} \\ &= 31\,830\,989\ \text{Hz} \\ &= 31.8\ \text{MHz} \end{aligned}$$

The minimum value of the decoupling capacitor referred to in the first requirement can be calculated using Eq. (28.2):

$$\begin{aligned} C &= \frac{(dI \times dt)}{dV} \\ &= [(5.0 \times 10^{-2}\text{A}) \times (1.0 \times 10^{-8}\text{s})]/2.5 \times 10^{-1}\text{V} \\ &= 2.0 \times 10^{-9}\text{F} \\ &= 2000\ \text{pF} \end{aligned}$$

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The frequency of the self-resonant circuit referred to in the second requirement can be calculated using Eq. (28.3):

$$f_c = \frac{1}{2\pi\,[(L_{PCB} + L_{IC} + L_C)(C)]^{1/2}}$$

$$= \frac{1}{2\pi\,[(2.0\text{ cm})(5.0 \times 10^{-9}\text{H/cm}) + (2)(3.93 \times 10^{-9}\text{H}) + (1.0 \times 10^{-9}\text{H})(2.0 \times 10^{-9}\text{F})]^{1/2}}$$

$$= 25{,}913{,}990\text{ Hz}$$

$$= 25.9\text{ MHz}$$

The second requirement is not met because the self-resonance of the capacitor combination (25.9 MHz) is lower in frequency than the integrated circuit switching frequency (31.8 MHz). If we change to a 14 lead SOIC package, the integrated circuit lead inductance is reduced to 1.81 nH per lead. Also, since the package is smaller, the printed circuit board trace length is reduced to 1 cm. The frequency of the self-resonant circuit is recalculated as shown:

$$f_c = \frac{1}{2\pi\sqrt{L_{PCB} + L_{IC} + L_C\,(C)}}$$

$$= \frac{1}{2\pi\sqrt{((1.0\text{ cm})(5.0 \times 10^{-9}\text{ H/cm}) + (2)(1.81 \times 10^{-9}\text{ H}) + (1.0 \times 10^{-9}\text{ H}))(2.0 \times 10^{-9}\text{ F})}}$$

$$= 36{,}284{,}204\text{ Hz}$$

$$= 36.3\text{ MHz}$$

Therefore, by changing the IC package from PDIP to SOIC, we can meet both requirements.

28.5.4 Summary and Discussion

Decoupling capacitor values calculated using the formulas in this paper will not be optimal for every application due to lead frame and printed circuit board trace inductances. Integrated circuit manufacturers need to continue their search for ways to minimize the inductances in the power and ground leads. They should investigate supplying integrated circuits with decoupling capacitors internal to lead frame packages. Until the integrated circuit manufacturers can help the design engineer, the following items should be considered before a decoupling capacitor is chosen:

1. The larger the decoupling capacitor value, the lower the self-resonant frequency.
2. Too small a decoupling capacitor will not have sufficient charge storage for transient current needed by the integrated circuit.
3. Different integrated circuit package configurations will change the integrated circuit lead frame inductance.

28.6 IC PROCESS SIZE AFFECTS EMC

Note: Parts of this section were taken from the article of the same name by James P. Muccioli published in the June 1993 issue of *EMC Test & Design* magazine.

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28.6.1 Abstract

This section focuses on how to measure the near-field radiated emissions generated by an integrated circuit. Testing was performed in a controlled manner that yields repeatable results using a miniature skin current probe. Integrated circuits are characterized by process size and its effect on radiated emissions.

28.6.2 Test Configuration

The devices under test (DUT) are all the same eight-bit microprocessor type with internal test ROM code. The only variable is the process size, which changes from 1.95 micron to 1.50 micron.

The DUT is in a standardized manufacturer IC test setup (Fig. 28.16) which is part of a ground plane to assure test repeatability. The DUT is powered by a low-impedance battery (alkaline) to assure that there is no possibility for conducted noise to interfere with or confuse the test results. The software for the programmable integrated circuit flows in a continuous loop and is part of the internal ROM.

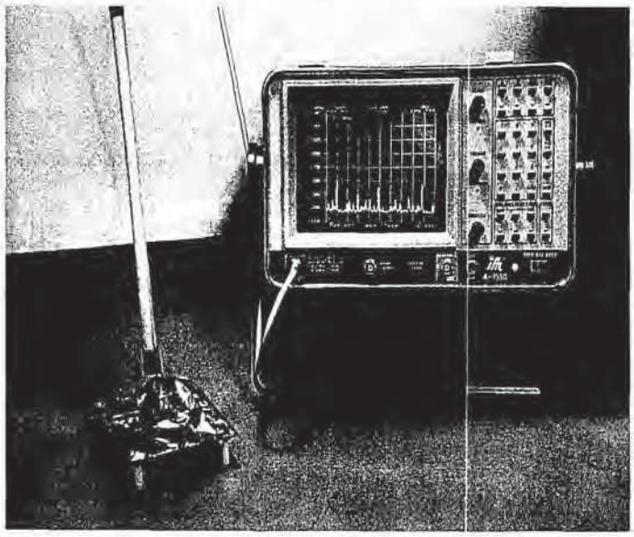


FIGURE 28.16 Picture of IC test setup with ground plane and skin current probe.

28.6.3 Test Methodology

The purpose for using a miniature skin current probe is to make quantitative measurements of currents (magnetic fields) generated by integrated circuits. The current probe can be used in a nonshielded room since only the magnetic fields related to the electromagnetic radiation potential of the integrated circuit affect the probe and it is relatively insensitive to stray electric fields.

The surface of the integrated circuit is mapped by orienting the probe for maximum sensitivity and then repeating the measurement after moving the probe to the next location. The skin current probe (Fischer Custom Communications, Inc. F-97) has a transfer impedance of 1 ohm ±20% from 70 MHz to greater than 1000 MHz as shown in Fig. 28.17.

The miniature skin current probe is in series with a 20-dB preamplifier (Mini-Circuits ZFL-1000LN) and is connected to a spectrum analyzer (IFR Systems, Inc. A-7550) as shown in Fig. 28.18. The system gain of the measuring equipment should be known with an accuracy

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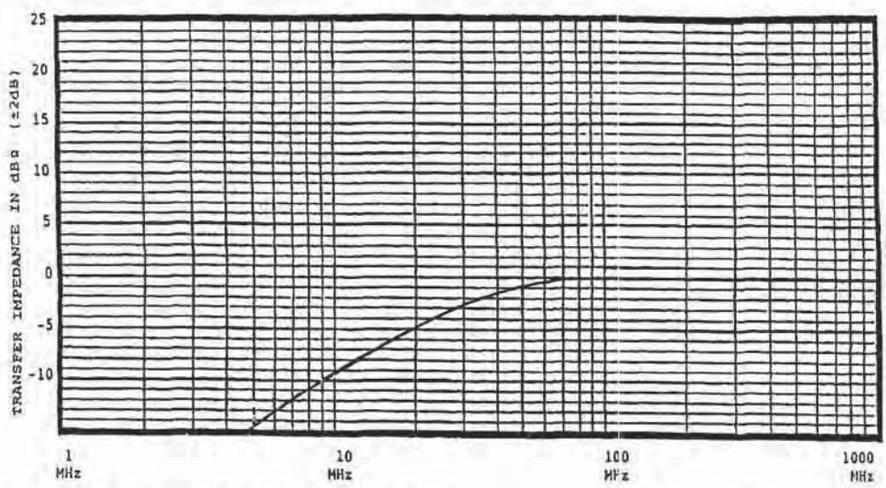


FIGURE 28.17 F-97 transfer impedance versus frequency. *(Courtesy of Fischer Custom Communications)*

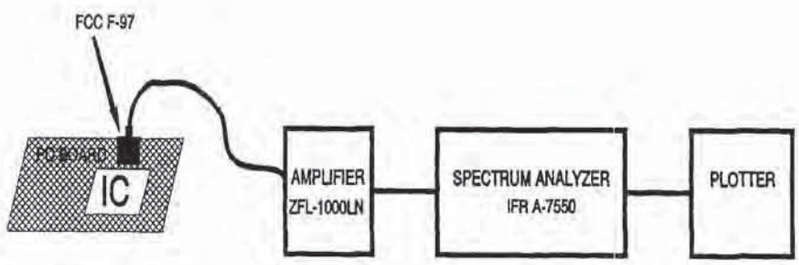


FIGURE 28.18 System test setup.

of ±0.5 dB. If the signals being measured by the skin current probe are within 6 dB of the system noise floor, then a smaller resolution bandwidth should be used on the spectrum analyzer.

The first measurement taken in each frequency band of the spectrum analyzer should be the ambient system level to assure that any ambient signals present are at least 6 dB below the signals of the integrated circuit. This is accomplished by taking the ambient measurement with the skin current probe placed on top of the integrated circuit in the measurement position with no power supply to the DUT. The DUT should be energized and a complete operational check of the integrated circuit test code performed to assure proper functioning of the device.

28.6.4 Test Results

Figures 28.19 and 28.20 show the system noise floor with the preamplifier and the F-97 probe. The frequency range of Fig. 28.19 is from 70 to 250 MHz with the center at 160 Mhz. The frequency range of Fig. 28.20 is from 250 to 500 MHz with the center at 375 MHz. The system noise floor from 70 to 500 MHz is below –120 dBm when the 20-dB gain is factored into the spectrum analyzer plot.

Figures 28.21 and 28.22 show the measured magnetic emissions of an eight-bit microprocessor with a 1.95-micron process size. The highest peak frequency from the microprocessor is at 72 MHz with a level corrected for preamp gain of –83.33 dBm

Figures 28.23 and 28.24 show the measured magnetic emissions of an eight-bit microprocessor with a 1.50-micron process size. The highest peak frequency from the microprocessor is at 72 MHz with a corrected level of –86.00 dBm.

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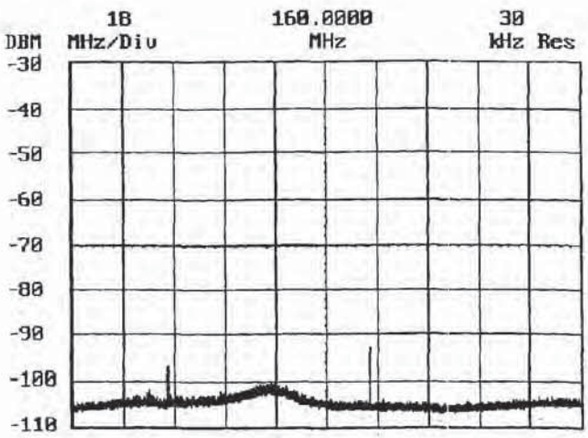


FIGURE 28.19 Ambient system level measurement from 70 to 250 MHz.

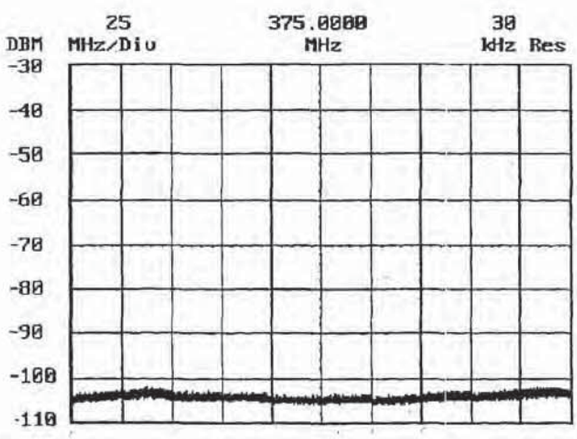


FIGURE 28.20 Ambient system level measurement from 250 to 500 MHz.

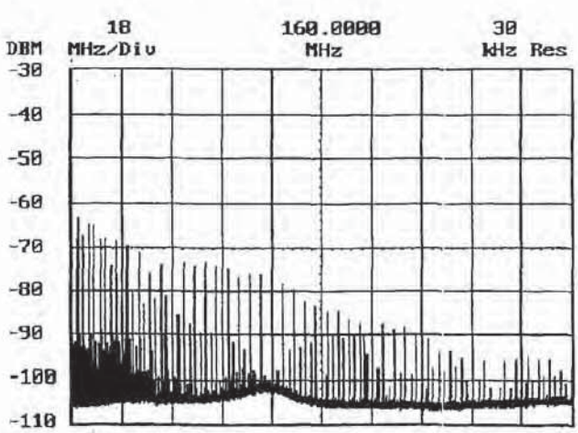


FIGURE 28.21 Magnetic emissions of 1.95-micron process from 70 to 250 MHz.

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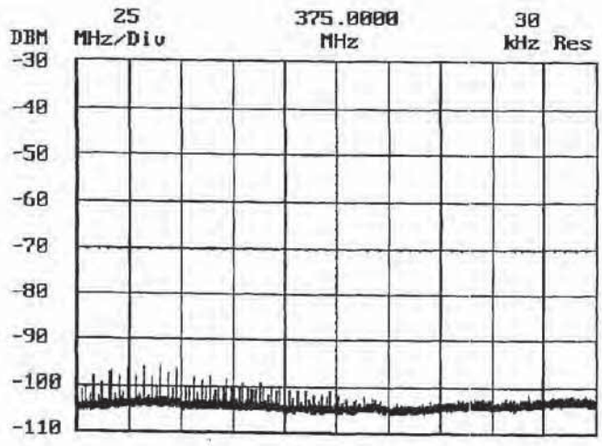


FIGURE 28.22 Magnetic emissions of 1.95-micron process from 250 to 500 MHz.

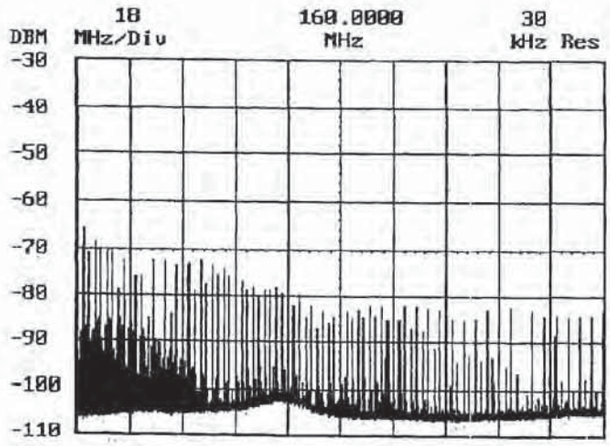


FIGURE 28.23 Magnetic emissions of 1.5-micron process from 70 to 250 MHz.

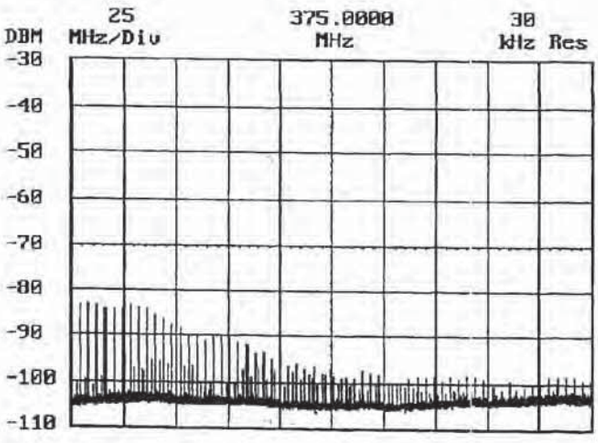


FIGURE 28.24 Magnetic emissions of 1.5-micron process from 250 to 500 MHz.

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28.6.5 Summary and Discussion

When analyzing the data from Figs. 28.21, 28.22, 28.23, and 28.24, the following statements can be made:

1. The 1.95-micron process size magnetic emissions drop off faster than the 1.50-micron process size.
2. The 1.50-micron data has a more intense magnetic field between 70 and 115 MHz than the 1.95-micron data.
3. The amplitude of the 1.95-micron data is typically 10 to 15 dBm less than the 1.50-micron data after 200 MHz.

From the data analyzed, the author demonstrated that integrated circuit process size changes do have an effect on electromagnetic compatibility. The rise time of the integrated circuit is also affected by the process size change. The 1.95-micron process size has a rise time of 6.4 ns and the 1.50-micron process size has a rise time of 2.4 ns. Until the integrated circuit manufacturers can supply typical emission-level data with integrated circuit process size changes, the design engineer must make quantitative measurements of magnetic emissions from the integrated circuit.

The author acknowledges the editing assistance of Sandra Muccioli.

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ABOUT THE AUTHOR

For information about the author, please refer to page 27.18.

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CHAPTER 29
NAVIGATION AIDS AND INTELLIGENT VEHICLE-HIGHWAY SYSTEMS*

Robert L. French
R. L. French & Associates

Autonomous navigation and route guidance systems with static databases are of considerable utility on a stand-alone basis. However, future versions will be linked to traffic management centers (TMC) by mobile data communications for maximum effectiveness. Automobile navigation technologies coupled with data communications also provide a basis for vehicle tracking and fleet management. These in-vehicle systems are viewed as a major subset of intelligent vehicle-highway systems (IVHS), a rapidly expanding worldwide movement to improve the efficiency, safety, and environmental aspects of road traffic through the application of information, communications, positioning, and control technologies.

29.1 BACKGROUND

Sophisticated vehicular navigation system concepts have become widely known only during the last decade. However, the historical roots of automobile navigation go much deeper.[1] The first vehicular navigation system was the "south-pointing chariot," a mechanical direction-keeping system developed by the Chinese around 200 to 300 A.D., almost 1000 years before the magnetic compass was invented. Its operation was based on the differential odometer phenomenon that, as a vehicle changes heading, the outer wheels travel further than the inner wheels by a distance that is a mathematical function of the change in heading.

Mechanical route guides for automobiles were introduced in the United States around 1910 to aid the drivers of early automobiles before roads were uniformly marked. These early devices incorporated the information of route maps in various forms including sequential instructions printed on a turntable, punched in a rotating disk, and printed on a moving tape, all driven by an odometer shaft in synchronization with distance traveled along the route.

For example, the 1910 Chadwick Road Guide rotated a metal disk in synchronization with distance traveled. The disk had holes spaced to coincide with decision points along the route

* As this book is going to press, the name "Intelligent Vehicle-Highway Systems" is being changed to "Intelligent Transportation Systems (ITS) in the United States.

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represented by the disk. An array of spring-loaded pins behind the slowly rotating disk was normally depressed, but when a punched hole traversed a pin, the pin released and raised a signal arm bearing a color-coded symbol indicating the action to be taken. In addition, a bell was sounded to draw the driver's attention to the signal.

The early mechanical route guidance systems faded out of the picture as roadside signs were standardized and became more plentiful by the 1920s. A resurgence of interest in route guidance occurred in the 1960s when ERGS (Electronic Route Guidance System) was researched by the U.S. Bureau of Public Roads.[2] Although ERGS was soon grounded from lack of Congressional support, it was followed in the 1970s by CACS (Comprehensive Automobile Control System) in Japan and by Autofahrer Leit-und Information System (ALI) in Germany.

Like ERGS, the CACS and ALI used real-time traffic information to compute best routes for downloading to on-board display equipment at strategically located proximity beacons. Thus, these early research and test projects, along with the evolution during the same era of advanced traffic management concepts for computerized control of area-wide traffic signals based on a centralized traffic database, set the stage for the much broader IVHS movements that started shaping up in Europe, Japan, and the United States in the mid-1980s.

Although comprehensive IVHS products and services, including data communication links between the traffic infrastructure and navigation-equipped vehicles, are not yet available, sophisticated autonomous navigation systems have been on the market in Japan since being introduced as a factory option by Toyota in 1987.[3] Approximately 500,000 had been sold by 1994, the year that OEM navigation systems were finally introduced in the United States and Europe.

29.2 AUTOMOBILE NAVIGATION TECHNOLOGIES

Positioning technologies are fundamental requirements of both vehicle navigation systems and vehicle tracking systems. Almost all vehicular navigation systems include dead reckoning with map matching as the main positioning technology, but most state-of-the-art systems also include a GPS (Global Positioning System) receiver now that the GPS satellite constellation is fully operational.

Map matching as well as route guidance must be supported by digital road maps. Another important supporting technology is mobile data communications for traffic and other traveler information. Although vehicle tracking systems may not require digital road maps aboard the vehicle (as is generally the case for navigation systems), they do require a mobile data communications link between the vehicle and dispatch office unless they use infrastructure-based integrated positioning and communications technologies. However, GPS and other radiopositioning technologies (e.g., Loran-C) are often used in conjunction with separate mobile communication systems for vehicle tracking.

