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ELECTROMAGNETIC INTERFERENCE EFFECTS ON MOTOR VEHICLE ELECTRONIC CONTROL AND SAFETY DEVICES

Volume III-Automotive EMC Guidelines

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16. Abstract

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The applications and technological developments concerned with current automotive electronics are discussed. The research conducted by the automotive industry to explore the feasibility of a central processor or control system and potential problem areasare reviewed. A section is presented on the automotive electrical environment including a summary of source and coupled waveforms. A large section discusses guidelines for design, installation and testing of electronic control and safety devices in automobiles.

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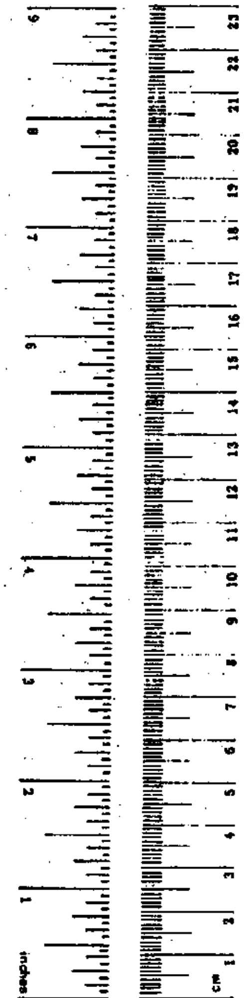
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

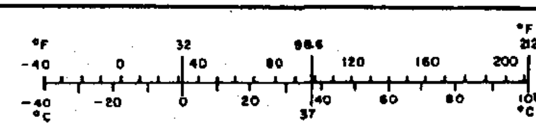
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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ELECTROMAGNETIC INTERFERENCE EFFECTS ON MOTOR VEHICLE ELECTRONIC CONTROL AND SAFETY DEVICES

Volume 3 - Automotive EMC Guidelines

R.H. Espeland and E.L. Morrison, Jr.*

This report is a set of basic guidelines to promote EMC in the use of electronic control and safety devices in automobiles.

The applications and technological developments concerned with current automotive electronics are discussed. The research conducted by the automotive industry to explore the feasibility of a central processor or control system and potential problem areas are reviewed. A section is presented on the automotive electrical environment including a summary of source and coupled waveforms. A large section discusses guidelines for design, installation, and testing.

Key Words: Electromagnetic compatibility, automotive electronic systems, automotive electrical environment, EMC guidelines.

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1. INTRODUCTION

The period from the introduction of the first electric ignition system to the automobile in 1885 until electronic ignition systems became standard equipment on many U.S. automobiles in 1975 spans 90 years. Today, twelve other electronic subsystems, in addition to entertainment and communication subsystems, are available as standard or optional equipment on many U.S. and foreign manufactured automobiles. Except for the primary electrical power package (including the battery, generator, starter and lamps), which was introduced in 1912, these additional electronic subsystems have become available only in the last 15 years.

This recent integration of electronic subsystems into a previously mechanical environment has not come easily in the highly cost and reliability conscious automotive industry. Most new subsystems take three-to-five years from prototype to standard equipment, including a typical test-evaluation period and fleet trial-evaluation period.

Many proposed automotive subystems have the potential of being accepted. Factors that control this rate of acceptance include: 1) a requirement that the electronic device which replaces its mechanical counterpart do so on a cost-effective basis and meet reliability/ warranty standards, 2) a requirement that the device provides the only practical way to fulfill mandatory safety requirements, or 3) a requirement that it is an optional, extra-cost item.

Today's automotive electronic subsystems have been added or offered as stand-alone units. Many have the potential of being combined with other devices or of being designed into an overall system controlled by a central processor. This use of electronic subsystems for performance of safety and control functions in automobile operations has not been without some problems and barriers. Among these is the hostile environment of the automobile and highly variable primary (12 V) power supply.

The first part of this research was to assess the electromagnetic environment of representative motor vehicles and to determine, analytically, the susceptibility of various electronic components and subsystems to this environment (Espeland, et al. 1975). The current research effort has been to further the investigation of the internal environment and to test selected subsystems to determine the susceptibility of these devices. The results of this measurement work, testing, and further analytical studies are reported in Volume 2 of this report. A principal objective of this research has been to develop general guidelines for the packaging and installation of electronic safety and control devices on motor vehicles to accomplish electromagnetic compatibility (EMC).

These guidelines are the subject of Volume 3 and are based on the results of the tests and measurements, and the reportings of current research and development by the automotive and electronic industries.

This report is divided into five parts. The first reviews automotive electronics and includes a survey of applications and functions employed. It also deals with preliminary studies of future electronics in automobiles. Among these is the use of a central control or processor system.

The second section is a summary of the electrical environment (both internal and external) encountered by the vehicle and discusses various aspects of signal coupling between cables and from electromagnetic fields into cables.

Sections 3 through 5 include discussion of accepted practices and rules regarding EMC of electronic systems and provide general guidance in interpretation of these rules in the automobile environment. These guidelines have been compiled with an eye to the future. Where the capability to withstand high voltage-high current of interface devices has established compatibility in many of the less complex, stand-alone subsystems of today, the more complex, higher density applications (central processors) of the future will require additional protection and isolation to function properly.

2. AUTOMOTIVE ELECTRONICS

2.1 Applications and Functions

A number of lists of actual and proposed automotive electronic applications have been compiled. The list in Table 2.1 is a composite of several of these lists and divides the applications into four categories: 1) safety, 2) performance, 3) convenience, and 4) entertainment. Several of these applications might logically fall into more than one category. The tire pressure monitor, for example, could be classified as both a safety device and a convenience. Those marked with an asterisk are presently available.

The common elements of typical automotive electronic control subsystems are shown in Figure 2.1. The titles inside the blocks define the elements of the control system. Many of the elemental functions can be performed with electronic devices. Those listed below the blocks can be performed electronically.

Requirements and applications of some automotive interface electronics are similar to those used in industrial control. Thus, it is possible the developments for industry will have application in motor vehicles. Some of the new products will serve both industries. The motivation for this development has been to overcome some environmental problems, to reduce costs, and to improve reliability.

2.2 Future Electronic Systems

The presently available subsystems, either standard or optional, are basically of stand-alone, semi-autonomous design. This means that each device was designed to perform a specific function and contains all the circuits and components necessary to perform that function without consideration of how it might share input data from other subsystems or subsystem sensors or how it might share its derived information.

2.2.1 Systems Research

Several automobile manufacturers are studying the use of microprocessors and/or other computation and control devices in modular and

Table 2.1 Automotive Electronic Applications

Safety

Road Conditions Alarm
*Electronic Headlight Dimmer Control
*Vehicle Velocity Sensor (Speed Control)
*Windshield Washer/Wiper Control
*Air Bag Systems
*Seat Belt
*Anti-skid Breaking (Skid Control)
Collision Avoidance Radar
Obstacle Detector
Sobriety Detector (Physiological Tester)
*Sequential Turn Signals
*Door and Ignition Locks
*Emergency Flashers
Brake Fluid Sensor

Performance

*Electronic Fuel Injection
*Electronic Ignition (Solid State)
*Electronic Fuel Pump
*Voltage Regulation
*Alternators (Rectifier)
*Pollution Control (Emission Control)
Transmission Control
RPM Limiter
*Catalytic Converter

Convenience

*Heater (Air Conditioner Temperature Control)
*Speed Indicator
Tire Pressure Monitor
*Anti-Theft Alarms (Security Alarms)
*Clocks (Solid State)
*Tachometer - Speedometer - Odometer
*Emergency Radio Transmitter
Radar Speedometer
*Low Fuel Indicator
Digital Display (Instrumentation Display)
Periodic Service Reminder Indicators (Automotive Diagnostics)

Entertainment

*AM/FM Radio
*Tape Player

*Presently available

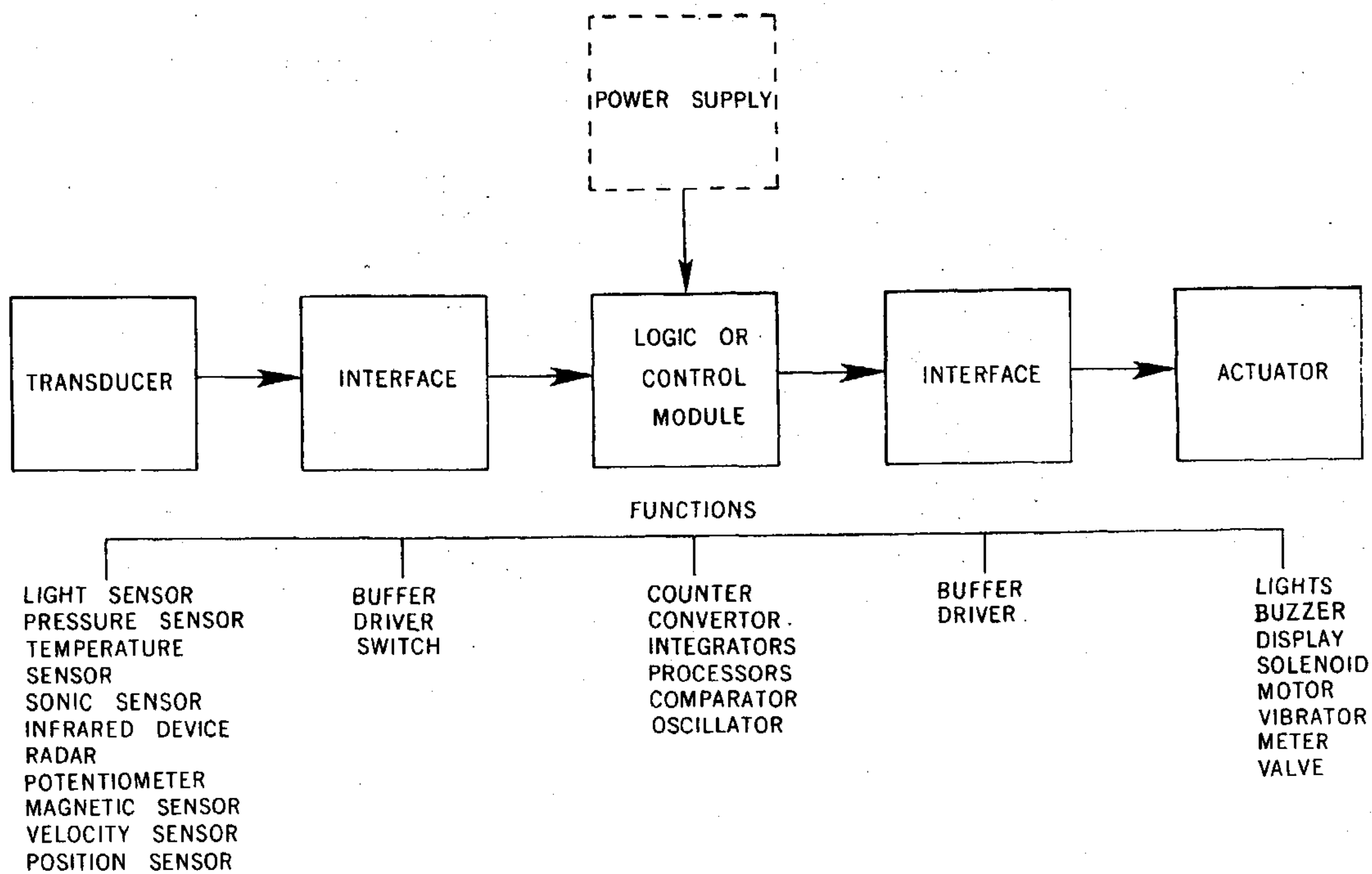

Figure 2.1 Functions and Elements of Electronic Subsystems

central processor applications (Jurgen, 1975). Ford Motor Company is working on the development and demonstration of a digital control system that maximizes fuel economy and driveability for a given level of emissions (Oswald et al., 1975). General Motors (Jones, 1975) has had an extensive research program underway in which several in-vehicle, experimental, integrated electronic systems have been built and studied. Four separate studies have been conducted bearing the series names Alpha, Sigma, Delta and Beta. Overall system integration was studied in the Alpha series and the Sigma series dealt with display systems. Both on-board and off-board diagnostics were explored in the Delta series, and driver physiological considerations were undertaken in the Beta series. The findings from these studies have been combined and analyzed to form the basis for Omega - an automotive central processor.

The result of the Alpha IV program is an operating vehicle system utilizing an MOS LSI microprocessor on a time-shared basis to perform multiple functions. By effective engineering, the 4-bit word length and limited memory of these microprocessors was not a deterrent to the application of this technology to automobiles (Jones, et al., 1975). Although the feasibility of this approach has been proven, areas exist where further work must be done. The diagram in Figure 2.2 shows progression from subsystems operating as discrete separate functions to modules using multiplexing and special connectors and harnesses. The last step is toward the central processor, probably in conjunction with one or more subsystem microprocessors. Major development requirements to realize fully integrated electronic control systems are transducers, processors, actuators, and displays. Associated with these requirements are such factors as cost, size, and data and power distribution. Even if all these barriers are removed, the progression will still probably be modular, because of such factors as consumer acceptance and regulatory legislation.

2.2.2 Problem Areas

The following paragraphs discuss the potential problems of electromagnetic compatibility associated with modular and fully integrated