29.2.1 Radiopositioning

Radiopositioning is the processing of special signals from one or more radio transmitters at known locations to determine the position of the receiving equipment. Although a number of radiopositioning technologies are potentially applicable, satellite-based GPS is by far the most popular.

GPS, which is operated by the U.S. Department of Defense, includes 24 satellites spaced in orbits such that a receiver can determine its position by simultaneously analyzing the travel time of signals from at least four satellites. GPS has the advantage of giving absolute position (albeit with an uncertainty of up to 100 m for civil receivers unless corrected by differential GPS). However, GPS alone is inadequate for automobile navigation because signal reception on roadways is sometimes blocked by buildings, foliage, etc. Nonetheless, GPS is very effective for automobile navigation when integrated with dead reckoning and map matching.

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Proximity beacons provide another form of radiopositioning which is used in some vehicle navigation systems, particularly those that also use proximity beacons for communications purposes. Proximity beacons are devices installed at key intersections and other strategic roadside locations that communicate their location and/or other information to receivers in passing vehicles via very short-range radio, microwave, or infrared signals. The reception of a proximity beacon signal means that the receiving vehicle is within 50 m or so of the beacon, and provides an occasional basis for confirming vehicle position.

29.2.2 Dead Reckoning

Dead reckoning, the process of calculating location by integrating measured increments of distance and direction of travel relative to a known location, is used in virtually all vehicle navigation systems. Dead reckoning gives a vehicle's coordinates (X_n, Y_n) relative to earlier coordinates (X_o, Y_o):

$$X_n = X_o + \sum_1^n \Delta X_i = X_o + \sum_1^n \Delta l_i \sin \phi_i$$

$$Y_n = Y_o + \sum_1^n \Delta Y_i = Y_o + \sum_1^n \Delta l_i \cos \phi_i$$

where ϕ_i is the heading associated with l_i, the ith measured increment of travel as illustrated in Fig. 29.1. Dead reckoning for vehicle navigation thus requires sensors for measuring distance traveled and heading (or change in heading).

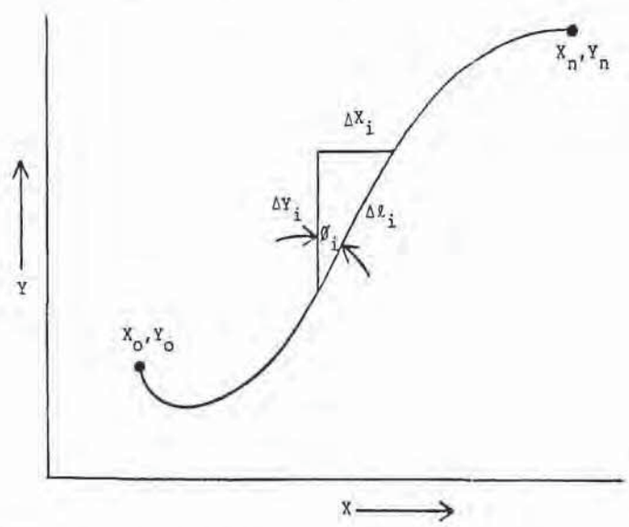


FIGURE 29.1 Dead-reckoning formulation.

Distance Sensors. Distance measurements for vehicle navigation systems are usually made with an electronic version of the odometer. Electronic odometers provide discrete signals from a rotating shaft or wheel, and a conversion factor is applied to obtain the incremental distance associated with each signal. Automobiles equipped with antilock braking systems (ABS) already have wheel sensors that may also serve as electronic odometers for navigation systems.

Odometers are subject to a number of error sources, some of which are systematic and may be corrected in the distance conversion process. The difference in the diameter of a new tire and a well-worn tire, for example, can contribute distance errors as high as 3 percent. The

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error in distance measurements increases by approximately 0.1 to 0.7 percent when vehicle speed is increased by 40 km/h due to the effect of centrifugal force on the tires, and a 10 psi change in tire pressure can induce an error of 0.25 to 1.1 percent.

Heading Sensors. Vehicle heading may be measured directly with a magnetic compass, or indirectly by keeping track of heading relative to an initial heading by accumulating incremental changes in heading. A number of alternative means are available for measuring vehicle heading or heading changes. However, most have at least one drawback. As a result, it is a common practice to use two different types of sensors in combination to offset one another's weaknesses.

The magnetic compass's well-known accuracy problems due to anomalies in the earth's magnetic field are compounded when installed in a vehicle by induced fields which depend upon vehicle heading. Nonetheless, some form of magnetic compass is used in most vehicular navigation systems. Compact solid state flux-gate compasses with software processes for compensating errors resulting from both permanent and induced magnetism of the vehicle are popular in current systems.

In many applications, both a flux-gate compass and a differential odometer or a gyroscopic device are used along with a software filtering process that combines the outputs. Higher relative weight is placed on the differential odometer or gyro output for short-term changes in heading and on the compass output for longer-term trends in absolute heading.

A differential odometer consists of a pair of odometers, one each for the wheels on opposite ends of an axle. When a vehicle changes heading by an amount Θ as illustrated in Fig. 29.2, the outer wheel travels farther than the inner wheel by ΔD, which may be expressed in terms of heading change and vehicle width:

$$\Delta D = D_R - D_L = \Theta(R_R - R_L) = \Theta W$$

Thus $\Theta = \Delta D/W$

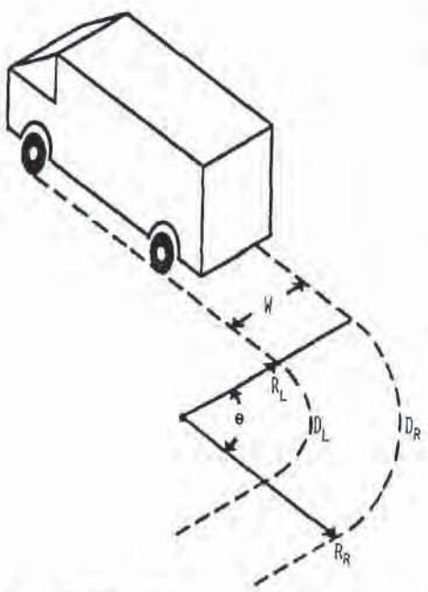


FIGURE 29.2 Differential odometer principle.

Several other types of heading-change sensors use some form of the gyroscopic principle. These range from traditional spinning devices and gas-jet sensors to vibrating bars and fiber optic gyros. Although more expensive than differential odometer sensors, they are much simpler to install. The fiber optic gyro started appearing in production automobile navigation systems in 1991. Finally, the more advanced forms of GPS receivers also support derivation of vehicle heading.

29.2.3 Digital Road Maps

Although a few route guidance systems use centrally located digital road map databases, the vast majority require an on-board database. The two basic approaches to digitizing maps are matrix encoding and vector encoding. A matrix-encoded map is essentially a digitized image in which each image element or pixel, as determined by an X-Y grid with arbitrary spacing, is defined by digital data-giving characteristics such as shade or color. In addition to requiring more data storage than vector encoding, matrix encoded maps are ill-suited for analytical treatment such as map matching or route finding.

The vector encoding approach applies mathematical modeling concepts to represent geometrical features such as roadways and boundaries in abstract form with a minimum of data.

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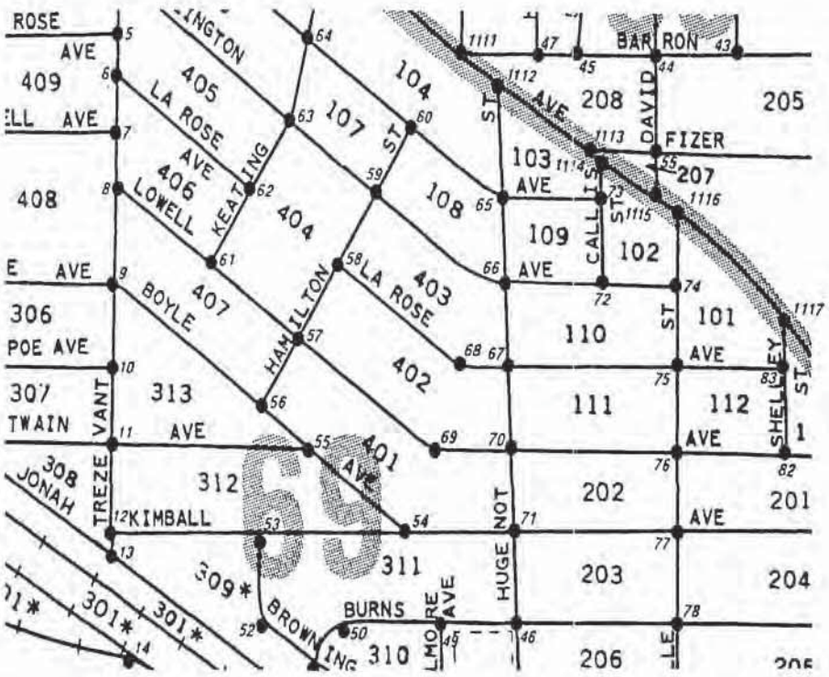


FIGURE 29.3 Nodes and street segments of vector encoded map.

By considering each road or street as a series of straight lines and each intersection as a node, a map may be viewed as a set of interrelated nodes, lines, and enclosed areas as illustrated by Fig. 29.3.

Nodes may be identified by their coordinates (e.g., latitude and longitude). Additional nodes "shape points" are positioned along curves where the link between two intersections is not a straight line. Curves are thus approximated by a series of vectors connecting shape points, whereas a single vector directly connects the node points representing successive intersections if there are no curves in the connecting road segment.

The X-Y coordinates of node points may be encoded from maps or aerial photographs. The classic approach uses special work stations which record the coordinates of a given point when the cross hair of an instrument is placed over the point and a button pressed. This process has been automated in varying degrees. In some cases, the printed map is scanned to obtain a matrix image, which is then converted to vector form by software.

Various combinations of attributes associated with the encoded road network are included in digital map databases. Of particular importance are roadway classifications, street names, and address ranges between nodes. Map databases used with systems that give turn-by-turn route guidance also require traffic attributes such as turn restrictions by time of day and delineation of one-way streets. Directory and yellow pages information for selecting attractions, parking, restaurants, hotels, emergency facilities, etc., are commonly included.

29.2.4 Map Matching

Map matching is a type of artificial intelligence process used in virtually all vehicle navigation and route guidance systems that recognize a vehicle's location by matching the pattern of its apparent path (as approximated by dead reckoning and/or radiopositioning) with the road patterns of digital maps stored in computer memory. Most map-matching software may be classified as either semideterministic or probabilistic.[4]

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Semideterministic. This approach assumes that the equipped vehicle is essentially confined to a defined route or road network, and is designed to determine where the vehicle is along a route or within the road network. The concept may be illustrated by tracking the location of a vehicle over the simple route shown in Fig. 29.4*a* which defines a route from node A through nodes B, C, D, E and thence back to A in terms of instantaneous direction (ϕ) of travel versus cumulative distance (L) from the beginning as shown in Fig. 29.4*b*. Locations of nodes where direction changes occur (or could occur) are thus defined in terms of distance *L*. The solid line gives heading versus distance corresponding to the simple route. Alternative routes emanating from each node are indicated by dashed lines.

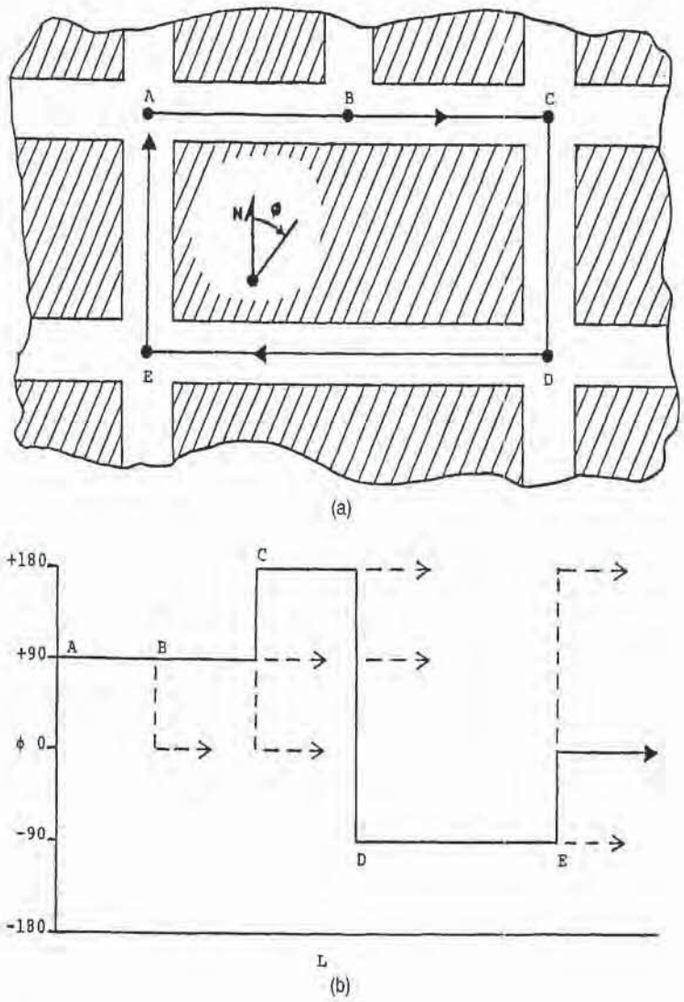


FIGURE 29.4 Simplified route and vector model.[4]

Figure 29.5 shows the kernel of a semideterministic algorithm in highly simplified form. Once initialized at a starting location ($\phi = 90°$ and $L = 0$ at Node A in the example), the algorithm, in effect, repeatedly asks, "Is the vehicle still on the route?" and "What is the present location along the route?" The vehicle is confirmed on the route if certain tests are satisfied. The location along the route is estimated by odometry, and error in the estimate is automatically removed at each node where it is determined that an expected change in heading actually occurs.

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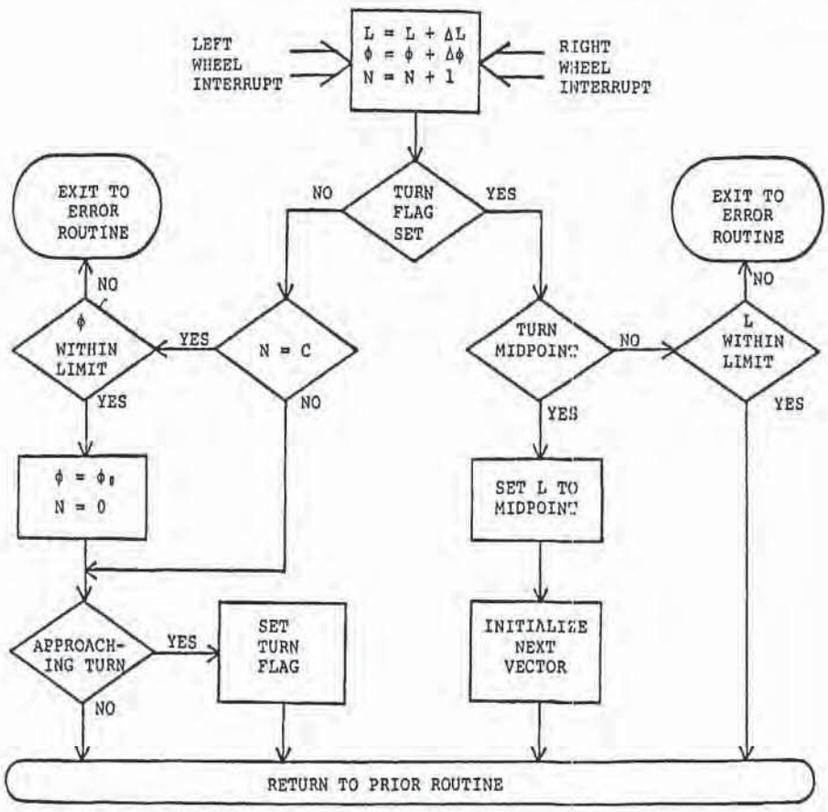


FIGURE 29.5 Simplified map-matching algorithm.[4]

The map-matching algorithm is driven by interrupts from differential odometer sensors installed on left and right wheels. The distance L from the beginning of a route segment is updated by adding an increment ΔL for each left wheel interrupt, and the vehicle heading ϕ is updated by adding an increment $\Delta\phi$ calculated from the difference in travel by the left and right wheels since the count N was last set to 0. As explained below, the N counter controls monitoring for unexpected heading changes occurring over relatively short distances.

Unless the turn flag is set to denote that the vehicle is approaching a distance L where a heading change should occur, count N is checked after each interrupt to determine if it has reached a limit C corresponding to an arbitrary amount of travel on the order of several meters. When the count limit C is reached, a test is made to determine if ϕ is within arbitrary limits (say ±5 degrees to allow for lane changes, slight road curvature, etc.). If so, ϕ is reset to ϕ_0 (the direction of the vector being traveled) and N is set to 0 to start another cycle of monitoring for unexpected heading changes.

In addition to verifying that the vehicle stays on the route between nodes, this process removes error in measured vehicle heading that accumulates while $0<N<C$. If the preceding test finds ϕ to be outside the limits, the vehicle is presumed to have turned off the route (perhaps into an unmapped driveway or parking lot) and other routines are called into play. For example, route recovery instructions could be issued.

When the vehicle approaches within an arbitrary distance (e.g., 75 m) of a node where a change in vehicle heading should occur, the turn flag is set and a route guidance instruction is issued, giving the direction of the turn and, if appropriate, the name of the next road. The algorithm then monitors for changes in ϕ to confirm that the midpoint of the expected turn is reached within an arbitrary limit (e.g., 10 m) of the value of L specified for the node, and afterwards to confirm that the turn is completed.

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Upon reaching the midpoint, the current value of L is adjusted to that specified, thus removing any error in the measured distance accumulated since the last turn. If the expected turn is not confirmed within the allowed limits on distance L, the vehicle is assumed to have missed the turn or to have taken an alternate turn (see dashed lines in Fig. 29.4*b*) and other routines may be called to identify the alternate route taken from the node.

The semideterministic algorithm concept outlined here may be extended to tracking a vehicle's location as it moves over arbitrary routes within a road network rather than following a preplanned route. As long as the vehicle stays on roadways defined by a vector-encoded digital map, the vehicle must exit each node via some vector. Thus, a map-matching algorithm can identify successive vectors traveled by measuring the direction of vehicle travel as it leaves each node and comparing the vehicle direction with that of various vectors emanating from the node.

Probabilistic. An enhanced type of map-matching algorithm is required for tracking vehicles not presumed to be constrained to the roads. When the vehicle departs from the defined route or road network (e.g., into a parking lot), or appears to depart as a result of dead-reckoning error, the routine repeatedly compares the vehicle's dead-reckoned coordinates with those of the links surrounding the off-road area which encompasses the vehicle location in order to recognize where the vehicle returns to the road network. Unlike while traveling on defined roadways, map-matching adjustments do not prevent accumulation of dead-reckoning error. Thus, depending upon the distance traveled off road and the accuracy of the dead-reckoning sensors, there may be considerable uncertainty in vehicle coordinates, which could produce misleading conclusions when tested against the surrounding links.

Probabilistic map-matching algorithms minimize the potential of off-road errors by maintaining a running estimate of uncertainty in dead-reckoned location, which is considered in determining whether the vehicle is on a street. The estimate of location uncertainty is reduced each time it is deemed that the vehicle is on a street, but the uncertainty resumes growth in proportion to further vehicle travel until the next match occurs. Thus, a probabilistic algorithm repeatedly asks, "Where is the vehicle?," with no a priori presumption that it is on a road.

29.3 EXAMPLES OF NAVIGATION SYSTEMS

Figure 29.6 is a block diagram showing the major elements of a typical automobile navigation system. Distance and heading (or heading change) sensors are almost invariably included for dead-reckoning calculations which, in combination with map matching, form the basic platform for keeping track of vehicle location. However, dead reckoning with map matching has the drawback of occasionally failing due to dead-reckoning anomalies, extensive travel off mapped roads, ferry crossings, etc.