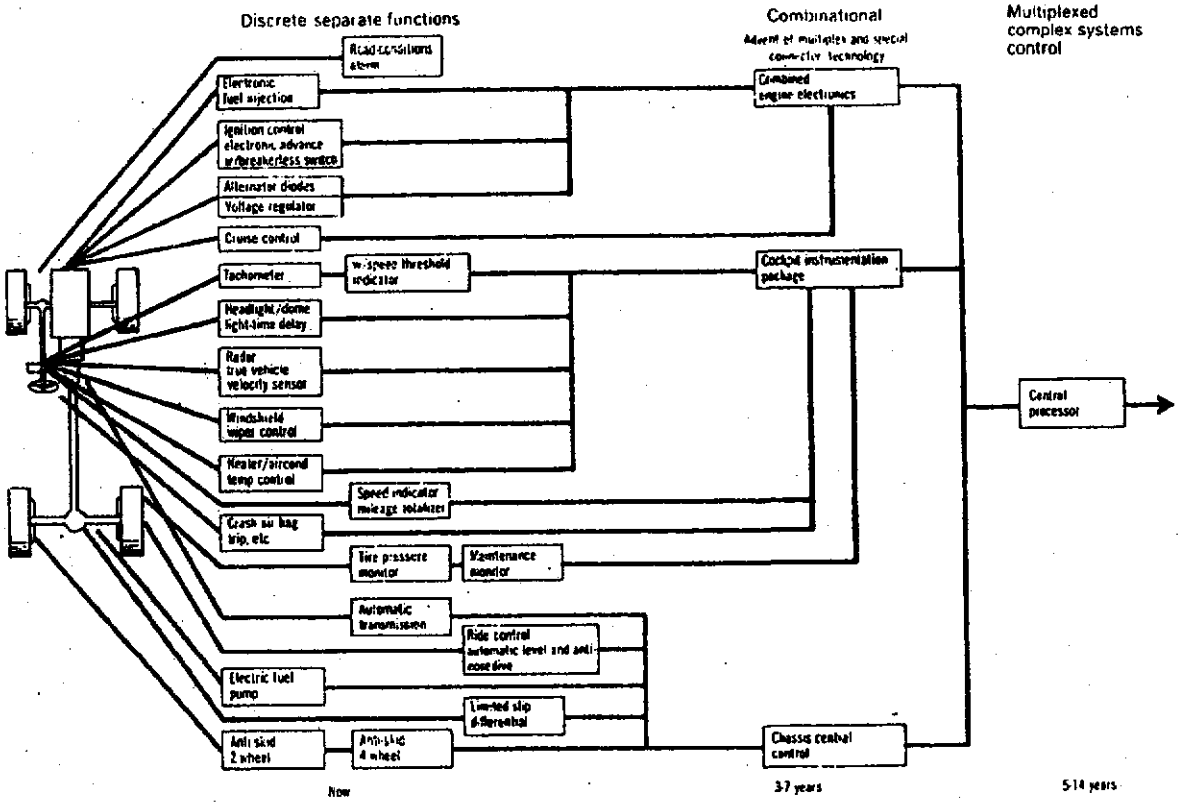

Figure 2.2 Automotive Electronic Subsystems (Hood, 1974)
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Society of Automotive Engineers, Inc., 1974,
all rights reserved.)

electronic control systems. Some of these problem areas result from attempting integrated systems control, and some (such as interface) would exist anyway.

2.2.2.1 Environment

One principal area of concern associated with the use of microprocessors in automobiles is their ability to survive in the extreme electrical and physical environments. This is indeed a concern with regard to all low-power digital logic circuits. The high reliability and performance standards achieved in many computer and data handling applications of similar digital circuits is due to the careful control of the environment. Various isolating and protective techniques could be used. An overall system design approach would appear advisable which considers not only the circuit design, but also optimum placement, powering, cable routing, etc.

2.2.2.2 Transducers and Actuators

Transducers are devices that sense or measure such physical parameters as temperature, pressure, and velocity, and convert these measured values to electrically scalable quantities such as voltage, current, or frequency. These electrical quantities may be used directly or they may be digitized for use in the control processors of the electronic subsystems. This requires analog-to-digital converters to interface with the control circuits, which adds to the cost and complexity of the system. Also, some desired transducers do not exist. For example, a need exists for a small reliable tail-pipe emissions sensor as part of the closed-loop engine and emissions control system (Jurgen, 1975). A further concern in regard to sensors is their precision and range. In some applications, absolute linear (or uniform) calibration may not be of great concern, but repeatability may be required. Also, these devices may be used not only in harsh electrical environments, but in such severe physical environments as those encountered on the axles and wheel mountings, where shock accelerations of 20 g's and temperature ranges of $100^{\circ}C$ are common.

Actuators are devices that accept commands in electrical form and respond with a mechanical, hydraulic, or pneumatic action. They serve as the interface between the control decision and the control action. Actuators are often cited as the largest single barrier to introducing cost-effective electronics to the automobile. In the electronic anti-skid control systems, the hydraulic brake pressure module is more costly than the electronic control unit (Jurgen, 1975).

The requirement for cost-effective, reliable transducers and actuators exists whether automotive electronics continue to be developed on the discrete separate function basis or progress to an integrated system. The one advantage of the integrated system approach is the multiple use of a given transducer, which has the effect of cost sharing. If on-board diagnostics are added to an overall electronic system, then certain sensor applications will be even more fully utilized.

2.2.2.3 Power and Signal Distribution

As more electronic devices are used in automobiles, and as these devices are more closely integrated, methods of data and power transmission must be more carefully considered. As the number of automotive electronic systems increases, a point is reached where discrete wire cabling is not cost-effective. This increased density of systems may cause space limitations and electromagnetic incompatibilities. It is, therefore, important that designers consider other techniques, such as multiplexed, continuous cable, communication systems and fiber optic systems. These systems would be isolated from the normal electrical power busses presently used (Ziomek, 1973). Also, it seems imperative that a dedicated power bus be provided for the electronics control systems. Such a bus could be protected from the severe transients and voltage variations typical of today's automotive power bus. It could be highly regulated and have a limited stand-by capability for data retention.

2.2.2.4 Displays

Displays are devices that indicate modes or conditions of system operation. They can be as simple as an "on-off" light or as sophisticated as a programmable digital meter. Some display requirements can be adequately met with warning lights and others could more desirably use meters with numerical read-outs. The meters would be more costly and require more space. However, they are adaptable to shared use. With proper engineering, a device such as a digital clock could be intermittently or temporarily used as the display for various other monitoring and diagnostic requirements.

2.2.2.5 Cost and Size

The use of a digital processor for vehicle control functions will have a high entry cost and relatively low incremental costs for added functions which require the arithmetic or logic capability. As stated before, the transducer and actuator costs are somewhat independent of method of control (discrete system vs. central processor). Cost effectiveness will jointly be provided by improved vehicle operating economy and in performance and safety improvements. Such areas as fuel metering (injection), electronic timing and ignition, emission controls, and integrated closed loop combination of these areas have the potential of providing cost-effectiveness. Applications of integrated control electronics may be possible on a modular basis designed for orderly expansion.

3. AUTOMOTIVE ELECTRICAL ENVIRONMENT

The electrical environment of the automobile is characterized by voltage fluctuations, noise, and severe transients. Mishandling (jumper starts and loose cables) and component degradation add to a normally difficult environment. Several authors have written on the various aspects of the internal automotive electrical environment. A survey of this literature and a study of the worst case external fields to which automobiles might normally be exposed were included in an earlier report (Espeland, et al., 1975).

In the current measurement work, a comprehensive survey was made of the many noise and signal sources within a vehicle and of the degree of signal coupling which results from normal cable bundling.

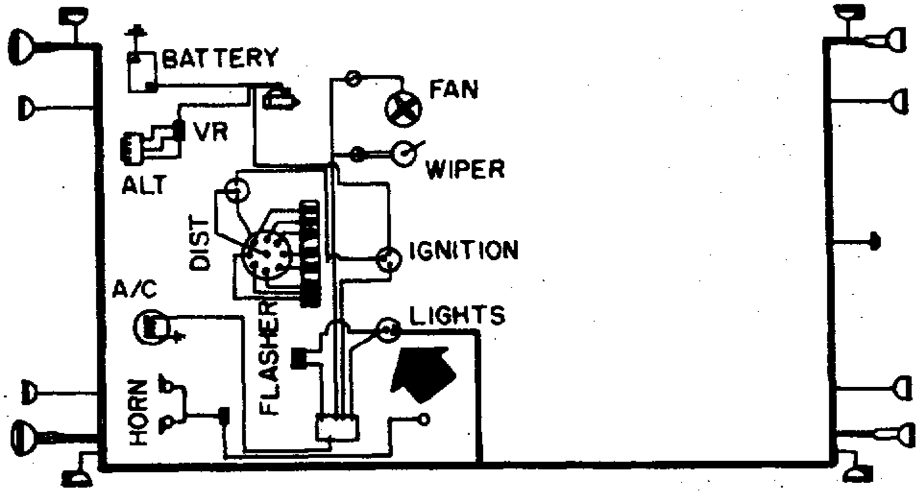
The data presented in this section includes the results of the source and coupled signal measurements (the complete report of this work is included in Volume 2) and a summary of the earlier survey and study. Regardless of what design changes occur in the future, it is reasonable to assume that the environment will not become worse and that this collection of data will serve as a good reference describing the most severe electrical environment to which present and future electronic devices will be exposed.