The *location sensor* indicated by dashed lines in Fig. 29.6 is an optional means of providing absolute location to avoid occasional manual reinitialization when dead reckoning with map matching fails. Although proximity beacons serve to update vehicle location in a few systems (particularly those that also use proximity beacons for data communication), most state-of-the-art systems use GPS receivers instead.

The recent evolution and present trends of automobile navigation and route guidance systems are illustrated by the following examples.

29.3.1 Etak Navigator™/Bosch Travelpilot™

The Etak, Inc. Navigator™ introduced in California in the mid-1980s was the first commercially available automobile navigation system to include digitized road maps, dead reckoning with

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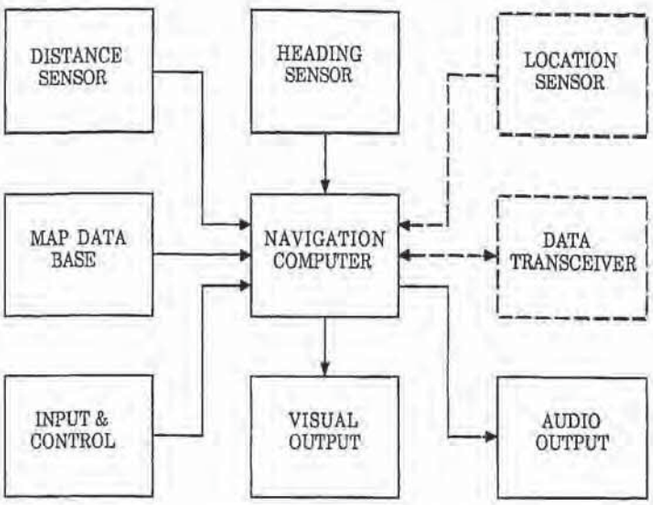


FIGURE 29.6 Typical components and subsystems of vehicle navigation system.

map matching, and an electronic map display. It used a flux-gate compass and differential odometer for dead reckoning. The equivalent of two printed city street maps were vector encoded and stored on 3.5-Mb digital cassettes for map matching and display purposes. Although sales were modest, the highly publicized Etak Navigator drew widespread attention to the concept of an electronic map display with icons showing current location and destination.

The Travelpilot, which is essentially a second generation of the Navigator, was jointly designed by Etak, Inc. and Bosch GmbH.[5] It was introduced in Germany in 1989 and in the United States two years later. One of the most conspicuous enhancements was the use of CD-ROM storage for digitized maps. The 640-Mb capacity permits the entire map of some countries to be stored on a single CD-ROM.

Like its predecessor, the Travelpilot displays a road map of the area around the vehicle, as illustrated by Fig. 29.7. The vehicle location and heading is indicated by the arrowhead icon below the center of the screen. The vertical bar at the right edge of the map indicates the dis-

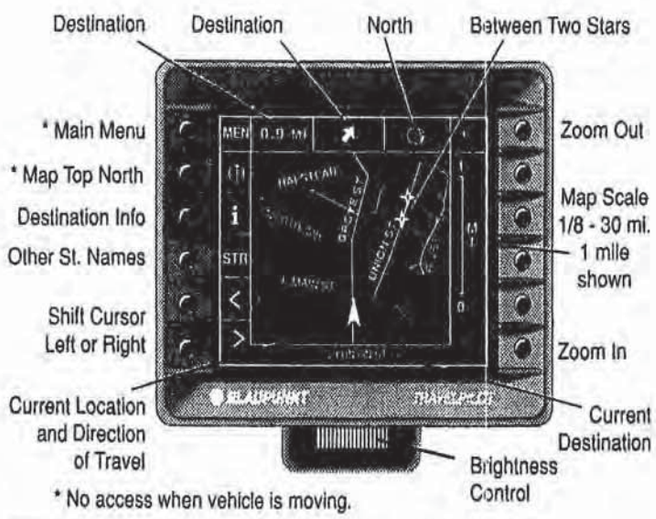


FIGURE 29.7 Bosch Travelpilot display and controls. (*Bosch literature*)

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play scale which can be zoomed in to ⅛ mile for complete street detail or out to 30 miles to show only major highways. The map is normally oriented such that the direction in which the vehicle is heading points straight up on the display, thus allowing the driver to easily relate the map display to the view outside.

When parked, a menu accessible through the MEN button permits use of soft-labeled buttons in a scrolling scheme to enter destinations by street address, intersection, etc. Travelpilot uses a process called *geocoding* to locate an input destination and display it as a flashing star on the map. As illustrated in Fig. 29.7, a destination geocoded by street address is bracketed by two flashing stars when the map is zoomed in. In this case, the stars mark the block whose address range includes the street number of the destination. A line of information across the top of the map display indicates the crow-flight distance and points the direction from the vehicle's current location to the destination. Up to 100 input destinations may be stored for future use.

A submenu provides several methods for the driver to reset the vehicle's position on the map if the Travelpilot gets off track. The frequency with which the system requires reinitializing depends upon dead-reckoning anomalies and the completeness and accuracy of the map data for the area being driven. For example, map matching typically fails once in a thousand miles when operating in an environment like greater Los Angeles or North Texas. As for location accuracy the rest of the time (i.e., with map-matching operative), Travelpilot is claimed to have infinitesimal error relative to the map. The map-matching performance is compared to that of a servo-amplifier in which map-matching failure corresponds to loosing servo-lock to the map.

The Travelpilot hardware includes a V50 processor, ½-Mb DRAM, 64-Kb EPROM, and 8 Kb of nonvolatile RAM for storing vehicle location while the ignition is off, calibration factors, up to 100 saved destinations, etc. The Travelpilot may interact with other devices through an RS-232 serial port and an expansion card slot. For example, Travelpilots in 400 Los Angeles fire trucks and ambulances are connected by digital packet radio to the city's emergency control center. The emergency operators can monitor each vehicle's location and status, and can send destinations directly to a vehicle's Travelpilot for emergency dispatch.

29.3.2 Toyota Electro-Multivision

The Toyota Electro-Multivision has undergone numerous refinements since it was introduced in 1987 as the first sophisticated navigation system available as a factory option on automobiles sold in Japan. Except for a few features, it is representative of the more comprehensive models of navigation systems now available in Japan from almost all of the major automobile and electronics manufacturers.

Many Electro-Multivision features may be summarized with reference to those of the Travelpilot previously described in more detail. Both use dead reckoning and digitized maps stored on CD-ROM for display on a CRT screen with an icon representing present position, and are generally similar in their basic navigation features. However, a raster-scan color CRT rather than a vector-drawn monochromatic CRT is used in the Electro-Multivision. Also unlike Travelpilot, the Electro-Multivision map database includes yellow pages information such as the locations of facilities likely to be of interest to motorists.

The Electro-Multivision also serves as a reference atlas. In the original version, for example, a display shows a color map of all Japan with 16 superimposed rectangles. Touching a particular rectangle causes the map area it encompasses to zoom and fill the entire screen, again with grid lines superimposed to form 16 rectangles. Thus, a few touches of the screen takes the driver from an overview of the entire country down to major roads and landmarks in some quarter of Tokyo.

However, in spite of Electro-Multivision's sophisticated map-handling capabilities, map matching was not used in the first version because the digital maps then available for Japan did not contain sufficient detail at the city street level. In addition to detailed digital maps and map matching, subsequent versions of Electro-Multivision include a GPS receiver and a color

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LCD rather than CRT display.[6] In 1991, a routing feature was added to calculate a suggested route to specified destinations and highlight the trace on the LCD map display. The most recent version[7] adds synthesized voice route guidance instructions.

As is the case for most other state-of-the-art navigation systems offered as factory-installed equipment in Japan, the Electro-Multivision navigation features are integrated with a full suite of entertainment features (e.g., AM-FM radio, tape cassette, audio CD player, color TV, etc.). In addition, the Electro-Multivision includes a CCD camera for rear vision on the LCD screen.

29.3.3 Oldsmobile Navigation/Information System

In January 1994, Oldsmobile announced its Navigation/Information System, the first navigation and route guidance system to be offered as a dealer-installed option from an automobile manufacturer in the United States. Initially sold only in California, the system was expected to be offered nationwide as digital map databases for other areas become available during 1994–1995.

The Oldsmobile system integrates a GPS receiver with dead reckoning and map matching. The dead-reckoning process uses gyroscopic and odometer inputs. A PCMCIA card is used for storing a map database which includes the locations of points of interest such as emergency services, restaurants, major retail stores, schools, office buildings, tourist attractions, etc. The major hardware modules of the system are shown in Fig. 29.8.

Destinations may be entered as specific street addresses or road intersections, or by selecting categories and scrolling through the points of interest included in the database. Routing criteria (e.g., avoiding expressways) may also be specified. The navigation computer then calculates the route and highlights it on a 4-in active matrix color LCD. Once underway, the distance to and direction of each turn is displayed on the screen and a voice prompt advises the driver as each turn is approached. A representative route guidance screen is shown in Fig. 29.9.

The Oldsmobile Navigation/Information system is supplied by Zexel USA Corp. and is an adaptation of Zexel's NAVMATE system which has been under development for several years specifically for the U.S. market.

29.3.4 TravTek Driver Information System

Whereas these examples of automobile navigation systems are already available in certain markets, TravTek was a functional prototype of a navigation-based in-vehicle traveler information system developed specifically for the TravTek IVHS operational field trial conducted for a one-year period ending in 1993 in Orlando, Florida. The field trial was a joint public sector-private sector project with the primary objective of obtaining field data on the acceptance and use by drivers of navigation and other information provided by comprehensive in-vehicle systems linked with traffic operations and other data centers.

The TravTek project used 100 General Motors automobiles equipped with the system shown schematically in Fig. 29.10 to provide navigation, route selection and guidance, real-time traffic information, local yellow pages and tourist information, and cellular phone service.[8] Most of the automobiles were made available to Orlando visitors through Avis Rent A Car for short-term trials and the rest were assigned to local drivers for extended periods. The American Automobile Association selected the test subjects and operated a TravTek Information and Services Center which could be accessed via cellular telephone.

TravTek navigation is based on a combination of dead reckoning and map matching, with a GPS receiver playing a "watchdog" role. TravTek's navigation function superimposes vehicle location on a map display screen, highlights suggested routes on the color CRT map display, and issues route guidance instructions via synthesized voice. Alternatively, turn-by-turn route guidance instructions may be displayed in the form of simplified graphics.

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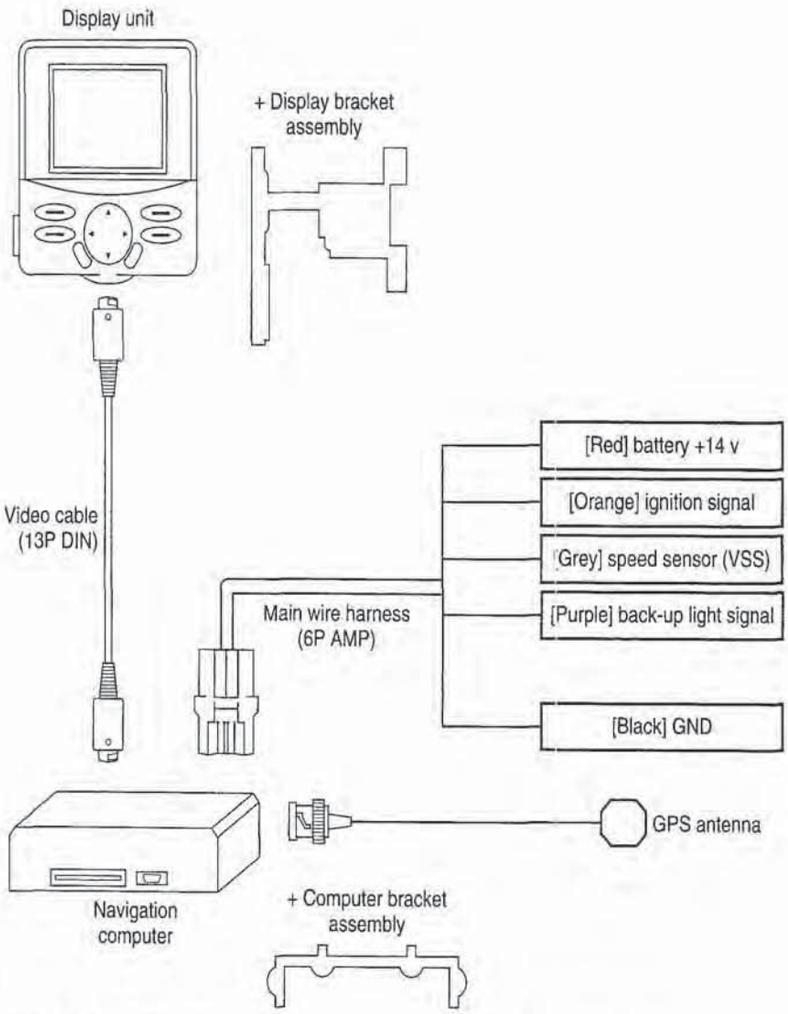


FIGURE 29.8 Oldsmobile Navigation/Information System hardware. (*Oldsmobile*)



FIGURE 29.9 Oldsmobile Navigation/Information System route guidance screen. (*Oldsmobile*)

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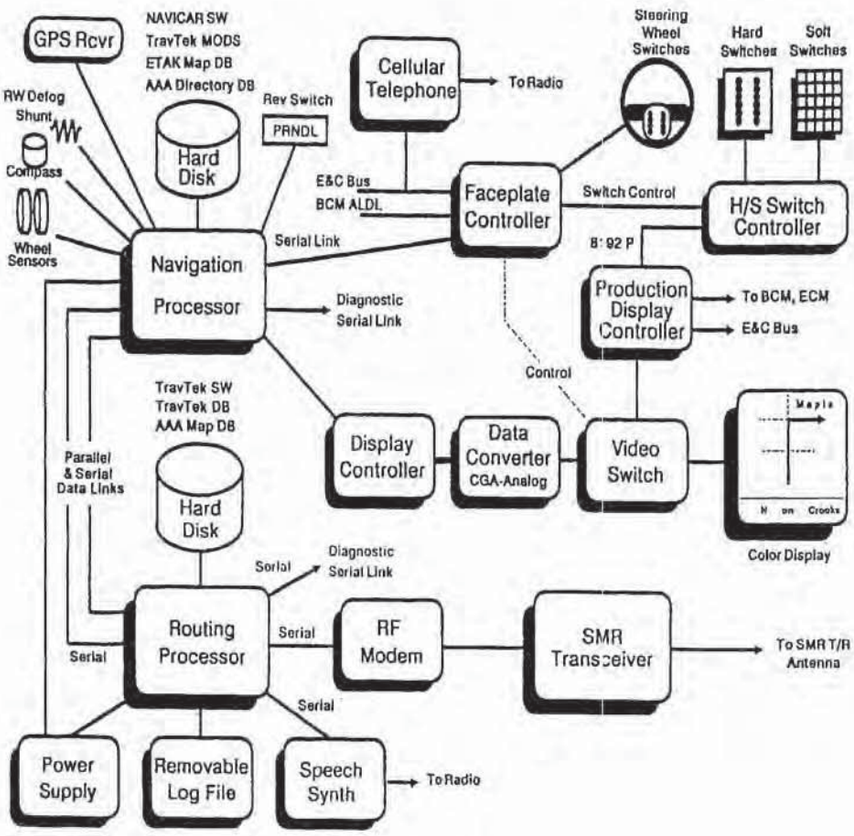


FIGURE 29.10 Architecture of TravTek vehicle system.[8]

Although functionally realistic, the TravTek in-vehicle system design used some features that would not typically appear in a production system. For example, rather than consolidated databases stored on a single CD-ROM or other data storage device, TravTek used separate map databases stored on separate hard disk drives for navigation processing and route guidance processing.[9]

However, compared to these examples of commercially available navigation and route guidance systems, TravTek's most distinct difference was the capability to superimpose information on current traffic conditions on the map display and to take traffic congestion levels into account in calculating recommended routes. The traffic information was received over a radio link from a special Traffic Management Center (TMC) operated by the City of Orlando in conjunction with the Federal Highway Administration and the Florida Department of Transportation. The TMC consolidated traffic data from various sources including "probe" data consisting of road segment travel times received via mobile radio from the TravTek vehicles themselves.

29.4 OTHER IVHS SYSTEMS AND SERVICES

A central aspect of IVHS (Intelligent Vehicle-Highway Systems) is the operation of advanced traffic management systems (e.g., the TravTek TMC outlined here) in conjunction with automobile navigation and route guidance systems. This requires the use of mobile data commu-

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nication links between the infrastructure and in-vehicle systems. Although the United States, Europe, Japan, and other developed countries are now systematically pursuing IVHS development, selection of mobile data communication approaches remains under consideration as this handbook is prepared. However, it is generally expected that one or more of the approaches characterized in Table 29.1 will be selected for most geographical areas.

TABLE 29.1 Characteristics of Alternative Mobile Data Communication Approaches

Approach	Characteristics
FM sideband	One-way Low data rates Extended area coverage
Proximity beacon	One-way or two-way High data rates Spot area coverage
Inductive loop	One-way or two-way Low data rates Spot area coverage
Land mobile	Two-way Local area coverage
Specialized mobile radio	Two-way Extended area coverage
Cellular radio	Two-way Local/extended area coverage
Mobile satellite	One-way or two-way Wide area coverage
Meteor burst	Two-way Wide area coverage Involves time delays

The vast scope of IVHS is made easier to comprehend by subdivision into several interrelated and overlapping categories that have been used to structure the IVHS program in the United States: Advanced Traffic Management Systems (ATMS), Advanced Traveler Information Systems (ATIS), Advanced Vehicle Control Systems (AVCS), Commercial Vehicle Operations (CVO), Advanced Public Transportation Systems (APTS), and Advanced Rural Transportation Systems (ARTS).

29.4.1 Advanced Traffic Management Systems (ATMS)

ATMS includes freeway surveillance and incident detection, changeable message signs, electronic toll collection, and coordination of traffic signal timing over wide areas in response to real-time traffic conditions. Major elements of ATMS have been around for decades. The first computerized traffic signal control systems were developed in the 1960s, and approximately 200 computerized traffic signal control systems were in use in North America by the end of the 1980s. About 25 major freeway surveillance and control systems were in use, including many dating from the 1960s and 1970s. Electronic toll collection did not start experiencing significant implementation until the 1990s.

An additional ATMS function is to supply real-time traffic information (e.g., link travel times) over mobile data communication links to ATIS. The final selection of one or more communication links is unsettled because, among other things, their requirements (e.g., data rates) are highly dependent upon system architecture and the division of functions between infrastructure and in-vehicle equipment.

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29.4.2 Advanced Traveler Information Systems (ATIS)

ATIS systems acquire, analyze, communicate, and present information to assist surface transportation travelers in moving from one location to another. Initially called ADIS (Advanced Driver Information Systems) by Mobility 2000 and essentially limited to navigation, route guidance, and traffic information presented by in-vehicle systems, ATIS concepts now also encompass the provision of transit schedules and connections to home, office, kiosk and handheld PPATIS (Portable ATIS) units as well as in-vehicle units. Vision enhancement devices for drivers also fall under the ATIS category.

Although PPATIS concepts are proliferating, most early ATIS market activity is expected to be what was originally called ADIS and will be centered on in-vehicle navigation and route guidance systems. A 1991 Delphi study by the University of Michigan forecasts some form of navigation incorporating GPS will be used in 5 percent of all vehicles sold annually by 2000 and in 50 percent by 2012. IVHS strategic planning assumes that manufacturers will sell 2.5 million vehicles annually with factory-installed ATIS by the year 2000.

The potential of the ATIS market is also illustrated by the fact that approximately 500,000 sophisticated automobile navigation systems had already been sold (mostly as factory options) in Japan by the end of 1993, even though they must operate autonomously because mobile communication links to ATMS traffic operations centers for enabling dynamic route adjustment according to traffic conditions have thus far been limited to developmental tests.

29.4.3 Advanced Vehicle Control Systems (AVCS)

Whereas ATIS assists drivers by providing information to facilitate efficient and safe operation, AVCS provides direct assistance with vehicle control. An existing example is ABS (antilock braking system). Other early forms of AVCS include obstacle detection and warning systems and intelligent cruise control. Intelligent cruise control automatically adjusts speed according to distance and speed of the vehicle being followed, and enables platooning concepts wherein closely spaced vehicles travel in groups to increase lane capacity and safety. AVCS may ultimately lead to fully automated chauffeuring.