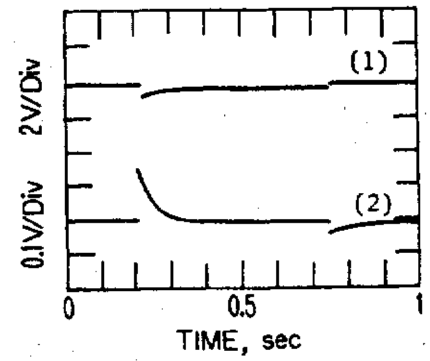
Future work by the automobile industry may effect an improvement in the electrical environment by using techniques to eliminate sources within the vehicle and to reduce penetration of external signals and coupling of internal signals.

3.1 Source Signal Waveforms

The data in sections 3.1, 3.2, and 3.3 are the results of the electrical signal measurements task. A 1975 Ford station wagon was used as the test vehicle. These data are considered typical of most passenger vehicles. The data shown in Figures 3.1 and 3.2 are typical of the waveforms recorded in the measurements task. These are respectively associated with switching of lights and activation of the horn circuit.

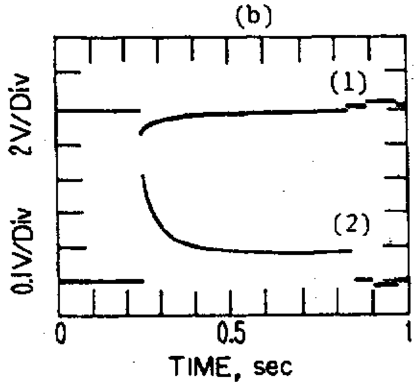
A summary of the results obtained is shown in Table 3.1. Identified in the table for each source equipment is the initial action the



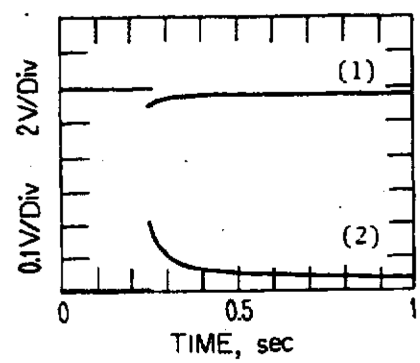


(a) 1 Main bus (low beam on-off)
2 Right front turn-signal lamp

(b)

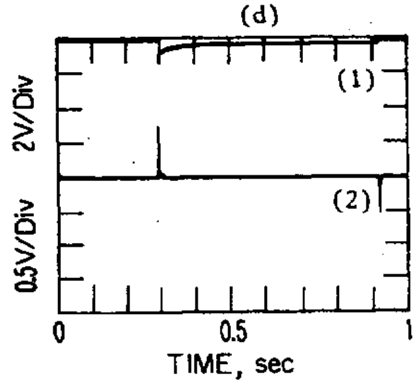


(b) 1 Main bus (high beam on-off)
2 Right front turn-signal lamp



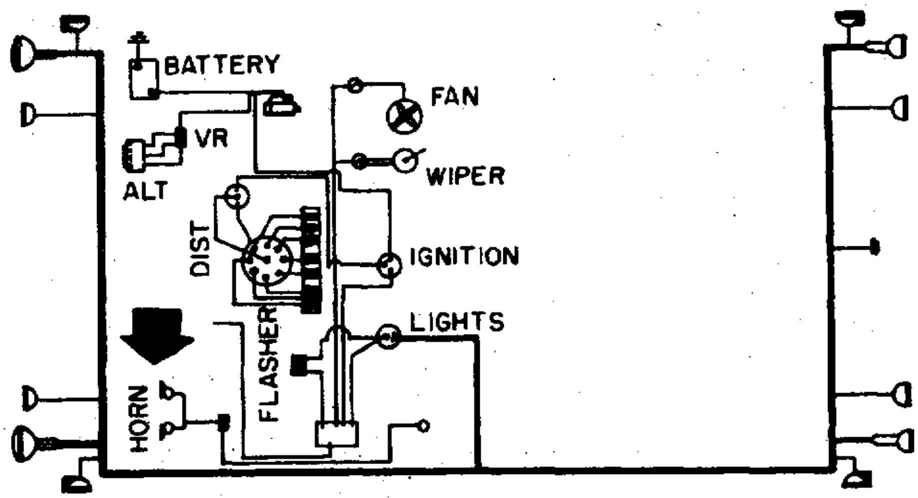
(c) 1 Main bus (high beam on-off)
2 Right front low beam lamp

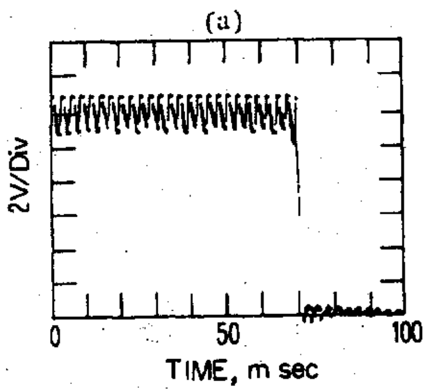
(d)



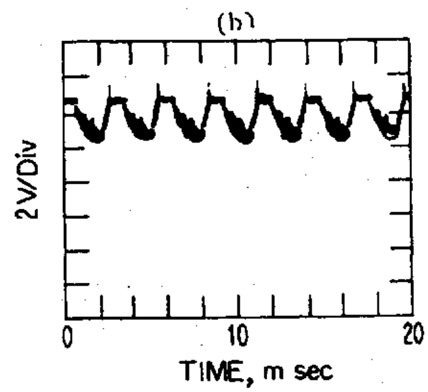
(d) 1 Main bus (high beam on-off)
2 Right front low beam lamp
(lamp removed)

Figure 3.1 Light Switch Signals

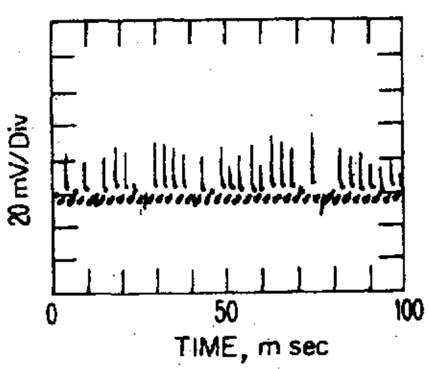




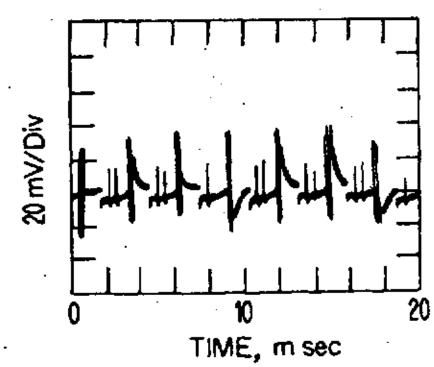
(a) Horn circuit
(on-off)



(b) Horn circuit
(horn sounding)



(c) Main bus
(horn sounding)



(d) Main bus
(horn sounding)

Figure 3.2 Horn Waveforms

Table 3.1 Source Waveform Summary

EQUIPMENT (SOURCE)	WAVEFORM	DURATION (FREQUENCY)	AMPLITUDE
Light Switch	1.) Switching Transient (Low Beam)	.2 s	≈1.0 V
	2.) Switching Transient (High Beam)	.2 s	≈1.0 V
	3.) Switching Transient (High Beam)	.2 s	≈1.0 V
	4.) Switching Transient (High Beam)	.2 s	≈1.0 V
Air Conditioner Clutch	Switching Transient (On-Off)	60 ms	70 V
Starter Solenoid and Starter	1.) Starter Solenoid (Switching Pulse)	(On-Off)	12 V
	2.) Main Bus (Disabled)	(On-Off)	12 V
Ignition System	1.) Ignition Spark	(RPM Dependent)	9 V
	2.) Breaker Points	(RPM Dependent)	700 V
	3.) Distributor Output	(RPM Dependent)	≈15 KV
	4.) Spark Plug	(RPM Dependent)	≈12 KV
Turn-Signal and Emergency Flashers	1.) T.S. Flasher Output (On-Off)	.25 s	≈12 V
	2.) Emergency Flasher		≈12 V