Most of the more advanced forms of AVCS such as automatic lane keeping (lateral steering control) are still in the laboratory stage. Although driver warning, perception enhancement, and assistance/control systems are under active research and testing in the United States, Europe, and Japan, the most comprehensive demonstrations to date have been accomplished under Europe's PROMETHEUS program.

29.4.4 Commercial Vehicle Operations (CVO)

In addition to benefiting from ATMS, ATIS, and AVCS functions, commercial vehicle operations may be made more productive through additional IVHS functions. These include automatic vehicle location monitoring, computerized dispatch and fleet management systems for dynamic scheduling and routing, weigh-in-motion (WIM), automatic vehicle classification (AVC), automatic vehicle identification (AVI), on-board data acquisition computers, etc.

The earliest CVO applications were for managing critical urban fleets (e.g., police vehicles starting in the 1970s). However, extensive application of communication and location reporting schemes to long-distance trucking fleets got underway in the 1980s. Much of the present CVO activities (e.g., AVI, AVC, WIM) focus on this application with the objective of eliminating stops and regulatory paperwork now required when traveling from state to state.

29.4.5 Advanced Public Transportation Systems (APTS)

APTS encompasses some forms of CVO (e.g., automatic vehicle location reporting), as well as additional functions such as schedule monitoring for transit buses. APTS also includes

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HOV (high-occupancy vehicle) lanes and instant car-pooling services. Although AVL implementation for transit buses was limited until the present generation of GPS-based systems started becoming available, extensive research and trials were conducted during the 1970s under auspices of the Urban Mass Transit Administration (recently renamed Federal Transit Administration). The use of AVL and communications technologies to monitor, control, and manage public transit continues to be a central thrust of APTS.

New APTS thrusts include making timely and accurate information on traffic conditions and on transit and ride-sharing alternatives readily available to travelers (especially commuters who normally drive alone) for pretrip planning. Another is to improve the customer interface through the use of integrated electronic fare systems such as smart cards valid for all transportation modes, and through the provision of real-time transit service information at homes, offices, and public places as well as at stops, aboard vehicles, etc. APTS also includes systems for controlling HOV access and enforcing proper usage.

29.4.6 Advanced Rural Transportation Systems (ARTS)

ARTS has the greatest overlap with other segments of the IVHS industry in that few, if any, additional functions or technologies are required. Instead, safety dominates rural IVHS planning with emphasis on in-vehicle safety advisory and warning systems, prevention of single-vehicle off-road accidents, prevention of passing accidents, warnings of animals on or near the roadway, vision enhancement, and Mayday calls from stranded vehicles. Although virtually all of these may evolve under other IVHS segments, ARTS communications considerations differ significantly from those of urban areas because lower population densities and fewer roads combined with greater distances among facilities require greater dependence upon wide-area communications.

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CHAPTER 30
ELECTRIC AND HYBRID VEHICLES

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Electric Transportation Application

30.1 INTRODUCTION

Electric vehicle (EV) technology is under rapid development. Several different types of experimental vehicles are in operation in the United States and elsewhere. Each vehicle uses different technologies and systems. Most are converted from standard internal combustion engine vehicles (ICEV). Because EV technology is still in its infancy, trends and future development cannot be assessed. Only the present status and a possible outlook can be identified.

This chapter will present a description of the current technology available in EVs today and identify the areas where technological breakthroughs will be required to produce EVs that can successfully compete with the ICEV.

30.1.1 History of the EV

Electric vehicle development preceded the development of cars with internal combustion engines (ICE). Thomas Davenport built the first battery-powered car in the United States in 1835.[1] Easy control and starting of electric motors and a lack of gas stations promoted the use of battery-powered cars. However, fast development of the internal combustion engine and discovery of the electric starter motor halted development of EV technology. The use of electric vehicles was restricted to a small number of local delivery trucks and cars. An example is the U.S. Postal Service which used battery-powered trucks for mail delivery in New York City for several decades.

Increasing air pollution in the late 1960s prompted the development of experimental electric vehicles. But the automobile industry significantly reduced vehicular emissions, which again halted EV development. In the early 1970s, a gasoline shortage following the Arab oil embargos renewed interest in electric vehicles, but generated only a few inadequate vehicles.

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The major problem with these EVs was their relatively small operating radius (traditional fuels have about a 20 times greater energy density than batteries).

Increased industry interest occurred recently when the California Air Resource Board (CARB) mandated that in California two percent of all new vehicles lighter than 1700 kg must produce zero tailpipe emissions by 1998.[2] The proportion of zero-emission vehicles must increase to five percent by 2001 and 10 percent by 2003. Other states in the Northeast are considering adopting similar regulations to improve air quality. Presently, electric vehicles are the only commercially feasible zero-emission vehicles.[3] This mandatory reduction of air pollution has promoted vigorous research programs in both the United States and abroad.[4] All major automobile manufacturers started programs in the late 1980s to manufacture viable electric vehicles by 1998.

30.1.2 Electric Vehicle Performance

The main focus of EV developmental programs is to produce cars that are competitive with present-day ICEVs. In order to demonstrate the present state-of-the-art technology, Table 30.1 shows the performance of the Solectria E-10 pickup trucks. The United States-made Solectria E-10 (Solectria Co., Arlington, Mass.) is commercially available and is typical of EVs on the market today, which allows for a direct comparison to ICE-powered pickup trucks.

TABLE 30.1 Performance Rating of the Solectria E-10 Pickup Truck

Performance parameter	Rating
System power	42 kW
Horsepower	56 HP
Torque	73 ft-lb
Gradeability	18%
Acceleration, 0–50 km/h	9 s
Top speed	100 km/h
Efficiency at 75 km/h	240 Wh/m
Curb weight	1680 kg
Range at 80 km/h	130 km
Payload (2 passengers +)	90 kg

The Solectria E-10 is powered by an ac induction motor with a direct-drive automatic transmission and a regenerative braking system. It has power-assisted brakes, power steering, an electric heater, and an on-board 2-kW 110-V battery charger. Typical ICEV pickup trucks have a range of 550 to 750 km and a top speed of 150+ km/h. The Solectria E-10 is a well-designed EV but with a top speed of 100 km/h and a range of 130 km, it does not compare very well to the ICEV pickup trucks.

A review of different electric vehicles has led to the assessment that present day EV performance is less than that of ICEVs. To demonstrate the status of EVs, major performance parameters are compared.

Range. The major limitation of EV performance is the small operating range. An average ICEV travels 750 to 1100 km on a tank full of gas and refueling requires 5 to 10 minutes. The range of present-day electric vehicles is less than 150 km and the "refueling" (battery-charging) time is measured in hours. Statistical surveys indicate that the average car travels less than 50 km a day, which is well within the operating range of present-day EVs. The short range is due to the low energy density in the batteries. The specific energy density in a lead-acid battery varies between 30 and 35 Wh/kg, which is significantly less than the 12,000 Wh/kg energy density of standard automotive fuel. The practical operating range depends on the speed, driving pattern, weather (temperature), and battery condition (age).

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Weight. Because of the low energy density, electric cars are heavier than similar gas-powered vehicles. The specific weight of a small electric car is around 20 W/kg.

Speed. The operating speed and acceleration of the EV is somewhat lower than today's ICEVs. This is particularly valid for highway driving. Although electric racing cars can run over 200 km/h for a short length of time, manufacturers normally limit the maximum speed of the electric vehicle to around 120 km/h. In general, the EV is well suited for city driving.

Acceleration. Starting acceleration of today's EVs is comparable to that of ICEVs. However, acceleration of the EV at high speeds (from 110 km/h) and hill-climbing ability is significantly less than the present-day ICEVs.[4] A lack of high-end acceleration may produce safety problems during highway driving.

Cost. Because of the low energy density in the batteries, lightweight construction and high efficiency will be required by the EV. To achieve high efficiency, the EV must have a low rolling resistance, low coefficient of drag (aerodynamic), and have a high efficiency air conditioning/heating unit. Simultaneously, the vehicle must be crashworthy. Most EVs use a large number of expensive power electronic components and microprocessors. Consequently, the initial cost of an EV is significantly higher than that of a gas-powered vehicle.

Expected operational costs of an EV should be less than a comparable ICEV. General Motors Corporation's Storm ICEV, with manual transmission, drives approximately 50 km on $1 worth of gasoline. The comparable General Motors Impact EV drives approximately 120 km on $1 worth of electricity, assuming the cost of electricity to be $0.12/kWh.[2]

Maintenance and Lifetime. Wear of the EV's electric components is significantly less than the wear on the ICEV that is operating at high temperatures, is liquid cooled, and has many more moving parts. Therefore, maintenance requirements for the EV are significantly less and the useful lifetime of an electric vehicle is significantly longer than the ICEV. The only component that requires high maintenance and has a short life span is the battery. Currently, the lifetime of lead-acid batteries is only a few years. This led to the proposal that the batteries should be considered as a part of the operating expenses. Roadside service may charge the battery pack instead of quick charging.

In order to assess the status and feasibility of commercial use of electrical vehicles, Table 30.2 gives typical performance and technical data for electric vehicles currently under development.

30.1.3 Motivation to Use Electric Vehicles

Zero emissions of the EV is the main motivation for considering its use. Air pollution produced by ICEVs in large cities have reached critical levels. These levels can be decreased by reduction of emissions from internal combustion engines. Switching to electric-powered vehicles will reduce pollution levels but will increase the consumption of electricity, thereby increasing the air pollution produced by electric power generation. Considering only vehicle and power plant pollution, a switch to electric vehicles would practically eliminate carbon monoxide, ozone, and volatile organic compounds from the air. Carbon dioxide levels would be halved and nitrogen oxide levels would be cut by 20 to 25 percent, but sulfur dioxide levels would increase. Sulfur dioxide is a byproduct of coal-fired power plants. It is hoped that by the late 1990s, power plants will install equipment to reduce nitrogen oxide and sulfur dioxide emissions, which will reduce acid rain.

A second motivation for EV use would be in a reduction of dependency on imported oil. Only four percent of the electric energy generated in the United States uses petroleum-based fuels, while fuels for ICEVs are exclusively based on petroleum. A third advantage is that most electric cars will be charged at night during off-peak hours. This increases utilization of

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TABLE 30.2 Selected Technical Data for Electric Vehicles.[2]

Vehicle	Developers	Type	Status	Battery	Range, km	Top speed, km/h	Comments
BMW E1/E2	BMW AG (Germany); Unique Mobility (U.S.)	4-passenger car	Concept; no production plans announced	Sodium/sulfur	240	120 (E1)	E1 uses a 32-kW permanent magnet dc motor
Ecostar	Ford Motor Co. (U.S.)	Minivan based on Ford's European Escort	80–100 were produced in 1993 and leased for 30 months	Sodium/sulfur	160	120 (governed)	Uses a three-phase, 56-kW ac induction motor integrated into front transaxle
Fiat Panda Elettra	Fiat SpA (Italy)	Passenger car	Production run of 500 planned	Lead/acid Nickel/cadmium	80 104 (city driving)	113	Uses a 9.2-kW series dc motor
GM Impact	GM, Aero-Vironment Inc. (U.S.)	2-seater sub-compact sports car	Commercial production in mid-1990s	Lead/acid	190 (at 90 km/h)	120 (governed)	Uses two 43-kW ac induction motors
G-Van	EPRI, General Motors Corp. (U.S.); Conceptor Industries Inc. (Canada)	Passenger/cargo van based on GM Vandura glider	About 100 in service in commercial fleets—mostly utilities	Lead/acid	96 (city driving)	83	Uses a 43-kW dc motor
LA 301	LADWP, SCE, Clean Air Transport (U.S.)	2-passenger, series hybrid car	Commercial production projected for 1993	Lead/acid Sodium/sulfur	96 154	97	Hybrid version with sodium/sulfur battery battery and auxiliary ICE has range of 240 km
Mercedes-Benz 190EV	Mercedes-Benz AG (Germany)	5-passenger, 4-door car	Research car	Sodium/nickel chloride	150	120	Uses two external-rotor dc motors
Nissan FEV	Nissan Motor Co. (Japan)	Passenger car	Concept; no production plans announced	Nickel/cadmium	160 at 72 km/h	120	Can accept a 40% charge in 6 min; has solar cells in roof to augment battery
Renault Zoom	Renault (France); Matra SA (France)	2-passenger car	Concept; production version under development	Nickel/cadmium	150	120	Wheelbase shortens from 1845–1245 mm for parking
Tepco Iza	Tokyo Electric Power Co. (Japan)	4-passenger car	Concept car; only one built	Nickel/cadmium	550 at 40 km/h	176	Has 25-kw brushless dc motor inside each wheel
TEVan	EPRI, Chrysler Corp., SCE (U.S.)	Passenger/cargo minivan based on Chrysler minivan glider	About 50 were produced in 1993	Nickel/iron	180	105	Uses a 46-kW dc motor
Volkswagen CityStromer	Volkswagen AG (Germany)	Passenger car	70 vehicles using lead/acid battery built and sold	Lead/acid Sodium/sulfur	140 120	104	Based on Jetta production vehicle

EPRI = Electric Power Research Institute; ICE = internal combustion engine; LADWP = Los Angeles Department of Water and Power; SCE = Southern California Edison Co.

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existing power plants and reduces energy costs. Utilities intend to offer lower rates to charge vehicles during off-peak hours and penalties to those charging during peak hours. The United States government is considering tax credits to EV users, which will partially offset the higher purchase costs.

30.2 SYSTEM DESCRIPTION

An electric drive system has been used in almost every transportation application that ICEV has used, including light cars and vans to large city buses. Most EVs use the body and mechanical parts of commercially available ICEVs. Two examples are Ford Motor Company's Ecostar van and the Mercedes-Benz 190E sedan. General Motors' Impact sports coupe is one of the few EVs that has been specially designed as an EV. Figure 30.1 shows a block diagram and the major components of a typical EV.

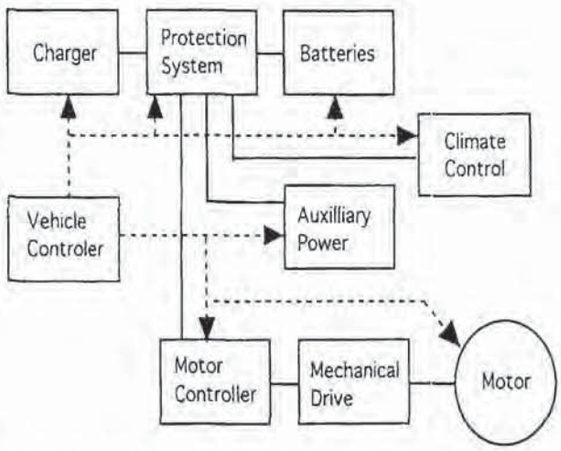


FIGURE 30.1 System-block diagram of a typical electric vehicle (EV).

The major components are:

1. *Charger.* It rectifies the ac network voltage for charging of the batteries.
2. *Protection system.* It consists of circuit breakers, relays, and fuses that are connected between the batteries and the rest of the electrical system and interrupt the supply in case of a fault.
3. *Motor.* EVs use both ac and dc motors.
4. *Motor controller.* This system controls the drive motor speed and torque. Both ac and dc drives are used.
5. *Mechanical drive system.* It consists of the transmission, differential, power steering, and so forth.
6. *Vehicle controller.* Most advanced EVs use a microprocessor-based controller that monitors the status of each of the major components and initiates control or protection actions as needed.
7. *Batteries.* The battery pack provides energy for the vehicle propulsion.
8. *Climate control system.* This system includes efficient air conditioning and heating systems.
9. *Auxiliary power.* It supplies the headlights, instrumentation, door opener, auxiliary motors (e.g., for the sunroof), power steering, etc.

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The location of the major components depends upon vehicle type and construction. Several different arrangements are used by the EVs currently available.

EV technology is being developed at a fast pace. Several new types of vehicles are currently being tested. In some vehicles, the major components identified in Fig. 30.1 are combined. Some of the components, such as the protection system and auxiliary supply system, are similar to those used on standard ICEVs.

30.3 CHARGER AND PROTECTION SYSTEM

EVs can be charged overnight during off-peak hours or at a roadside station. The overnight slow charging takes 8 to 10 hours using a 240-V, 30-A connection. Quick charging requires several hundred amperes and takes 15 to 30 minutes. Today's EVs are equipped with slow chargers.

30.3.1 Chargers

The charger on an electric vehicle consists of a rectifier that converts the 240-V ac to the proper dc level required for charging. In most cases, this rectifier is mounted on the vehicle. However, it was proposed that the rectifier be installed in the charging station, where an advanced computer control would determine the charging voltage and the battery charge level. Subsequently, the computer will adjust the charging voltage to assure efficient and fast charging of the batteries.

The most simple technical solution is to use phase controlled rectifiers which control the charging rate by the delay of the device turn on. Figure 30.2 shows the connection diagram and typical voltage and current waveforms of a single-phase thyristor-controlled battery charger. Variance of the delay angle changes the average dc voltage and the charging current.

In some vehicles, the battery-charging circuit performs a dual role and is used to control motor current while the vehicle is being driven. The Ford Ecostar minivan uses this concept of a combined charger and drive controller. It can be built with high-power transistors, MOSFETs, or insulated gate bipolar transistors (IGBTs). The circuit shown in Fig. 30.2 can be used as an inverter to drive ac motors or as a chopper to drive dc motors. A switching circuit is required to change from the charging mode to the drive (discharging) mode.

The connection between the vehicle and the charging station is currently under development. Two different systems have been proposed.[5] The first would use the transformer principle in which the ac system is connected to the vehicle charger through an inductive coupling, a transformer with two isolated coils. The coils are coupled with an iron core. The major advantage of this system is that the vehicle is not connected galvanically to the electrical network. This reduces the danger of touching energized parts or electrical accidents caused by ground faults. The separation of the vehicle from the network permits supplying of the inductive coupling from a higher voltage (480-V) three-phase system. This allows larger loads and suggests the use of the inductive coupling for quick-charging stations.

The second system connects the charging station to the vehicle charger through a metal plug similar to that used in outdoor appliances. Several different plug configurations are under development. The major requirements are that the plug has to be waterproof and touchproof, it has to withstand abuse and resist vandalism, it has to be energized only after it is connected to the vehicle charger, and damage of the plug should activate a protection system which would prevent energization.

30.3.2 Protection System

The battery and the electronic circuits must be protected against faults and short circuits. A short circuit in the car electric system discharges the battery. During a fault, the energy stored in the battery is converted to heat which can melt wires in the vehicle's electric system. Also,

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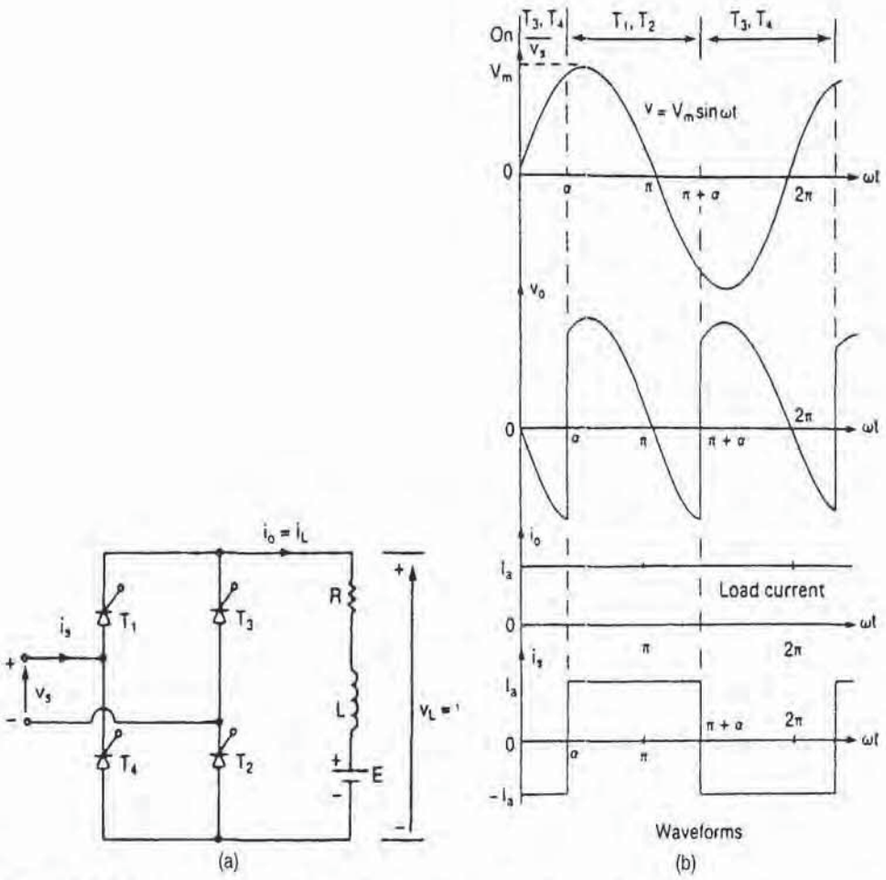


FIGURE 30.2 Thyristor-controlled battery charger: (*a*) connection diagram; (*b*) current and voltage waveforms.

a short circuit in a dc system may produce a large electric arc. Both the sudden heat generation and arcing endanger the life of the driver and passengers. Another problem is that the battery voltage in most EVs is between 100 and 200 V. In adverse conditions such as wet weather, this voltage level could cause electrocution.