Table 3.1 (continued) Source Waveform Summary

EQUIPMENT (SOURCE)	WAVEFORM	DURATION (FREQUENCY)	AMPLITUDE
Transient Simulator	Simulated Transient	250 ms	≈50 V
Fan Motor	1.) Fan Motor	(555 Hz)	≈100 mV
	2.) Switching Transient and Decaying Sinewave	.4 ms (Variable)	≈7 V ≈2.5 V
Alternator	Alternator Output	(RPM Dependent ≈900 Hz)	60 mv
Windshield Wiper	1.) Motor	(RPM Dependent ≈500 Hz)	≈.3 V
	2.) Switching Waveform	.1 s	12 V
Horn	Horn	(≈350 Hz)	≈3 V
Broadband Noise (measured on the main power bus)	1.) Ignition Key Buzzer	0-100 MHz	-22 dBmW @ 0-5 MHz
	2.) Horn	0-100 MHz	-40 dBmW near 50 MHz
	3.) Engine Idling	0-100 MHz	-15 dBmW near 1 MHz

signal frequency or duration, and the amplitude. The amplitudes range from less than 100 mV to 70 V (excluding the ignition system). The transient durations are typically less than a second and the frequencies of the repetitive waveforms are generally under 1 kHz. The repetitive waveforms are engine or motor speed dependent and can exceed this value. The larger transients are from the inductive loads or equipment. Voltages greater than 15 kV were measured at the distributor and spark plugs. Very typical of both the transient type and sinusoidal waveforms is an associated high frequency noise. The characteristics of this noise are determined by circuit loading, switching actions, and tuned or resonant components.

The transient simulator data described in Table 3.1 was recorded using a transient simulator that was constructed according to a design in SAE J1113 (SAE, 1975).

The broadband data described in Table 3.1 are measured at the power bus. These were the maximum values observed in the 0-100 MHz band. Additional broadband noise data are given in Section 3.5.

3.2 Coupled Signal Waveforms

The electronics developer and the automobile designer are interested not only in the characteristics of the signals as generated, but also the magnitude and characteristics of signals that have been coupled to other circuits and locations within the automobile electrical and electronic networks. The data represented in Table 3.2 result from the measurements work described above. These waveforms were measured not at the source, but at points remote from the source. In some cases, the data are recorded on isolated circuits to evaluate typical electromagnetic coupling conditions. Such a coupled waveform is shown in Figure 3.1(b). The data in the table identify the source equipment, the location of data recording, duration or frequency, and amplitude.

Measured amplitude values of coupled signals range from less than 50 mV to more than 1 V. Again, the spark plug signal values far exceeded this range. The sinusoidal signals are similar in frequency to those measured at the sources (described above). These waveforms resulted

Table 3.2 Coupled Waveform Summary

EQUIPMENT (SOURCE)	LOCATION	WAVEFORM	DURATION (FREQUENCY)	AMPLITUDE
Light Switch	1.) Turn Signal Lamp	Spike	100 ms	150 mV
	2.) Turn Signal Lamp	Spike	100 ms	300 mV
	3.) Low Beam Lamp	Spike	100 ms	200 mV
	4.) Low Beam Lamp (Bulb Removed)	Spike	5 ms	+700 mV -1.2 V
Air Conditioner Clutch	1.) Main Bus	Spike (Noise)	250 ms	300 mV
Starter Solenoid and Starter	Battery	Spike and Cogging	(While Cranking)	7 V 1 V
Ignition System	1.) Battery Plus Terminal	Pulse	(RPM Dependent)	50 mV
	2.) Main Bus	Pulse	(RPM Dependent)	1 V
	3.) Spark Plug Wire (No Arc Across Plug)	Damped Sinewave	(RPM Dependent)	≈35 KV
Turn-Signal and Emergency Flashers	1.) Lamp Ground Wire	Spike	40 usec	≈100 mV
	2.) Parking Lamp Wire	Spike	20 usec	≈600 mV
	3.) Back-Up Lamp Wire	Spike	20 usec	≈300 mV
	4.) Back-Up Lamp Wire (Lamp Removed)	Spike	10 usec	≈750 mV

Table 3.2 (continued) Coupled Waveform Summary

EQUIPMENT (SOURCE)	LOCATION	WAVEFORM	DURATION (FREQUENCY)	AMPLITUDE
Transient Simulator	Windshield Wiper	Spike	200 ms	150 mV
Fan Motor	1.) Main Bus Right Front Parking Lamp	Sinewave	(555 Hz)	50 mV
Alternator	1.) Main Bus	Ripple	(≈900 Hz)	20 mV
	2.) Main Bus (Abnormal)	Ripple	(≈900 Hz)	≈6 V
Windshield Wiper	1.) Main Bus	Ripple	(≈500 Hz)	.2 V
	2.) Battery Terminal	Ripple	(≈500 Hz)	≈30 mV
Horn	Main Bus	Periodic (Noisy)	(≈350 Hz)	60 mV
Broadband Noise (measured on the main power bus)	1.) Main Bus	(Broadband Noise)	0-100 MHz	-22 dBmW @ 0.5 MHz
	2.) Main Bus	(Broadband Noise)	0-100 MHz	-40 dBmW near 50 MHz
	3.) Main Bus	(Broadband	0-100 MHz	-15 dBmW near 1 MHz

generally from normal switching and motor actions. It is possible and suggested that even greater levels can result from abnormal conditions that would remove some of the normal loading impedances or which could create undesired resonant circuits.

3.3 Chassis DC Resistance Measurements

A set of dc resistance measurements between selected chassis points and a common ground point was made, and the results are shown in Table 3.3. The ground strap bolt between the engine and the vehicle frame was selected as the common ground point. The significance of these data is that they represent the actual impedance at these potential ground points and would be helpful in selecting the optimum locations for grounding electronic circuits.

3.4 Power Supply Characteristics and Severe Transients

The data in Sections 3.4, 3.5, and 3.6 are compiled from the final report of an earlier study (Espeland, et al., 1975). A complete discussion of the motor vehicle electrical environment sources is given in Section 2 of that report. Two summary tables describing the automobile voltage regulation characteristics and automotive transient voltage characteristics are given in Tables 3.4 and 3.5, respectively. Table 3.4 shows both normal and abnormal voltage ranges of the main power bus. The three transient types shown in Table 3.5 are the most severe encountered in the automobile. This range of values is typical of what has been measured and reported by researchers in the automotive industry.

3.5 Normal Noise Levels

In addition to the data on discrete sources and specific waveshapes associated with those sources (sections 3.1 and 3.2), several measurements were made of broadband noise in the automobile, and the results are included in Tables 3.1 and 3.2. As a supplement to those data, summaries of investigations by researchers in the automobile industry regarding noise characteristics and noise envelopes are included in this section. These results are shown in Table 3.6 and Figures 3.3 and 3.4. The data in Figure 3.3 is described as an oscillogram of automotive

Table 3.3 Chassis DC Resistance Measurements

FUNCTION	LOCATION	RESISTANCE (MILLIOHMS)
Ground	1.) Starter Solenoid (Right Front Fender)	3
	2.) Battery Post (Negative)	1
	3.) Engine-To-Fire-Wall Cable	2
	4.) Instrument Panel	2
	5.) Hood Grounding Tab	1
	6.) Head Lamp Groung Lug (Left)	3
	7.) Head Lamp Ground Lug (Right)	3
	8.) Tail Lamp Ground Lug (Left)	2
	9.) Dome Light Ground	3
Ground Wires	1.) Tail Lamp Ground Wire (Left)	22
	2.) Tail Lamp Ground Wire (Right)	13
	3.) Park Lamp Ground Wire (Left)	22
	4.) Park Lamp Ground Wire (Right)	43
	5.) Head Lamp Ground Wire (Left)	22
Housing	1.) Tail Lamp Housing (Left)	25
	2.) Tail Lamp Housing (Right)	24
	3.) Cigar Lighter Housing	16
Frame	1.) Alternator	1
	2.) Rear Seat Frame	1
	3.) Front Seat Frame	1
	4.) Front Door (Left)	1
	5.) Rear Door (Left)	4
	6.) Tailgate Door	6
	7.) Hood Hinge	4
	8.) Front Bumper	10
	9.) Rear Bumper	9
Axles *	1.) Rear Axle (Right)	104 (0.104 ohms)
	2.) Front Axle Shaft (Right)	1416 (1.416 ohms)
	3.) Front Wheel (Right)	1440 (1.44 ohms)
	4.) Front Wheel (Left)	1060 (1.06 ohms)

* Vehicle not equipped with a radio - the grounding modification kit (axles) not installed .