Recognizing these problems, the manufacturers build electric vehicles with an ungrounded floating electrical system. The metal parts of the car's body are insulated from the electrical system and the tires insulate the car's body from the ground. In such a system, the first insulation fault between the electric system and the body will not produce battery discharge current. However, the second fault will short circuit the battery and endanger the operator. A possible fault scenario is a leakage path created by the conducting deposits produced by acid discharge from the battery. This conducting path can connect one terminal of the battery to the body, which is the first fault. Cable friction against body parts could cut the insulation, which may connect the conductor to the body of the vehicle and produces the second fault. This second fault will generate a short circuit. Figure 30.3 shows a schematic of the electric circuit and the current paths produced by the faults.

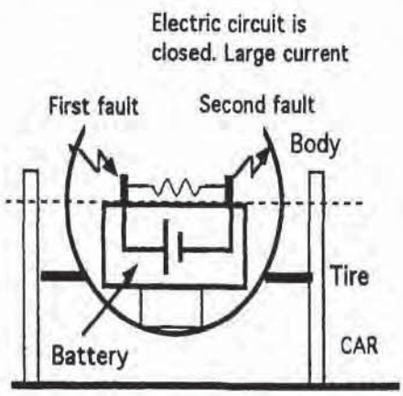


FIGURE 30.3 Effect of insulation faults in an EV.

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Detection of the first insulation fault is very important. This may be achieved by a sensitive ground-fault protection circuit, which is similar to that used in bathrooms and kitchens in United States homes.

The second fault produces a short circuit which must be interrupted within milliseconds to prevent battery discharge. Fast-acting magnetic or electronic circuit breakers and/or fuses can provide adequate protection.

The operation of EVs in adverse conditions—snow, mud, and long inclines—may produce overloading of the electrical drive circuit and overheat the battery, motor, or cables. Overheating also reduces the life span of the insulation. The electronic drives have built-in overload protection but backup protection in the form of circuit breakers or fuses will prevent costly damage from fault conditions.

The electrical circuit backup protection used in most EVs consists of devices which are similar to those used in standard ICEVs. In addition to the breakers and fuses, microprocessor-based vehicle controllers are equipped with protection circuits, which provide primary protection by turning off systems which are affected by the fault.

The EV requires interlocks to assure safe operation.[4] The interlocks can be software-programmable in the vehicle control system or can be of the mechanical or relay type. Some of the frequently used interlocks are:

- *Charger interlock.* Prevents the starting/driving of the vehicle when the charger is plugged in; disables the electric drive circuit while the charger is plugged in or operating.
- *Heater/air conditioner interlock.* Disables the climate control system or switches it to the charger while the vehicle is being charged.

30.4 MOTOR DRIVE SYSTEM

The first electric vehicles used standard ac or dc motors but the required high efficiency and torque led to the development of special motors.

30.4.1 Motors

Important factors in choosing motors for EV applications include high efficiency, favorable torque characteristics, maintenance-free operation, and insensitivity to overload and contamination. Cost is also a major factor in motor selection.

AC Motors. EVs which use an ac drive system use a three-phase induction motor which has a three-phase stator winding and squirrel cage rotor consisting of copper or aluminum bars installed in the slots of the iron core. The bars are short circuited at each end by a copper or aluminum ring.

Variable-frequency three-phase voltages supply the stator. The three-phase currents produce a rotating magnetic field which induces a current in the short-circuited rotor bars. The interaction between the rotor current and the magnetic flux produces the driving torque. Speed of the rotating magnetic field is determined by the frequency of the supply voltage and the motor construction. The rotor speed is always a few percent less than the speed of the magnetic field because the voltage induced in the rotor becomes zero if the motor and magnetic field speeds are equal.

Because of the squirrel cage rotor, these motors need very little maintenance. The sealed construction protects against spraying water and road mud. Motor efficiency varies with speed. As an example, a 7-kW motor has a maximum efficiency of 97 percent at 6000 rpm and 82 percent at 1500 rpm. The maximum speed of the same motor is around 15,000 rpm. The

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motor torque can be varied by reconfiguring the stator winding connections. The stator is delta-connected when the vehicle is at highway speed. The connection is switched to wye when a large amount of torque is needed for hill climbing or acceleration. The commercially available mechanical delta-wye switch can operate as a high-to-low gear shift.

DC Motors. EVs which have dc drive systems use series dc motors that have excellent speed-torque characteristics. Motor speed is proportional to the supply voltage, which simplifies the control circuit. The dc motors are less efficient than induction motors and the dc motor construction is more complicated because of the commutator. It requires regular maintenance and is sensitive to speeding and overloads. The dc motor maximum speed is less than the similarly rated induction motor. DC motors in an electric vehicle require a multispeed mechanical transmission.

The stator of a dc motor has poles with field windings. In a simple case, the rotor coils are connected in series and the end of each coil is connected to a commutator segment. The rotor winding is supplied by dc current through brushes connected to the commutator. The dc supply drives current through the field and the rotor windings, both of which generate a magnetic field. The interaction between these two fields generates a torque which tries to align the two fields. To assure continuous rotation, the commutator changes the direction of the coil current when it passes through the neutral zone.

Most dc motors are equipped with auxiliary poles, supplied by the rotor current, located close to the brushes. The poles reduce the magnetic field around the brushes to improve commutation.

The most suitable motor for electric vehicles is the series motor, where the field coil has low resistance and is connected in series with the rotor. This motor has a large starting torque but it decreases with increasing speed. This characteristic is suitable for urban driving but can produce problems on the highway. A lane change may require acceleration but the series motor torque is low at high speed. Some vehicles use compound motors, with a series and a separately excited field winding, which have higher torque at high speed.

The efficiency of series dc motors can be improved by replacing the current excited stator poles with permanent magnets. The expensive rare earth permanent magnets produce a higher magnetic field than the current excited coils, which leads to smaller and more efficient motors.

Brushless DC Motor. The brushless dc drive is basically a high-frequency ac synchronous drive. The motor consists of rotating permanent magnets and, typically, three or four sets of coils mounted on the stator. These coils are supplied by a dc current through electronic switches, where the coils are energized in sequence. At any given time, only one coil is energized. The rotation is generated by the force between the permanent magnet and the magnetic field generated by the energized coil. As an example, when coil one is energized, an attractive force develops between pole one and coil one. This force tries to align the energized coil with the permanent magnet. The alignment of the coil's field and the permanent magnet's field stops the rotation. To avoid this, before the field alignment occurs, the next coil is energized to maintain the driving force. The rotor position is monitored by a pickup coil. Switching time is determined by rotor position. The electronic switches energize the stator coils in a sequence to assure continuous motion. The sequential synchronous switching of the coils requires complicated electronic circuits to accurately measure the rotor position and activate the switches at the proper instants. The primary advantage of this drive is the elimination of brush friction and commutator arcing. The brushless dc motor has a higher efficiency and reliability than dc motors with brushes. Simultaneously, there is a significant increase in both the motor and the related electronics costs for the brushless dc motor. Its drives are particularly advantageous at constant high-speed driving. Most electric racing vehicles are built with brushless dc motors and drives.

Most vehicles's motors are mounted on the axle and connected to the wheels through fixed or variable ratio gears. An interesting experiment is the direct drive of the wheels with an in-wheel motor.

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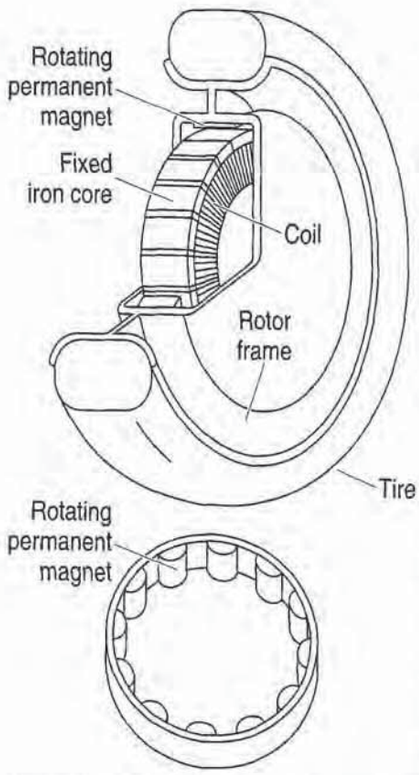


FIGURE 30.4 In-wheel brushless dc electric motor. (*Courtesy of Tokyo Electric Power Co.*)

Figure 30.4 shows the Tokyo Electric Company's in-wheel brushless dc motor. The rotating wheels with the tiers are equipped with an array of samarium-cobalt permanent magnets. The stator coils are installed on a stationary rim which is attached to the body of the car. Four motors have been used to drive an experimental car. The lack of gears makes the control of the four motors very difficult.

30.4.2 Motor Controller

The motor controller regulates the speed and torque of the electric motor, which drives the car. The motor controller also limits the motors' maximum current. Both ac and dc drive systems are used. The electric vehicle drive technology is changing continuously with the development of new electronic devices. Manufacturers are experimenting with different types of controllers that might be beneficial to EV design. The major requirements are smooth control of speed from zero to the maximum and the highest possible efficiency. Controllers should also have the capability of regenerative braking, forward-neutral-reverse control, overload/overheating protection, and production of a high starting torque.

Most dc drives use the traditional series dc motors with mechanical commutators. This well-tested motor is controlled by a simple electronic chopper (dc/dc converter). The dc motor efficiency can be improved by replacing the excitation coils with permanent magnets. However, the rare earth permanent magnets are expensive and difficult to manufacture because of the brittle nature of the material.

The latest motor development that has been incorporated into an EV is the electronically commutated brushless dc motor or ac synchronous motor, which eliminates the expense and high maintenance requirements of the mechanical commutator. These motors compete with inverter-driven ac motors. AC drives use variable-frequency inverters and three-phase induction motors. This technology is frequently used in the power industry. ac motors are inexpensive, more suitable for mass production, and are almost maintenance-free, but they do require complex electronic control circuits. Recent developments in high-power, high-current electronic devices like MOSfets and IGBTs will increase the power ratings and reduce the cost of inverters, which will increase the feasibility of using ac drives.

DC Drives. The concept of a commutator-type series dc motor with regenerative braking is shown in Fig. 30.5. The motor speed is controlled by regulation of the armature voltage. The system consists of two transistors or IGBT switches. Each switch is shunted by a power diode to permit the circulation of inductive current and avoid high reverse voltages across the switching devices. The diode provides a path for the armature current when the switch is off. Switch T_1 operates as a chopper and regulates the average armature voltage. The motor speed is proportional to this voltage. When switch T_1 is closed, the battery drives current through the

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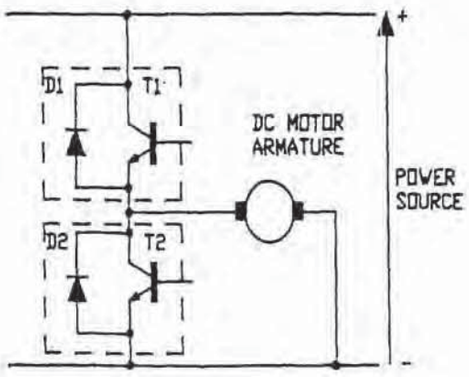


FIGURE 30.5 Concept of a commutator-type series dc motor drive.

motor. When T_1 is off, the motor current circulates through the diode D_2. The motor is driven only when the switch is on. The average armature dc voltage is proportional to the switch duty cycle, which is the ratio of the switch ON time and total switching period (ON time + OFF time). The motor speed is proportional to the armature voltage and, consequently, to the chopper duty cycle.

In the regenerative braking mode, T_1 is off. The motor operates as a dc generator and drives the current through diode D_1 back to the battery. This charging current is regulated by switch T_2. When T_2 is closed, the motor current will be diverted from the battery. The rate of recharging and braking action can be regulated by the duty cycle of switch T_2.

A more sophisticated double chopper circuit for compound dc motors is shown in Fig. 30.6. This circuit has been used in the Fiat Daily E2 van. The illustration shows the motor control cir-

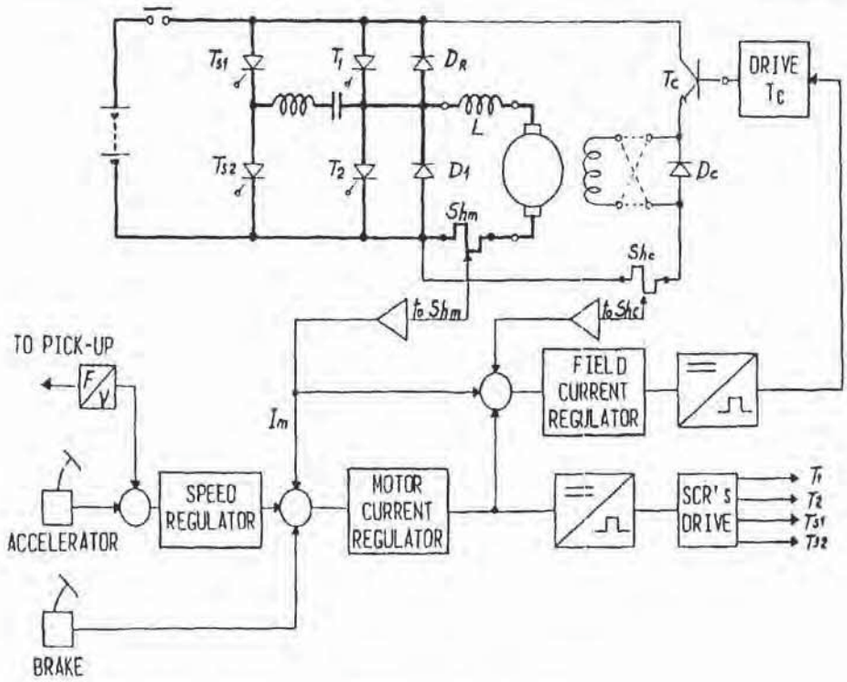


FIGURE 30.6 Double chopper for separately excited dc commutator motor.

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cuit and the concept of the vehicle control. This vehicle uses a compound dc motor with a low resistance series and separate high-resistance field excitation windings. The former is connected in series with the armature while the field winding is separately excited. The armature voltage and current are controlled by a thyristor chopper, which is, in this case, a forced commutated thyristor bridge. Thyristor T_1 is turned on and off to regulate the motor armature current in drive mode. Thyristor T_2 is turned on and off to regulate the motor armature current in the regenerative braking mode. These thyristors are commutated by the discharge of the LC circuit through the auxiliary thyristors T_{s1} and T_{s2}. The diodes connected in parallel with thyristors T_1 and T_2 provide a path for the inductive motor current and eliminate the high reverse voltage. This circuit can be simplified by replacing the thyristors with high-current IGBTs.

The current of the separate field excitation winding is regulated by transistor Tc, which also operates as a chopper. The compound dc motor with the double chopper results in better speed and torque regulation.

Figure 30.6 also shows the concept of the vehicle control. Both the motor and the field excitation winding current, together with the motor speed, are monitored. The speed pickup signal and the accelerator pedal position activate the speed regulator. The speed regulator signal is compared with the motor current and the resulting signal activates the motor current regulator. The output signal of the regulator is converted to impulses that control the firing of the thyristors. A second control circuit is formed to regulate the field current. The motor current, motor current regulator output signal, and actual field currents are compared and the resulting signal controls the field current.

Brushless DC Drives. Brushless dc drives are the product of the latest developments in power electronics. The brushless dc motor[6] has permanent magnets on the rotor and coils in the stator. The elimination of the commutator from this dc motor made necessary the sensing of rotor position and sequential switching of the coils to the dc source to maintain rotation. The rotor position is sensed by a pickup coil. Each coil can be supplied either from the positive or the negative bus through a transistor switch. Each transistor is shunted by a diode to avoid high reverse voltages. The transistors are controlled from the control bus.

AC Drives. The ac drives use three-phase squirrel-cage induction motors supplied by a three-phase, voltage source, variable-frequency inverter using three-phase sine wave pulse-width modulation (PWM) voltage control. The motor speed is regulated by the variation of the supply voltage frequency. The change in voltage regulates the magnetic flux in the motor, which affects the motor torque and current. Regulation of the motor speed, torque, and current requires the simultaneous regulation of frequency and amplitude of the motor supply voltage. The most simple method is to maintain a constant supply voltage and frequency ratio. The voltage amplitude is controlled by pulse-width modulation (PWM).

The concept of ac motor regulation is shown in Fig. 30.7. The voltage source inverter consists of three parallel connected switching units. Each unit contains two switches connected in series. Each switch is built with a semiconductor device (transistor, IGBT, etc.) and a diode connected in parallel. The diode provides a path for the motor inductive current and eliminates dangerous reverse voltages across the switching devices.

The three-phase voltage, without PWM, is generated by the sequential operation of the switches. In each instance, three switches located in different branches, are turned on. As an example, switches Q_1, Q_2, and Q_3 can be turned on simultaneously. This connects the negative battery terminals to phase "c" and the positive terminals to phases "a" and "b." The simultaneous turn-on of switches Q_1, Q_4, and Q_6 is a prohibited combination because the simultaneous turn-on of Q_1 and Q_4 short circuits the battery. The turn-on of the switches is shifted from each other by 60 degrees and each switch conducts for 180 degrees. The turn-on gating signals are shown in Fig. 30.8. In each cycle, the switches are turned on in the following order: 123, 234, 345, 456, 561, and 612. It can be seen in Fig. 30.8 that this circuit produces square shape voltages and does not permit the regulation of the motor current. It can be regulated and circuit performance improved by using PWM when each switch is operated several times during each half cycle.

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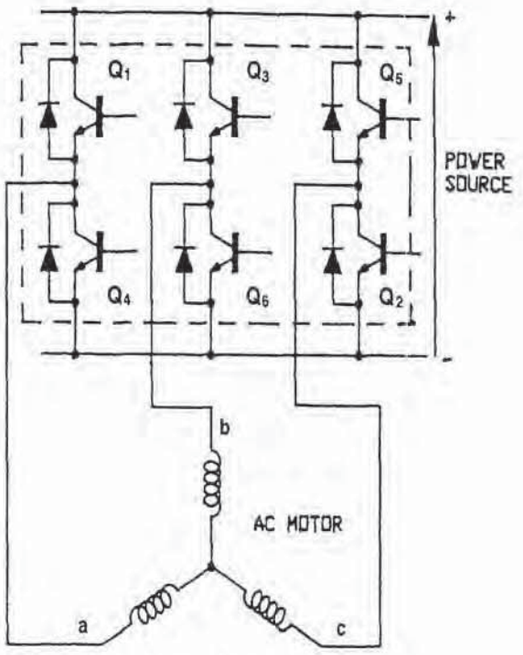


FIGURE 30.7 Concept of ac motor regulation.

The on and off time of the switch is determined by the comparison of a sinusoidal input signal with a triangular carrier signal. When the carrier amplitude is higher than the sine wave's amplitude, the switch is on; when it is lower, the switch is off. The described switch operation generates a pulse train of variable width at the terminals of the motor. The motor inductance integrates the variable-length voltage pulse train. Due to this integration effect, the variable-length pulse train drives a practically sinusoidal current through the motor. The widths of the output voltage pulses and the motor current are regulated by variation of the input sine wave amplitude. The described PWM method eliminates most of the harmonics from the motor current and results in a high-efficiency operation over a wide range of speeds. The expected peak efficiency is around 85 to 91 percent. These drives are particularly well suited for urban driving.

Switching Devices. The key component in both ac and dc drive systems is the semiconductor switching device. The device ratings for cars with a 40 to 50 kW drive and variable ratio transmission must be about 200 V and 250 A and for cars with fixed-ratio transmission, 400 to 600 V and 400 to 500 A.[7]

The advanced motor controllers should operate at a frequency between 10 and 20 kHz. High-frequency operation reduces the electronically generated audible noise. The disadvantage is the increase in switching losses and the generation of rf disturbances. The time of the transition from ON to OFF or OFF to ON state is important. The shorter transition time reduces the switching losses. Due to the wiring inductance, the fast switching may generate short duration overvoltages, which may be detrimental to the semiconductors. These overvoltages are controlled by selecting short leads and using filters or snubber circuits. The desired switching time is less than one microsecond.

Thyristor or Silicon Controlled Rectifier (SCR). SCRs have been used by the power industry for years in variable-speed drives. They have a large current-carrying capacity and high voltage ratings and relatively low voltage drop, but the current flow cannot be controlled after

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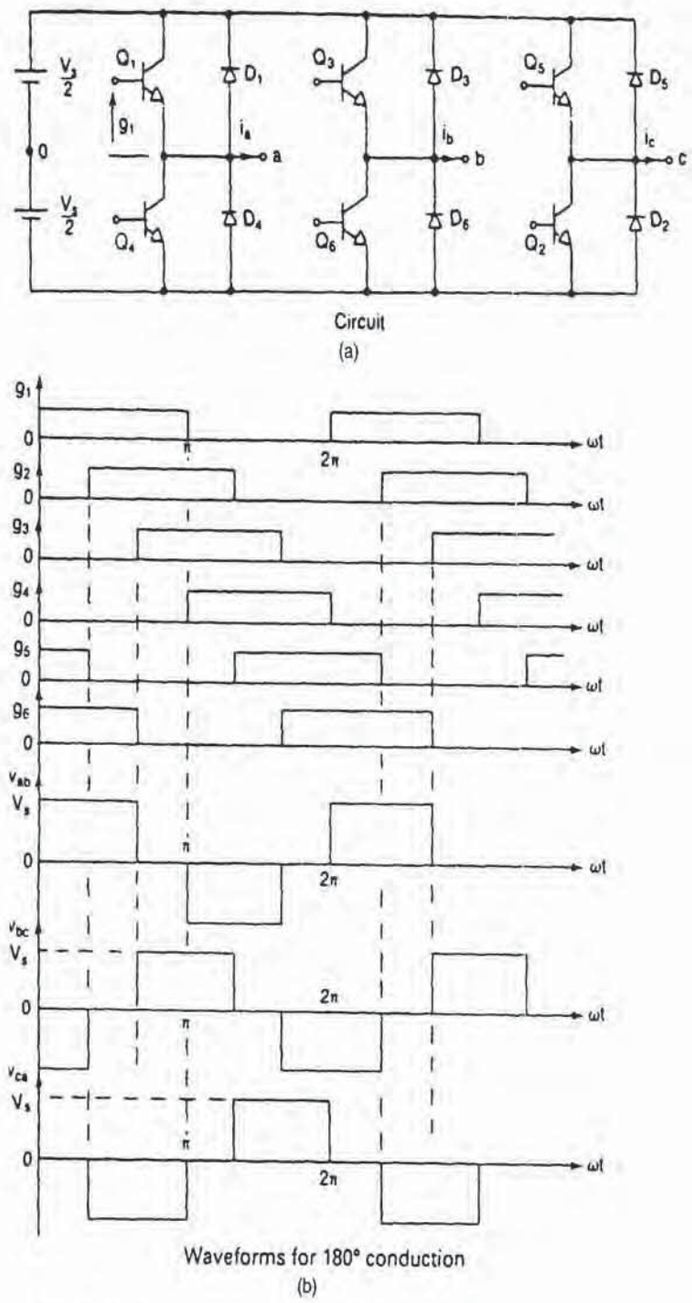


FIGURE 30.8 Three-phase voltage-controlled inverter operation.

firing. The turn-off requires cumbersome auxiliary circuits. In spite of these disadvantages, some EVs use SCRs.

Gate Turn-Off Thyristor (GTO). The gate turn-off thyristor can be turned off by a powerful gate signal. The problem is that the device can only operate at low frequencies (1 to 5 kHz) and the voltage drop is significantly higher than the SCR's voltage drop. Also, the firing and turn-off require large currents, which increase losses in the device.

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Power Transistors. Both the voltage drop and the gain of power transistors are low. The low gain requires expensive gate drive systems. The transistors can operate in the required audio frequency range. The performance can be improved by connecting two transistors in a Darlington pair configuration. In this connection, the first transistor serves as an amplifier, which permits control of the device with low current. The Darlington connected transistors are sold as a unit at an attractive price. This is a frequently used circuit.

Power MOSFET. The MOSFET is a voltage-controlled device as compared to current-controlled (thyristor/transistor) and is designed for high-frequency operation. However, the saturation voltage drop and its temperature sensitivity limit the MOSFET application in power circuits.

Insulated Gate Bipolar Transistor (IGBT). The IGBT is a transistor which is controlled by a MOSFET. The IGBT requires low drive current, is suitable for high-frequency operation, and has a fast switching time. Disadvantages are that the device voltage drop and cost are higher than the Darlington transistor configuration. The large current capability and operating voltage, together with the low power drive circuit, makes the IGBT attractive for electric vehicles.

MOS-Controlled Thyristor (MCT). The MCT has a low voltage drop and can be turned on and off with a voltage signal (low switching losses). It can also be designed for high-voltage and high-current applications. This new device is very attractive for EVs.

The semiconductor industry frequently produces better and more powerful semiconductor switches which have potential for EV applications. The typical ratings of the most frequently used devices are shown in Table 30.3.[6]

30.4.3 Mechanical Drives

Lack of high-speed acceleration and the efficiency problems can be mitigated by the use of mechanical gears, similar to those used in today's ICEVs. The efficiency of an EV drive depends on the speed. Typically, ac drives operate at better than 80 percent efficiency in the range of 2000 to 12,000 rpm and the series dc drives in the 2000 rpm to 5000 rpm range. The brushless dc drives' efficiency is better than 85 percent in the 3000 to 8000 rpm range.

Another consideration is torque-speed characteristics. Most drives keep the motor torque more or less constant, in the 0 to 4000–5000 rpm range. However, at higher speeds, the torque begins to decline. This means that acceleration in the 65 to 105 km/h range is poor. This may create problems during highway driving.

These examples show that the efficient operation of electric drives requires more than 2000 to 3000 rpm, but the wheel speed at 105 km/h highway speed is only about 500 rpm. Frequent acceleration is characteristic of city driving, which requires high torque. In spite of the advancement in electronic drive technology, efficient EV operation requires mechanical gears to reduce motor speed. Typically, a gear ratio is between 4:1 and 8:1.

TABLE 30.3 Comparison of Power Switching Devices

	Darlington BJT	Power MOSFET	IGBT	MCT
Power capability	1200 V, 800 A	500 V, 50 A	1200 V, 400 A	600 V, 60 A
Gating	Current	Voltage	Voltage	Voltage
Conduction drop, V	1.9	3.2	3.2/1.7*	1.1
Switching frequency, kHz	10	100	20/40*	20
Reapplied *dv/dt*, V/μs	Limit for device loss and SOA	Limited by Miller effect	Limit for device loss	5000
Turn-on *di/dt*, A/μs	100	Very high	Very high	1000
Turn-on time	1.7 μs	90 ns	0.9 μs	1.0 μs
Turn-off time	5 μs	0.14 μs	1.4 μs/200 ns*	2.1 μs

* Second generation.

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Multiratio Variable Drives. The multiratio variable drive utilizes present automotive technology, where motor speed is regulated with an automatic or manual transmission and the wheels are driven by a differential gear for further speed reduction. Most converted EVs use the same transmission and differential originally designed for the ICEV. In these vehicles, the internal combustion engine is replaced by an electric motor. However, the multiratio (manual transmission) variable gear is used in some of the cars designed specifically for electric operation. A typical example is the Fiat Panda Electric which has only a 9.2-kW motor with a manual four-speed transmission plus reverse gear. The multiratio variable-speed mechanical drives are used frequently in connection with series dc motor drives. These drives have a relatively narrow range of efficient operation. The multiratio gear permits the more accurate matching of the electric drive characteristics with different operating conditions.

Single-Ratio Drives. Some of the electric drives, like variable-frequency ac drives, have a broad range of efficient operation. A single-ratio reduction gear can match the drive characteristics with road conditions. Most vehicles designed for electric operation use this technique. The motor is mounted on the axle and the reduction gear is integrated with the motor. A typical example is the Ford Ecostar. In this vehicle, a 75-kW induction motor is mounted directly on the front transaxle.

An example of the integration of the motor and reduction gear is the transaxle-mounted motor[8] shown in Fig. 30.9. The maximum speed of the permanent magnet motor is 7500 rpm. A 7.5:1 ratio gear and a planetary differential, mounted on the motor, drives the wheels with a reduced speed. This transaxle arrangement matches the motor with road conditions.

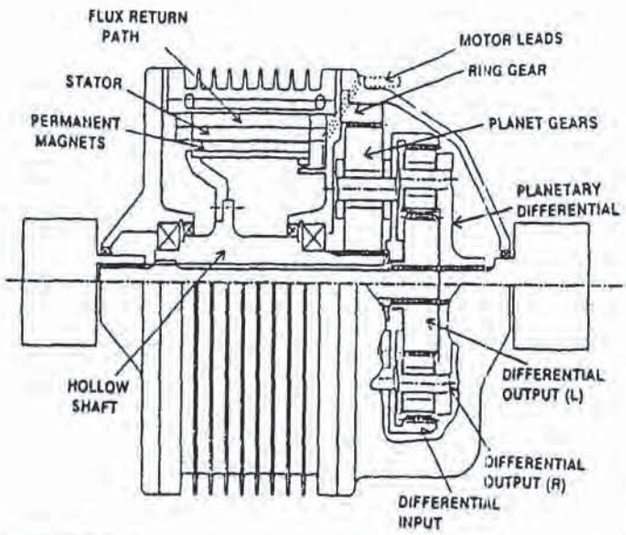


FIGURE 30.9 Integrated transaxle motor, gear, and differential arrangement.[8]

Direct Drives. The direct driving of the wheels by in-line motors is a desirable concept for EVs. An in-wheel drive eliminates gears and simplifies the mechanical construction of the vehicle, but it requires complicated electronic controls and sacrifices some vehicle performance. A typical example of in-wheel drive is shown in Fig. 30.4, where the motor is mounted directly on the wheel. The performance of direct drives can be improved by modifications to the motor connection by a switch. Typical solutions are a switch from delta to wye connection and a switch from series to parallel connection in a motor with two windings.

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30.5 BATTERY

For the EV to become a viable option for transportation, the primary technological issue which must be improved upon is energy storage. Short range and long charging times have daunted EV design efforts since the early 1990s. The lead-acid battery, which has not improved much since the early EVs, is the only readily available and inexpensive battery technology available today.

In order to address the issues involved with the research and development of new battery technologies, major United States automobile manufacturers (Ford, Chrysler, and General Motors) created the United States Advanced Battery Consortium (USABC).[9] In 1992, the USABC working with the government began a $260 million project to develop more efficient energy storage systems for use in EVs. Since the lead-acid battery did not hold promise for EV use in the long run, its development was not addressed by USABC. But since lead-acid batteries are used extensively in current EV designs, another group—The Advanced Lead-Acid Battery Consortium (ALABC)—was formed to work with the government and industry in further development of lead-acid batteries for EVs.

30.5.1 EV Battery Requirements

EV batteries have the following requirements: high specific energy, high specific power, high efficiency, long cycle life, low cost, safety, reliability, maintenance free, reasonable recharge time, and recyclable materials. Since current batteries have deficiencies in many of the requirements, the motivation is strong to develop a battery that will meet most, if not all, of the requirements.

30.5.2 Battery Characteristics

Specific energy (energy density) is the most commonly used specification for batteries. It denotes the energy capacity per unit weight for a given battery, which normally relates to the driving range of the battery pack. To derive the specific energy, the total energy which can be removed from the battery for a given discharge profile is divided by the total weight of the battery. The ohmic losses (due to I^2R heating from internal resistance and contact resistances) and chemical energy losses represent energy which is stored in the battery during charging but not available during the discharge cycle. The energy efficiency is the ratio of the available energy for discharge to the total stored energy.

The specific power (power density) represents the maximum power that the battery can deliver, which is an indication of the battery's ability to perform under EV acceleration and hill climbing. Specific power will vary depending on the test parameters (DOD, current, age of batteries, etc.).

Table 30.4 lists characteristics of different battery technologies currently available and those under development.[6]

TABLE 30.4 Comparison of Battery Technologies (Relative to Lead-Acid)

Battery	Pb-acid	Ni-Fe	Ni-Cd	Ni-MH	Zn-Br	Na-S	Li-FeS2	Li-Poly
Relative energy density	1.0	1.5	1.6	1.7	2.2	2.5	4	4
Relative peak power density	1.0	1.2	1.9	2.1	0.6	1.1	4	3.5
Relative range	1.0	2.0	2.1	2.3	2.1	3.4	4	4
Energy efficiency, %	68	58	80	76	75	91	80	85

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30.5.3 Battery Technologies

This section will cover battery technologies which are currently in use and those which are still under development.

Lead-Acid. The lead-acid batteries are still the most commonly used for EVs today. Efforts are underway for the development of advanced lead-battery concepts for the short-term requirements of EV energy storage. A metal plate used in a liquid electrolyte configuration is the most inexpensive battery on the market today. Lead-acid batteries have a specific energy of about 35 Wh/kg and specific power of 93 W/kg.

Ni-Fe Battery. Another metal plate in liquid electrolyte battery is the Ni-Fe battery which has a much longer cycle life than the lead-acid battery. The Ni-Fe battery is very robust but has a relatively small specific energy and specific power. It requires water to be added during each charging cycle (high maintenance), which means the battery cannot be sealed. Hydrogen release is also a problem and complicates the design of Ni-Fe battery equipped EV. The Ni-Fe battery is also expensive and has a specific energy of about 50 Wh/kg and a specific power of about 100 W/kg. Since the Ni-Fe battery has been extensively developed, it seems less likely that there will be a major breakthrough for its technology than for other newer technologies.

Ni-MH. The nickel metal hydride batteries show promise for EV application. They use one nickel hydroxide electrode and one metal alloy electrode which has the property of being able to store hydrogen in the solid state. Typically the Ni-MH battery has specific energy and specific power of 54 Wh/kg and 174 W/kg, respectively. It also has a relatively long cycle life. The specific energy of one experimental Ni-MH battery is 81 Wh/kg.[2]

Zn-Br. The Zn-Br battery uses carbon electrodes and pumps the electrolytes (zinc bromide/zinc bromide + bromine) to separate sides of the cell. Pumping of the electrolytes provides cooling and uniform plating of the electrode. The Zn-Br battery has a high energy density (72 Wh/kg), but a relatively low power density (53 W/kg). Because of the high energy density, the research will probably continue on the Zn-Br battery, but problems with low power density, higher cost (pumps, reservoirs, and lines), and the corrosive nature of the materials used will make it unlikely that this battery will be the long-term solution for EV use.

Na-S. The sodium-sulphur battery does not have solid electrodes. It uses molten sodium (heated to 300 °C) as the electrode. The Na-S battery has a specific energy of 80 Wh/kg and a specific power of 100 W/kg. A distinct advantage of the Na-S technology is its long self-discharge time, which can be years. It comes about because the electrolyte is an insulator which allows only migration of sodium ions and not electrons. A long self-discharge time would be advantageous in any EV application where long periods must be tolerated without a recharge. High operating temperature and hazardous materials (sodium and sulphur) would require rigid packaging requirements (crashworthiness) for the Na-S battery, which would add substantially to the cost. Another drawback is the possibility of the molten sodium electrode solidifying after a period of nonoperation. The addition of heaters for the battery will also add additional cost. And continual solidifying and reheating of the electrode will eventually damage the battery.

Lithium-Based Technologies. Lithium-based electrode batteries (lithium-iron sulfide, lithium-iron disulfide, and lithium-polymer) show promise for future EV use. Extensive research is underway. Heat dissipation during charging and discharging and manufacturing issues are fundamental problems which must be addressed.

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30.5.4 Future of Battery Development

The USABC has projected goals for the development of new battery technologies. These goals have been divided into two categories: midterm and long-term. Table 30.5 lists the goals set by the USABC.[6]

TABLE 30.5 Midterm and Long-Term Objectives of the USABC

Criteria	Midterm	Long-Term
Primary criteria		
Power density, W/L	250	600
Specific power, W/kg (80% DOD/30 s)	150* (*200 desired)	400
Energy density, Wh/kg (C/3 discharge rate)	135	300
Specific energy, Wh/kg (C/3 discharge rate)	80* (*100 desired)	200
Cycle life, cycles	600 (5 years)	1000 (10 years)
Ultimate price, US$/kWh	<150	<100
Operating environment, °C	−30 to +65	−40 to +85
Recharge time, h	<6	3 to 6
Continuous discharge, % of rated energy capacity (no failure)	75	75
Secondary criteria		
Efficiency, % (C/3 discharge, 6 h charge)	75	80
Self-discharge	<15% in 48 h	<15% per month
Maintenance	Zero	Zero

30.6 VEHICLE CONTROL AND AUXILIARY SYSTEMS

30.6.1 Vehicle Controller

In addition to the motor drive, the EV has several other systems which must be monitored and controlled. Figure 30.10 shows the block diagram of a vehicle control system. It is divided into four major parts: motor controller, pedals, hand controls, and dashboards. The advanced system uses a microprocessor to monitor all subsystems. Quantities like temperature, speed, current, and voltage—which are relevant to the subsystem operation—are measured with transducers that convert operating conditions to analog signals. The signals are then digitized and supplied to the microprocessor. It evaluates the subsystem signals and sends out control signals. The microprocessor also shuts down the system in case of a fault. The vehicle controller also assures close to optimal operating conditions and optimal use of energy stored in the batteries. The batteries' condition is monitored and the available approximate mileage range is reported to the driver.

30.6.2 Climate Control System

The air conditioner and heating system consumes a considerable amount of power. The Ford Ecostar equipped with a 75-kW motor and its heater, for example, consumes 5 kW and its air conditioner, 6 kW.[2] This is particularly significant considering that the same vehicle requires about 8 kW of power when driven in accordance with the Federal Urban Driving Schedule. The use of the air conditioner or heater significantly reduces the vehicle range.