Table 3.4 Automotive Voltage Regulation Characteristics (After SAE, 1974)

Condition	Voltage
Normal operating vehicle	16 V max 14.2 V nominal 10 V min
Cold cranking at -20 F (-29 C)	4.5 V
Jumper starts	24-36 V for 5 min. Reverse polarity
Voltage regulator failure	17 V
Battery electrolyte boil-off	75 V - 130 V

Table 3.5 Automotive Transient Voltage Characteristics (After McCarter, 1974)

Type	Maximum Amplitude	Rise	Decay	Remarks
Load Dump	125 V	100 ms	0.1-4.5 s	Damage Potential
Inductive Switching	-0210/+80 V		320 μs	Logic Errors
Alternator field Field Decay	-100 V	2 ms	200 ms	Occurs at Shutdown Only

Table 3.6 Summary of Automotive Electrical Continuous Noise Characteristics (After SAE, 1974)

Type	Max. Amplitude	Duration	Repetition Rate	Remarks
Normal Accessory Noise	1.5 V peak	Frequency	50 Hz to 10 kHz	Total pulse height: 3V-PP
Normal Ignition Pulses	3.0 V peak	10-15 μs	Dependent on engine speed	Total pulse height: 6V-PP
Abnormal Ignition Pulses	75 V peak	∿90 μs	Dependent on engine speed	
Transceiver Feedback	15-20 mV	Carrier	Frequency	Sinusoid

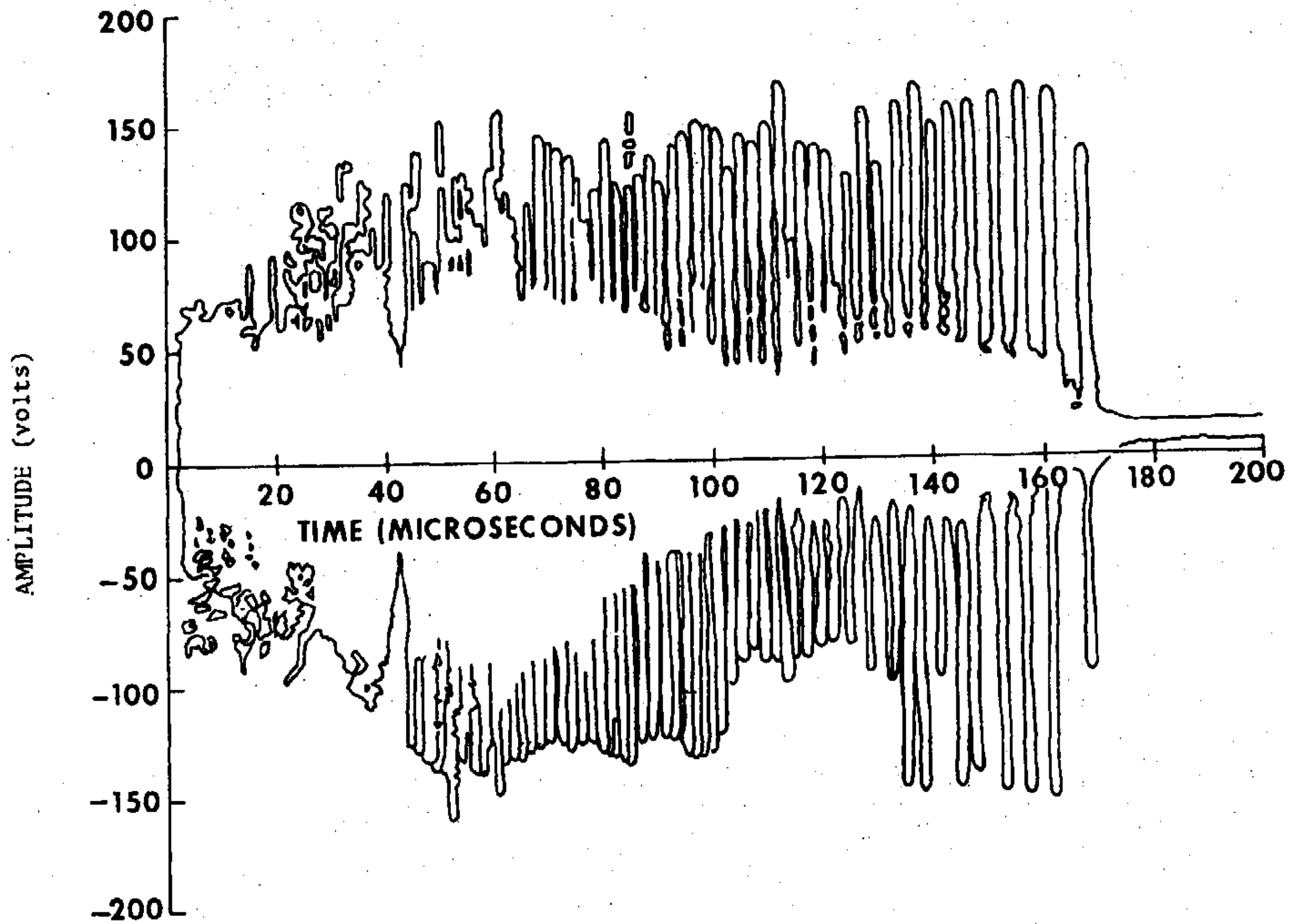


Figure 3.3 Power Line Electrical Noise (After SAE, 1974)