EV Air Conditioner. A car's air conditioning system is designed to operate, typically, at outside temperatures of 44 °C and a relative humidity of 40 percent. The air conditioner cools the

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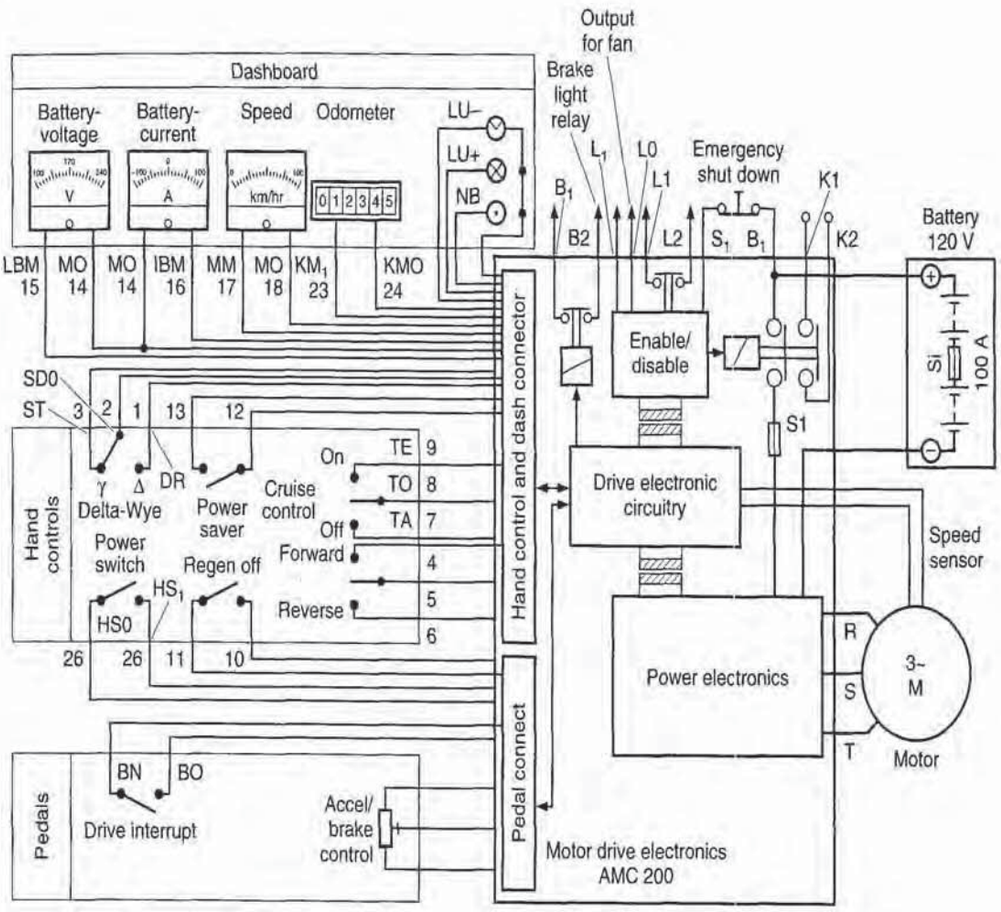


FIGURE 30.10 An electric vehicle control system.

inside of the vehicle to 27 °C and a relative humidity of 50 percent. The interior of the vehicle must be ventilated and this increases the air conditioning system heat load. The ANSI/ASHRAE 62-1981R "Ventilation for Acceptable Indoor Air Quality Code" requires 15 ft^3/min ventilation air per passenger. The finished car interior provides sufficient heat insulation, but EV side windows must be tinted and doors must be properly sealed to reduce heat loss.

A typical air conditioning system has relatively low efficiency, which reduces vehicle range considerably. Several research projects have dealt with the development of more efficient systems. The most promising concept is shown in Fig. 30.11. This system is built with a variable-speed compressor driven by a brushless dc motor. The compressor increases the coolant pressure and temperature. The coolant then expands in the expansion tube and evaporates in the evaporator, thus reducing its temperature. The evaporator coils cool the air, which is blown into the interior of the car. A variable-speed drive improves the air conditioner performance. Tests indicate, however, that better roof insulation, the use of wavelength-selective window tinting, and cooling of the parked vehicle by a small 20-W fan reduce the air conditioning thermal load and permit the use of a smaller and lighter unit.

EV Heating. Current EVs use liquid fuel heaters, which are expensive and pollute the air, and the use of two fuels in a vehicle is not desirable. An alternative heating method is the use of the air conditioner as a heat pump, together with vehicle waste heat. In extreme conditions, the system can be supported by additional electric resistance heaters. Unfortunately, such a heating system also reduces vehicle range.

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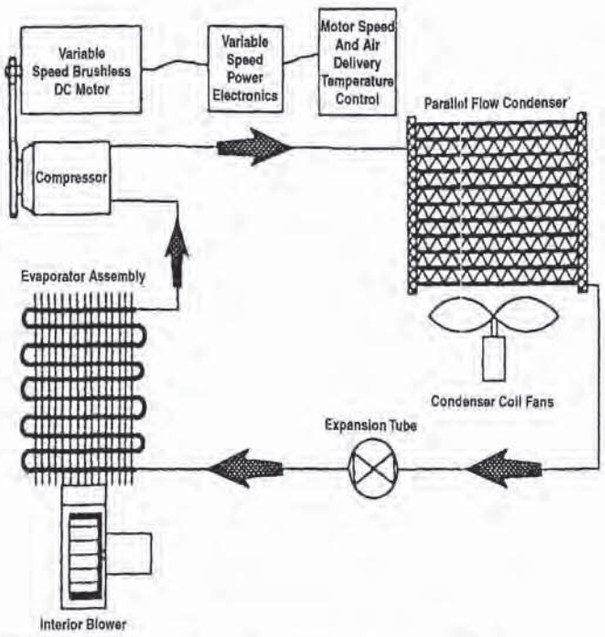


FIGURE 30.11 An EV advanced air conditioning system.[10]

30.6.3 Auxiliary Power

Proper operation of the vehicle requires an electric supply for power steering, power brakes, the headlights, turn indicators, etc. All these systems are well developed and optimized for ICEVs. Supply of the auxiliary equipment with more than 100-V batteries jeopardizes electric safety. Higher voltage requires better insulation and increases costs. Consequently, most electric vehicles have a 12-V auxiliary power supply and distribution system. One solution is a chopper, which charges a normal 12-V battery. Another solution is a constant voltage switching power supply like those used in the electronics industry.

30.7 INFRASTRUCTURE

The increasing use of ICEVs initiated the development of a highway system, the network of gas stations, the gas distribution system, and the increased production of high-quality grades of gasoline. Most of these facilities, except the gas supply and distribution, will be used by EVs. The electrical network is well developed, but the refueling of large numbers of vehicles may require an increase in network capacity.

30.7.1 Electric Network Reinforcement

The EV can be charged slowly overnight at the owner's home or it can be charged at charging stations at a much faster rate. The method of charging has a major effect on the electric system requirements.

Slow Charging. EVs are charged from the local electric distribution system. The present concept[2] is that EVs will be charged at the owners home during off-peak hours (overnight).

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This requires 5 to 10 hours from a 240-V, 30-A outlet. Also, credit card or coin-operated charging facilities will be installed in public parking lots and garages. These facilities will charge the vehicles with 30 to 50 A to provide a partial recharging while the vehicle is parked. Slow overnight charging will improve utilization of the electric network and does not require network reinforcement. But daytime charging of large numbers of EVs will increase the peak load and require both generation and distribution system improvement. The utilities will use time-of-day pricing, in which the night rate is significantly lower than the day rate. The use of interruptable tariffs may be considered. This would allow the utility to interrupt the vehicle charging by a remote signal during peak hours. It both cases, the customer is charged with a lower rate.

Quick-Charging. In the future, high-capacity quick-charging stations will be available to the EV user. Quick-charging will require several hundred amperes and special equipment, which is currently under development. The large charging current will produce high peak loads on the local distribution system. To reduce these loads, the use of energy storage devices is being considered. These include batteries, flywheels, and superconducting magnetic storage systems. Quick-charging stations will not be designed to fully charge a discharged battery, but will provide an additional 110 to 160 km of driving range with a 10- to 30-min charge.

It can be visualized that quick-charging stations will be similar to today's gas stations. They will be located along highways where the electric distribution system is weak. The utility distribution system must be reinforced if quick-charging is to be used.

30.7.2 Harmonics and Power Factor

EV chargers are electronic devices that generate harmonics and consume reactive power. Expected operating conditions in a future slow-charging station can be estimated from the measurements performed during the APS Electric 500 Race in Phoenix, Arizona, in 1994. Figure 30.12 shows the supply cable current when 30 different vehicles were charging.[11] The maximum charging current per vehicle was limited by a circuit breaker to 50 A at 240 V. The figure shows severe harmonic distortion.

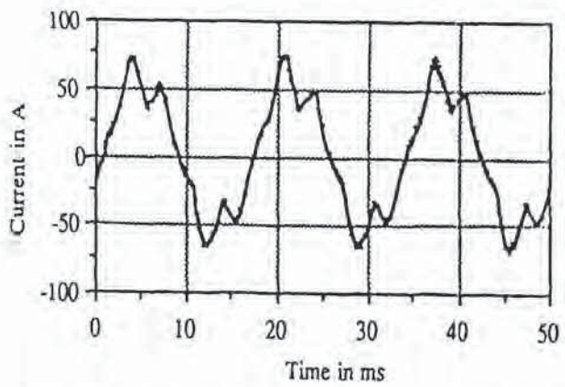


FIGURE 30.12 Charging current waveform at a slow-charging station.[11]

The measured power factor for the different chargers varied between 0.75 to 1. The cumulative distribution of the power factor at the supply cable shows that 50 percent of the chargers had a power factor less than 0.86.

The measured harmonic distortion factor was between 5 and 50 percent. The cumulative distribution of the harmonic distortion factor at the supply cable shows that 80 percent of the

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chargers operated with a distortion factor less than 30 percent.[11] The measured values are alarming and indicate the need for improvement.

Reactive power consumption can be reduced by the use of a voltage source type rectifier for charging. This circuit uses transistors instead of diodes or thyristors. The transistors are switched in such a way that the voltage and current are in phase. Another technique for reactive power control is to use phase correction capacitors.

The harmonic content of current in a charging station can be significant but it can be reduced by the use of pulse-width modulation (PWM) at the chargers. This method also requires transistors and a significantly more complicated control circuit. The current harmonic content in a charging station decreases as the number of vehicles being charged simultaneously increases. This is due to the phase shift between the harmonics being generated by the different types of chargers. The phase shift provides cancellation of harmonics.[11] Nevertheless, the harmonics generated by large numbers of EVs may produce significant problems for utilities.

30.7.3 Magnetic Field Generation

The current in an EV can be a few hundred amperes. It produces magnetic fields both inside and outside the EV. The magnetic field generated by the dc drives has both dc and ac components. The ac component is superimposed on the much higher dc component. The ac drive produces magnetic fields, which are distorted sine waves. The fundamental component is determined by the speed of the vehicle. The higher-frequency components up to the tenth harmonic are not negligible.

The highest magnetic field was measured during acceleration and regenerative braking. In this condition, the maximum field in the engine compartment was about 120 mG. The magnetic field in the passenger compartment was negligible due to the shielding effect of the car body.[12]

The magnetic field in a future charging station can be estimated from the measurements performed during the 1994 APS Electric 500 Race. The results indicate that the highest field around 50 mG was measured near the charging cables. The field 50 cm from the vehicles was between 20 and 30 mG.[13] Numbers suggest that the future charging station design has to consider the use of shielded cables and cable arrangements with low field emission.

30.8 HYBRID VEHICLES

The inherent low operating range of EVs suggests the building of hybrid vehicles with both electric and gas systems. Hybrid vehicles are equipped with an internal combustion engine and an electric motor drive and battery. In highway driving between cities, where the pollution is not critical, the car is driven by the internal combustion engine (ICE), which also charges the battery. In the city, the electric motor and drive are used. The operation can be improved by recharging the battery at night.

The two basic configurations for hybrid vehicles are series and parallel. Figure 30.13 shows two conceptual arrangements for hybrid vehicles.

30.8.1 Series Hybrid Drive

In a series hybrid drive, the ICE drives a generator, which charges the battery and supplies the electronically controlled motor. The electric motor propels the car. In this system, the ICE operates at constant speed with maximum efficiency. The vehicle is controlled electrically. The electric control simplifies the mechanical gears and differential. The disadvantage of this

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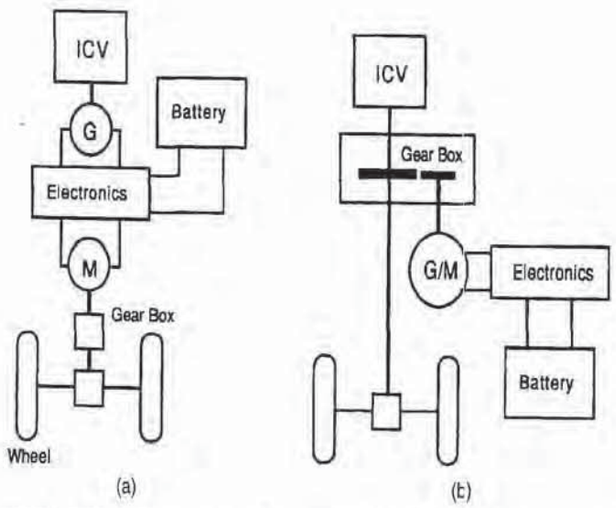


FIGURE 30.13 Two conceptual arrangements for hybrid vehicles: (*a*) series hybrid drive; (*b*) parallel hybrid drive.

arrangement is that both the ICE and the electric drive have to be rated to the maximum power. Another problem is low overall system efficiency.

30.8.2 Parallel Hybrid Drive

The parallel system consists of an ICE and an electric drive connected by a mechanical gear. The electric drive is built with a motor/generator, electronic control, and battery. The mechanical gear drives the wheels through a differential. In highway driving, the ICE propels the vehicle and charges the battery. The electric motor operates as a generator. In city driving, the battery and the electric motor drive the vehicle. During hill climbing or other conditions when the maximum power is needed, both engine and motor drive the vehicle. This arrangement results in better efficiency, less weight, and lower cost.

Hybrid vehicle technology is under development with several other arrangements which have been proposed and are being evaluated. Volkswagen built a city taxi[14] which performed well during a 100,000-km test. The problem with this vehicle is the weight. Today's lead acid batteries added 200 to 300 kg to the vehicle's weight.

GLOSSARY

Battery Self-contained electrochemical cell/cells or system which converts chemical energy to electrical energy in a reversible process.

Battery technologies Ni-Fe (nickel-iron), Ni-Cd (nickel-cadmium), Ni-MH (nickel-metal hydride), Zn-Br (zinc-bromine), Na-S (sodium-sulphur), Li-FeS_2 (lithium-iron disulfide), Li-Polymer (lithium-polymer).

Brush Conductor used to maintain an electric connection between the moving and stationary parts of a motor.

Capacity Energy storage capability of the battery.

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Charge/discharge profile Different charging/discharging schemes used for evaluation of a battery.

Commutator Mechanical switch which transfers current from one coil to another at the proper instant.

Depth of discharge (DOD) Percentage of capacity (ampere-hours) which has been removed from the battery.

Electric drive system The motor, motor controller, and cabling used to drive an electric vehicle.

Electric vehicle (EV) Automobile, truck, or any vehicle powered by rechargeable or non-rechargeable batteries and an electric motor.

Electrolyte Medium in which current flows by movement of charged particles (ions).

Gear box Gear that reduces the speed of a motor by connecting together different ratios of gears.

Inductive coupling The association of two or more circuits by means of inductance mutual to the circuits.

Phase-controlled rectifier A converter for conversion from ac to dc that varies the point within the cycle at which forward conduction is permitted to flow through the semiconductor elements.

Quick-charging Charging batteries at a rate that will produce a 40 to 50 percent charge in about 15 minutes.

Regenerative braking Capability of an electric drive to return the kinetic energy, stored in the velocity of the EV body, to the battery during braking.

Specific energy (energy density) A battery's energy storage capability per unit weight (Wh/kg).

Specific power (power density) Power delivery capability per unit weight of a battery (Wh/kg).

Squirrel-cage rotor A rotor winding consisting of conducting bars connected by metal rings or bars at each end.

State of charge (SOC) The battery level of charge can be stated as either DOD or SOC.

Transaxle An axle that includes the differential and gear box.

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CHAPTER 31
NOISE CANCELLATION SYSTEMS

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Active noise cancellation is not a new idea. Creating a copy of the noise and using it to cancel the original dates back to the early part of this century. The first systems used a simple "delay and invert" approach and showed some promise, but the variability of real-world components limited their effectiveness.

In the mid-1970s, a major step forward took place with the application of adaptive filters to generate the antinoise. This greatly enhanced the effectiveness of the systems, because they could continuously adapt to changes in their external world as well as changes in their own components. A second breakthrough in the mid-1970s was the recognition that many noise sources, particularly those produced by man-made machines, exhibit periodic or tonal noise. This tonal noise allows a more effective solution, because each repetition of the noise is similar to the last and the predictability of the noise allows creation of an accurate antinoise signal.

Practical application of this approach still had to wait as the electronic technology available at that time was not sufficient for implementation of active noise cancellation systems. Now digital computer technology has evolved to the point where cost-effective digital signal processing (DSP) microcomputers can perform the complex calculations involved in noise cancellation. This advance has made it feasible to apply active noise cancellation at reasonable cost to previously difficult problems in low-frequency automotive noise and vibration.

31.1 NOISE SOURCES

Sources of noise and vibration exist throughout an automobile. One type of noise is due to turbulence and is, therefore, totally random and impossible to predict. This makes it a difficult noise to cancel unless the source of the noise is well understood.

Engineers like to look at signals, noise included, in the frequency domain. That is, "How is the noise energy distributed as a function of frequency?" These turbulent noises tend to distribute their energy evenly across the frequency spectrum and are, therefore, referred to as broadband noise. Examples of broadband noise in cars are wind and most road noise. A typical broadband noise spectrum is shown in Fig. 31.1.

A large number of noises are different. These narrowband noises concentrate most of their noise energy at specific frequencies. When the source of the noise is a rotating or repetitive machine such as an automobile engine, the noise frequencies are all multiples of a basic noise

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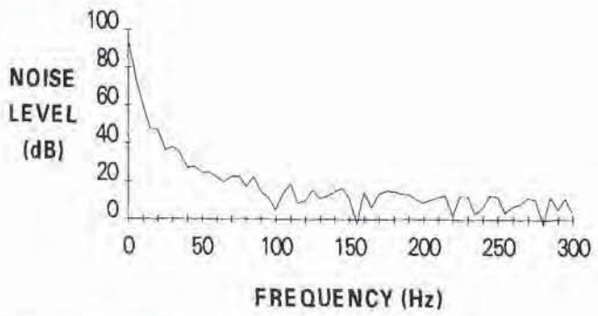


FIGURE 31.1 A typical broadband noise spectrum.

cycle and the noise is approximately periodic. The repetition rate of the noise cycle of a four-stroke automobile engine is two full revolutions (all cylinders firing). A typical narrowband noise spectrum is shown in Fig. 31.2.

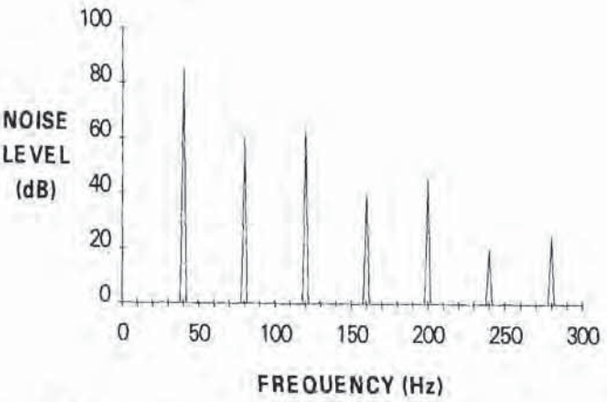


FIGURE 31.2 A typical narrowband noise spectrum.

Examples of sources of narrowband noise in automobiles include exhaust noise, along with broadband noise due to turbulence generated in the muffler; engine vibration, the major source of the "boom" in the passenger cabin; ventilation fans, again accompanied by broadband noise due to turbulent flow; and tire noise, with a regular tread pattern.

31.1.1 Noise Measurement

Any variation in air pressure is perceived by the human ear as sound. The pitch of the noise is related to the speed at which the pressure varies. As a reference, when the pressure fluctuates 440 times per second, the ear perceives it as the musical note "A" above middle "C." The intensity of the noise can be stated either in terms of the peak sound pressure level (SPL) or in terms of the noise power that varies proportionally with the square of the SPL.

Noise is usually measured in decibels and is defined as:

$$\text{Noise}_{dB} = 20*\log_{10}[\text{SPL}/\text{SPL}_{ref}]$$

or equivalently,

$$\text{Noise}_{dB} = 10*\log_{10}[(\text{noise power})/(\text{noise power}_{ref})]$$

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where the reference (0 dB) is set as the softest 3-kHz tone that an average human can hear in a perfectly quiet environment.