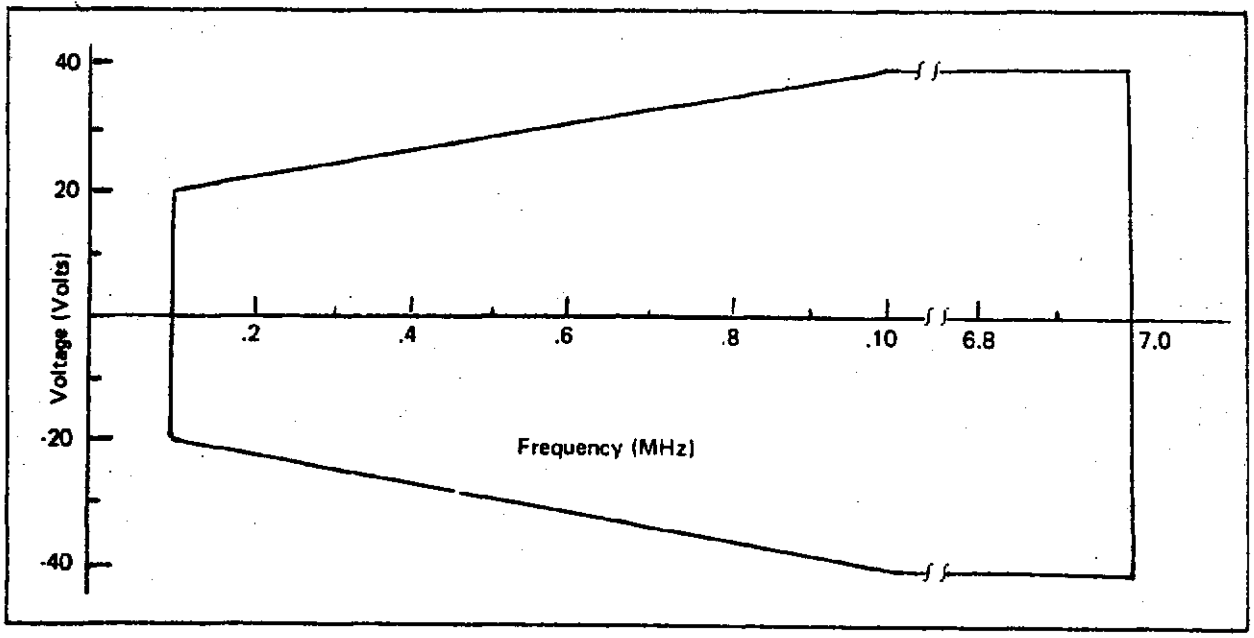


Figure 3.4 High Frequency Noise Envelope
(After Caiati and Thompson, 1973)

electrical noise. The envelope described in Figure 3.4 is part of system functional requirements suggested by the authors of a study on "The Feasibility of a Car Central Computer" (Caiati and Thompson, 1973).

3.6 External Sources

A survey of the external electromagnetic environment to which motor vehicles are exposed was conducted and reported in the final report (Espeland, et al., 1975). A summary of results is given in Table 3.7. These data are based on reported figures or calculated from appropriate equations. These data are considered to be worst case for normal driving conditions. These external fields are exterior to the vehicle. Any normal body, enclosure, or cable shielding would reduce these values.

Table 3.7 External Electromagnetic Fields

Source	Frequency	Distance	Field Strength
Broadcast Signal			
AM (Commercial)	535-1605 kHz	160 m	40 V/m @ 50 kW
FM (Commercial)	88-108 MHz	160 m	10 V/m @ 100 kW
TV (UHF)	470-806 MHz	160 m	76.1 V/m @ 5000 kW
Radar			
Military	1-10 GHz	310 m	200 V/m (AN/FDS-16)
Airport		600 m	1378 V/m (ARSR-2)
Mobile Radio			
HF-VHF	25-50 MHz	2 m	27 V/m @ 100 W
VHF	150-174 MHz		
UHF	406-512 MHz		
Power Transmission Lines	20 Hz to 1 kHz	underneath the line	greater than 1 V/m (values as high as 1000 V/m @ 60 Hz)
Arc Welders	2-3 MHz	300 m	0.1 mV/m
Wood Gluer	10-20 MHz	300 m	1.0 mV/m
Flourescent Lamp	10 kHz	1 m	0.1 V/m
Lightning	1 kHz to 18 kHz	500 m	1700 V/m
		1000 m	1000 V/m

4. GUIDELINES FOR DESIGN

In preparing these guidelines, and similarly for Sections 5 and 6 (on installation and testing), care has been taken so as not to dictate the type of circuit, components, design, etc., to be used in any electronic device for motor vehicles. These decisions should be made by the automobile manufacturer or his designates (electronic and auto parts manufacturers). However, the manufacturer can be required to adhere to certain minimum standards and practices that affect performance and safety of electronic devices, and it is the role of this report to highlight those areas that will help establish these standards in relation to EM environment effects.

The safe and proper functioning of electronic devices in a harsh electrical and physical environment is not unique to the automobile. Similar environments have been experienced in certain military and industrial applications. One area that can be considered unique, however, is the enormous range and experience of operators and "repair and maintenance" people to which these devices will be exposed. This factor must be considered in the design areas that will impact on equipment service and maintenance.

The following paragraphs will point out areas of consideration and good practices that should be reviewed in the establishment of design guidelines for automotive electronics. The first section reviews some material on device sensitivities and noise immunity. The selection of components in the design can be very important in meeting the immunity requirements of the subsystem. In the second section, examples of technological development are given which demonstrate the dynamics of this industry and the impact it can have on the safety and control features of automobiles. The remaining sections discuss other considerations such as modular design, use of proven devices, advantages of a single power supply, component shielding, and component selection.

4.1 Device Sensitivities and Noise Immunity

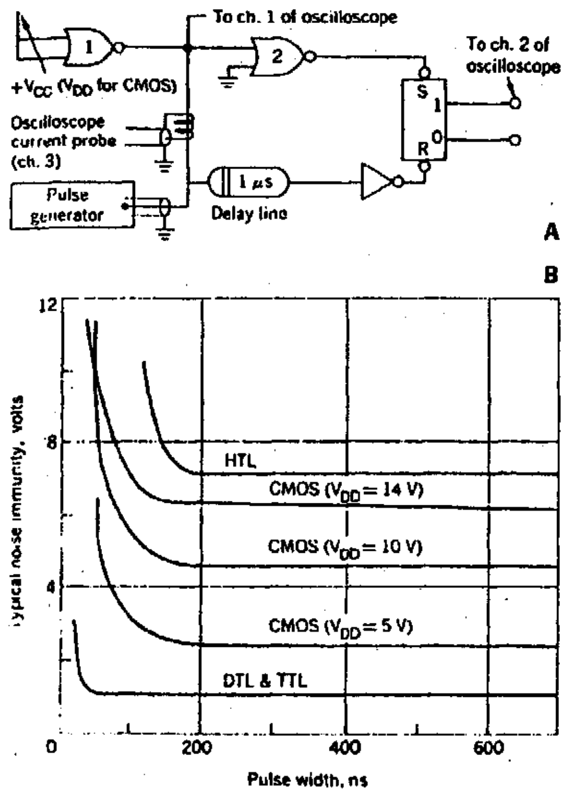
A definition of electromagnetic susceptibility is the characteristic of an object that permits undesirable responses when irradiated with electromagnetic energy. The stimulus parameters of interest in defining susceptibility are amplitude, duration, and spectrum of the electromagnetic energy encountered and the means of coupling. Noise immunity describes the noise rejection capability of a circuit on the basis of inherent characteristics of components, circuit design techniques, and other measures to reduce or suppress interference signals.

Most noise consists of spiked or time varying functions that may be generated in a random manner. A common error in evaluating noise immunity is to examine only the voltage applied. In reality it is the total energy of the noise spike that causes erratic operation, not simply the voltage input.

No matter what its source, noise can enter a control system by two methods: conduction or direct radiation. It can be radiated directly into the control logic by capacitive or inductive coupling, or it can be conducted along input, output, power, and ground wiring. Thus, noise rejection should be considered as a systems problem rather than just a logic or circuit design problem.

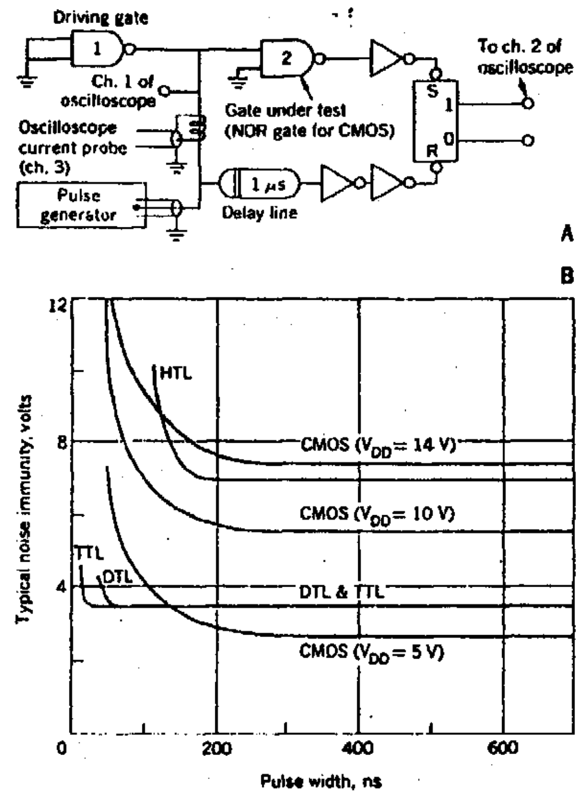
The noise energy immunity of a logic family (a series of circuits using the same material and construction technique) is determined by its input voltage threshold, the current necessary to force a signal line driven by another gate to that threshold, and the time it takes a gate to respond to the noise pulse.