An overall measure, commonly used in specifications, is A-weighted noise (dBA). It is adjusted to compensate for the fact that the average human ear has lower sensitivity at low and high frequencies at normal listening levels.

31.1.2 Passive Noise Control

The first line of defense against noise is good design. All machines should be well balanced. Symmetry in design and careful manufacturing can significantly reduce vibration and noise. Turbulence can be reduced by good aerodynamics. High "Q" resonances in structures and gas flows should be avoided.

The second line of defense is to absorb noise and vibration energy and control its propagation using passive materials. The use of sound-absorbing and rigid materials to reduce noise levels is an effective approach at high frequencies. Below 500 Hz, however, the cost, weight, and inefficiencies due to passive sound attenuation often make this approach ineffective or impractical. Another technique for noise control is required.

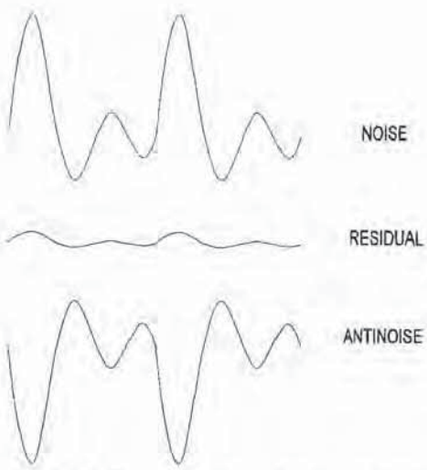


FIGURE 31.3 Relationships in time among noise, antinoise, and residual noise.

31.1.3 Noise Cancellation Technologies

Antinoise. The idea to create a copy of the noise and use it as antinoise to cancel the original dates back to the early part of this century. Figure 31.3 shows the relationship, in time, of a noise signal, an antinoise signal, and the residual noise that results when they meet. Note that active noise cancellation does not mask the noise; it removes a significant portion of the noise energy from the environment.

Digital Feed Forward. Digital feed forward is shown in Fig. 31.4 as used to reduce the noise in an air duct. This is the classic example application for active noise cancellation and is widely discussed in the technical literature. It is also the method to use to control blower noise in automotive ventilation systems and is discussed further in the applications section later in this chapter.

Referring to Fig. 31.4, a microphone is placed upstream in the duct to get a reference sample of the noise. The effect of the duct on the noise is modeled to produce an antinoise waveform at the output speaker. A residual microphone is placed downstream in the duct to determine how well the system is operating and the duct model is continuously adjusted to maintain peak cancellation. Feedback compensation is also required since the antinoise waveform also propagates backwards along the duct and makes the reference signal inaccurate. Incorrect feedback compensation results in unstable operation.

Systems that cancel broadband noise require causality (the reference signal must give a sufficiently advanced indication of the approaching noise). Noise that correlates with the reference will be canceled. Digital feed forward systems can readily achieve 6 to 10 dB (50 to 70% reduction in sound pressure level) in practical use.

Most active noise cancellation systems employ a variant of the LMS algorithm known as Filtered-X. The basic LMS algorithm correlates an error signal (the residual noise in this case)

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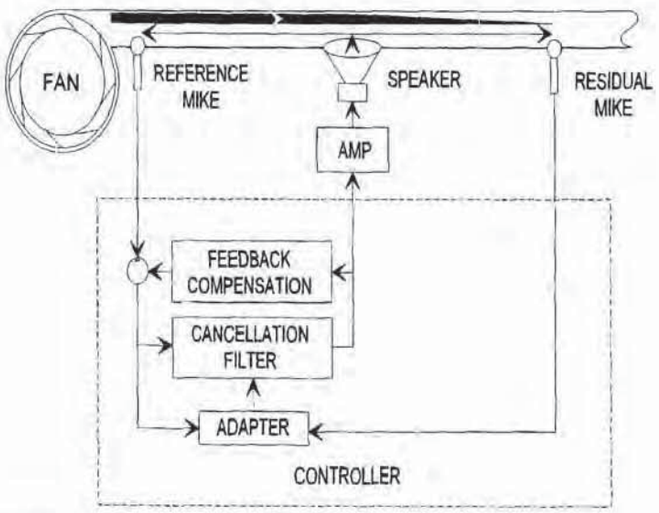


FIGURE 31.4 Feed forward cancellation system.

with a reference signal (called "X" by Widrow and Stearns, *Adaptive Signal Processing*, Prentice-Hall, 1985). The result is then multiplied by an adaptation rate constant and used to adjust the relevant parameter of the adaptive filter. This is done repeatedly for each filter parameter with the objective being convergence to an operation that minimizes the average power in the error signal.

In real-world systems, the LMS algorithm does not converge due to the delay and gain effects of the physical path taken by the antinoise signal. Using a compensation filter on the reference signal (hence, the name Filtered-X), restores stability and produces a well-behaved system.

Synchronous Feedback. The technique known as synchronous feedback, developed by G. B. B. Chaplin in the mid-1970s, is very effective on repetitive noise and does not rely on causality. Here, instead of the reference microphone, a tachometer signal is used to provide information on the rate of the noise. Since all of the repetitive noise energy is at harmonics (or multiples) of the machine's basic rotational rate, the DSP micrometer can dedicate its resources to canceling these known noise frequencies.

Figure 31.5 shows the configuration of such a system applied to reduce engine exhaust noise. Its basic operation is described in the applications context in the next section.

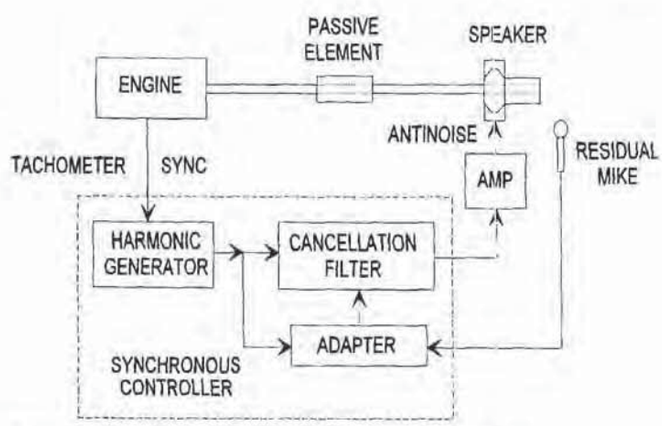


FIGURE 31.5 Narrowband noise cancellation (an active muffler).

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31.2 APPLICATIONS

31.2.1 Canceling Exhaust Noise

The Passive Muffler. Passive mufflers are now used to control exhaust noise in automobiles. There are three classes of these mufflers.

Absorptive Mufflers. These are the straight-through or "glass pack" mufflers that were used in the hot rods of the 50s. They consist of a length of pipe with holes wrapped by fiberglass (or other sound-absorbent material) which is then enclosed by a larger diameter pipe. Absorptive mufflers are very effective at high frequencies, reduce turbulence in the exhaust, and produce little or no back pressure. They have little effect, however, on the low-frequency tonal noise from the engine unless the muffler is made impractically large.

Dispersive Mufflers. These mufflers work by creating a tortuous path for the exhaust, dissipating some noise energy while spreading the remaining noise energy across frequencies through turbulent flow. A significant amount of exhaust gas pressure is created in this process. The backpressure decreases engine efficiency. Gas mileage is reduced (typically 5 percent in city driving and 1 percent in highway driving) and peak horsepower is wasted (up to 10 percent) pushing the exhaust gasses against the back pressure. Dispersive mufflers can be effective in noise reduction at low frequencies at a reasonable size but only at the cost of high backpressure. They can have less backpressure, but then can be impractically large and heavy.

Reactive Mufflers. Reactive mufflers use acoustical resonances to reflect noise energy back to the source. This technique is often used to handle a strong noise at a particular frequency. It is a good technique for fixed rpm engine noise, but does not deal effectively in automobiles where engine rpm (or temperature, since the speed of sound, nominally 1100 ft/s, changes with temperature) varies. Reactive mufflers do introduce some backpressure but much less than dispersive mufflers.

The passive mufflers found in today's automobiles use a combination of dispersive and reactive techniques.

An Active Muffler System. Figure 31.5 shows an active muffler system as it would be applied to an automotive engine exhaust. The passive element is a simple straight-through glass pack muffler (absorptive) that controls noise above 500 Hz. The active muffler is a speaker cabinet that is concentric to the exhaust pipe and outputs the antinoise in a ring around the end of the exhaust. The symmetry of the noise and antinoise sources in this arrangement provides for global cancellation of the low-frequency noise (at very low frequencies, a side-by-side arrangement can also work). A microphone in the exhaust sound field feeds back the residual noise (after cancellation) so that the adapter (usually an LMS adaption algorithm) can continuously adjust the cancellation to drive the residual noise toward zero at the noise frequencies. The tachometer signal drives a harmonic generator to internally provide pure tones at the harmonics of the engine's basic cycle (two full revolutions in a four-cycle engine). This sets up the whole system to concentrate its efforts on the noise from the engine.

The cancellation algorithm is executed in a modern DSP computer that fits on one 250-cm^2 printed circuit board. Included on this board are:

- A digital signal processing computer (such as the ADSP-2101 from Analog Devices) capable of 10 million operations per second
- Two low-pass filters set at 500 Hz to avoid aliasing (the confusion of high-frequency signals with low-frequency signals due to sampling)
- An A/D converter to measure the noise remaining after cancellation
- A D/A converter to output the antinoise

The electronic equipment also includes an audio power amplifier (100 W for a typical automobile exhaust system) to generate the required antinoise power. Since the antinoise is at low

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frequencies, a Class D switching amplifier should be used to further enhance energy efficiency. The total electronics package for a single-channel control system should be under $100 when produced in volume.

System Performance. Active muffler systems can significantly attenuate exhaust noise. In steady state driving conditions, strong tonal components can be reduced by more than 25 dB with only a slight decrease in the attenuation level during rapid changes in driving conditions, such as gear shifting or sudden acceleration. The sound quality can also be managed by adjusting the attenuation level as a function of frequency, harmonic number, or engine conditions.

Current Status. Active muffler systems for cars, busses, and trucks are currently under development by several companies. They have been demonstrated on production cars and passed life tests. Larger systems have been tested on trucks and busses and field trials were underway in 1993 on several metropolitan bus fleets in the United States and Canada. This is a viable technology that is going to be used in production vehicles in the middle of this decade due to the effective performance and fuel economy enhancements it provides in automotive designs.

31.2.2 Controlling Engine Vibration

Passive Vibration Control. A primary consideration in modern automobile design is fuel economy. Automobile engines are therefore smaller and have fewer cylinders than the engines of a few years ago. Limiting this trend is the desire for a smooth-running car. It is difficult to balance the vibrational forces in an engine—especially the component at twice the engine rotational rate—with a small number of cylinders. One option is to use counter rotating shafts inside the engine that have a slight imbalance and spin at twice the engine rpm. The forces generated by the extra shaft can be designed to cancel the undesired vibration. The drawback to this approach is that it uses a significant percentage of the engine power (up to 10 percent has been estimated) by adding weight and friction losses.

Given that the engine vibrates, much design effort has gone into rubber engine mounts. Making the mount soft prevents engine vibration from propagating through the supporting members into the passenger compartment. The problem with soft mounts is that the engine is the heaviest single component in the car. If the engine is not firmly mounted, the handling characteristics of the automobile will suffer. The automotive designer is therefore left with a compromise among performance, economy, and comfort.

Active Engine Mounts. A solution to the vibration problem is to provide an active mount that is compliant or soft only at the vibration frequencies. Here an active vibration control system dynamically adjusts the dimensions of each engine mount so that engine vibrations are isolated from the car chassis. Again, the energy needed by the electronics is much smaller than the energy that would be lost using the passive solution. A more energy-efficient car is the result.

Figure 31.6 shows synchronous cancellation applied to create an active engine isolation mount. The antivibration continuously works against the stiffness of the mount to keep the mount out of the way of the engine at harmonics of the vibration cycle. No vibration forces are then passed through the mount from the engine and the supporting frame is vibration free.

System Performance. An active mount system can reduce peak vibrational components up to 25 dB. When applied to the major engine-mounting sites, active mounts significantly reduce vibration in the passenger compartment. They can also reduce secondary acoustical noise generated by vibrating surfaces in the passenger compartment—the major source of boom noise in cars.

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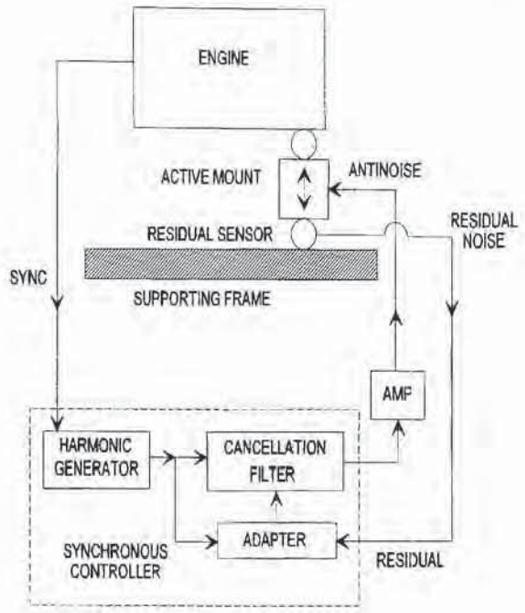


FIGURE 31.6 An active engine mount.

Current Status. Active mounting systems have been demonstrated on several production vehicles and are under development for aircraft engines. The systems can also solve vibration and mounting problems in commercial and industrial rotating machines. The remaining technical hurdle before they are ready for the automotive market is to make certain that the mounts and their actuators can stand up to the harsh shock environment in the engine compartment. Active mounts should be ready for automotive production in the latter half of this decade.

31.2.3 Passenger Cab Quieting

The primary cabin noise that active noise cancellation technology can deal with is due to the engine. Many car designs are completed only to find that at some speeds there is a disturbing low-frequency boom noise in the cabin. This noise is caused by a resonance in the structure of the cabin and is difficult to deal with using sound-absorbent materials. The boom usually occurs between 90 and 150 Hz whenever one of the harmonics of the source noise moves into the bandwidth of a resonance in the cabin structure.

The source of the noise can be either the exhaust or engine vibration passing through the mounts, vibrating cabin panels, and creating secondary noise in the cabin. The exhaust noise can be easily dealt with through the use of a good muffler and isolation of the exhaust pipes from the car body and frame. Engine vibration control is the job of the engine design and/or the mounting system but, as described earlier, it involves many tradeoffs.

Most of the other noises in the cabin are broadband noise. They include road noise, wind noise, and blower noise. The technology to deal with zonal control of broadband noise is still in the research stage.

Passive Control. Passive control of cabin noise is best done with sound and vibration absorbing materials. Fiber batting in door and ceiling panels is a significant help at higher frequencies. Vibration deadening panels (a laminate of steel and plastic) are quite effective but add significant cost to the vehicle.

At low frequencies, car cabin dimensions are comparable to the wave length of the noise. It is therefore possible to match the sound field with an antinoise field that is generated by a

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small number of speakers. If a set of residual microphones is placed around the volume to be silenced, spaced less than ¼ wavelength apart, a multichannel noise cancellation control system can synthesize the required antinoise field. Figure 31.7 shows a general configuration and the resulting quiet zone.

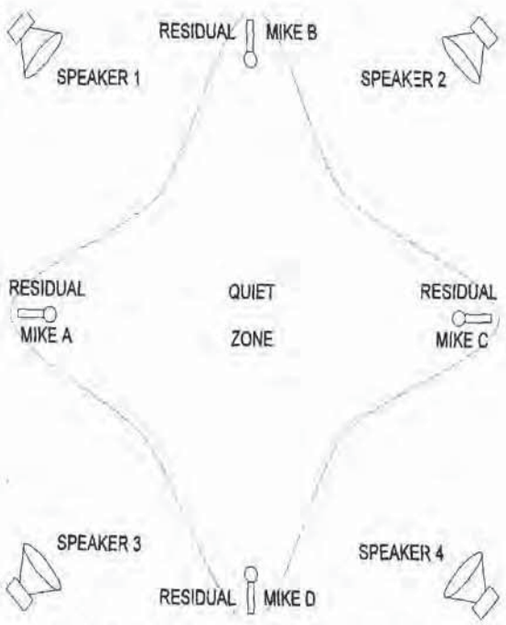


FIGURE 31.7 Zonal noise control for an automobile.

The algorithm is more complex than in single-channel applications since each residual microphone now "hears" antinoise from each of the antinoise speakers, and the electronic equipment is more expensive. This also occurs to a lesser extent for dual exhaust and multiple mount systems.

System Description. Figure 31.8 shows a zonal noise control system adapted for use as an automotive cabin-quieting system. The four to six residual microphones are placed near normal passenger head positions in the roof liners, seat backs, and/or door panels. Extra microphones are used, since at some frequencies resonances in the cabin will place a null of the sound at some locations.

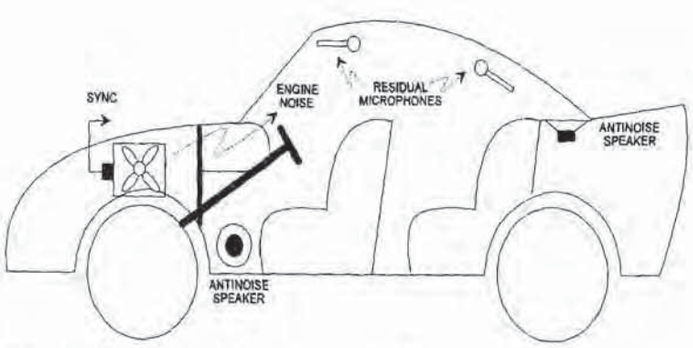


FIGURE 31.8 An automobile cabin-quieting system.

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Four antinoise speakers are placed at convenient locations in the cabin. The existing sound system can be used to save money but care must then be taken to insure that the high-level antinoise tone does not create distortion in the amplifiers and speakers. This will usually require an upgrade in speaker quality, and separate low-frequency subwoofer speakers are desirable.

Proper design of a cabin-quieting system involves a careful analysis of cabin acoustics to determine proper speaker and microphone placement. It also depends on the existence of sufficient sound-absorbing materials in the cabin to limit the strength of resonances so that the mathematics of the algorithm do not require excessive precision.

System Performance. Cabin-quieting systems can reduce the peak boom by up to 10 dB. This significantly enhances any vehicle that has a major boom problem.

Current Status. Cabin-quieting systems have been installed and tested in a number of production cars. One model car with a cabin-quieting system was marketed in Japan in 1992. An aircraft manufacturer has announced the intention to market similar, but significantly larger, systems in its 1994 model turboprop aircraft. This is a currently viable technology to enhance automotive designs.

31.2.4 Controlling Blower Noise

Most of the noise from the heating/ventilation/air conditioning (HVAC) blower in cars is due to turbulent flow in the distribution ducts. This noise can be reduced through careful design of the ducts. Some guidelines follow:

- Reduced air velocity is the strongest factor in controlling turbulence. Larger duct cross sections and larger output ports should be used wherever possible.
- Duct liners made of sound-absorbing material can attenuate the higher-frequency noise.
- Discontinuities in the air flow should be eliminated. All turns should be smooth as any change in air flow direction or obstructions will generate additional turbulence and noise.

Passive controls can give 6 to 10 dB of improvement in the noise level and the successful use of active noise control for further reduction requires that attention be paid to passive controls first.

An Active Duct Silencer. The feed forward cancellation system in Fig. 31.4 has already been described in the context of controlling broadband noise in an air duct. Implementation of a duct cancellation system requires a close interaction with the physical design of the air distribution system in the car. A successful system will result only after several design iterations between the group doing the cancellation system and the design group responsible for the cabin design.

A good duct cancellation system in these small ducts can reduce the noise by 10 to 15 dB from 50 Hz to 1 kHz. This results in a typical noise reduction in the dBA noise measurement of 4 to 6 dB.

Duct cancellation systems for commercial applications have been available for several years. The cost-effective (less than $50 system cost) application of this technology to home appliances has been announced and will see production in 1994. This is another viable application of active noise control in current automobile designs.

31.2.5 Active Suspension Systems

The technology used in an active suspension system is closely related to that used in active noise cancellation. For a description of active suspensions, see Chap. 17.

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