Several techniques have been developed to compare the noise-rejection characteristics of different families. These test methods are based on the three ways noise can enter a circuit: 1) coupling on gate-to-gate signal lines; 2) superposition on ground points; and, 3) injection on the power-supply leads. A basic technique is to inject a signal between two gates to determine the component's immunity to signals at the various entry points. Figures 4.1 through 4.4 show the test methods and results of measurements to compare several types of logic families. Those compared are complementary metal oxide semiconductor (CMOS), diode-transistor logic (DTL), transistor-transistor logic (TTL), and high-threshold logic (HTL). This method requires the setting of a



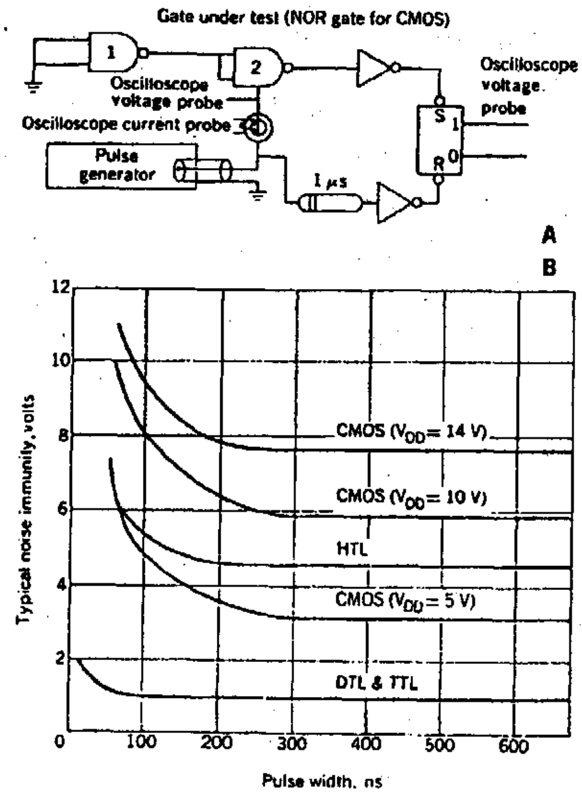
Signal-line-noise immunity measurement (NI_{lh}). A—Gate 1 is set (output in low state) and high-going noise pulses are injected. B—NI_{lh} noise-immunity characteristics as measured with this circuit.

Figure 4.1 Signal-Line Noise Immunity Measurements (After Boaen, 1973)



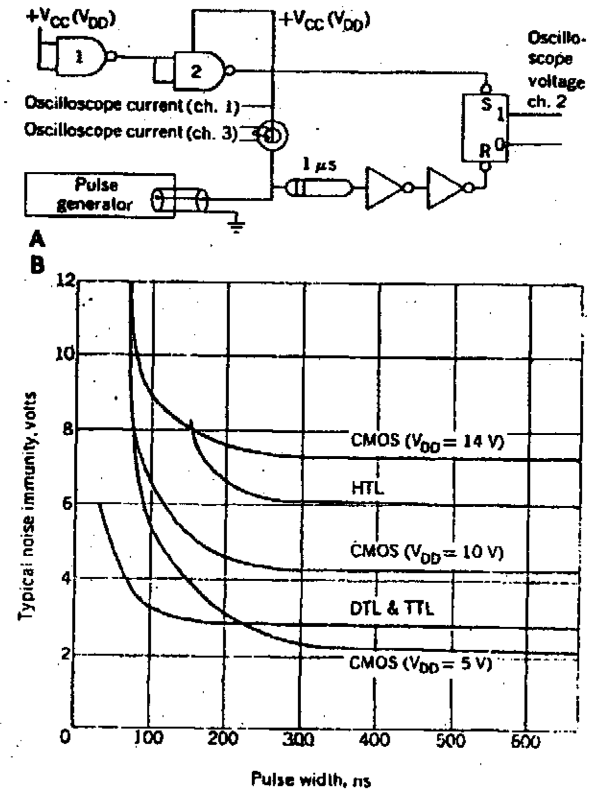
Signal-line-noise immunity (NI_{hl}). A—Gate 1 is reset and negative-going noise pulses are injected. B—NI_{hl} noise characteristics. When CMOS logic is under test, gate 2 is a NOR circuit.

Figure 4.2 Signal-Line Noise Immunity Measurements (After Boaen, 1973)



[9] **Ground-line-noise-immunity measurements. A—Test circuit. B—NI_{j} characteristics. This circuit arrangement is somewhat similar to signal line noise immunity tests and here CMOS comes out on top for high level operation.**

Figure 4.3 Ground-Line Noise Immunity Measurements (After Boaen, 1973)



Power-line-noise immunity. A—test circuit. B—NI_{j} noise response. Only negative-going pulses are required for this test, whereas the others require both positive and negative signals.

Figure 4.4 Power-Line Noise Immunity Measurements (After Boaen, 1973) gate followed by the injection of more pulses to cause the gate to change state. The energy level of the noise pulses is then calculated and plotted. The data in these figures are respectively for high-going noise on the signal line, low-going noise on the signal line, noise on the ground line, and noise on the power line.

Looking at the noise voltage immunity curves (Figures 4.1-4.4) for the logic families, it becomes evident that, for noise pulses greater than 200-300 ns, the noise immunity of a given family is determined solely by the input threshold of the gate under test and by the output impedance of the preceding gate. When pulse widths exceed 200 ns, propagation delay and output rise and fall times play an increasingly important part in the determination of noise immunity, until a point is reached at which the noise pulse is so short that the output of the gate cannot respond to it. The "knees" of these noise voltage immunity curves show the minimum energy necessary to generate a spurious output; this energy level should be used as the basis of comparison between the various logic families that are being considered.

Both dc and ac noise should be considered in the design of digital systems. The dc noise is the steady drift in the voltage levels of the logic states, and ac noise is the narrow pulses that are created, primarily, by switching transients.

The dc noise immunity of a digital circuit is the ability of that circuit to maintain a logic state in the presence of dc noise. The dc noise immunity is expressed by the following equations (Kostopoulos, 1975):

$$N_L = V_{ILmax} - V_{OLmax}$$

$$N_H = V_{OHmin} - V_{IHmin}$$

where

N_L = Noise immunity of the digital circuit input when the input signal is LOW,

N_H = Noise immunity of the digital circuit input when the input signal is HIGH,

V_{ILmax} = Maximum input voltage that can be read by the circuit as LOW,

V_{OLmax} = Maximum output voltage that can represent LOW,

V_{OHmin} = Minimum output voltage than can represent HIGH,

V_{IHmin} = Minimum input voltage that can be read by the circuit as HIGH.

Integrated circuit manufacturers do not always state the noise immunity of their digital circuits on the data sheets. They do, however, include the maximum and minimum input threshold levels as well as the limits of the output levels. From those values, the dc noise immunity can be computed.

For example, a certain type of digital circuit has the following input and output level characteristics (Kostopoulos, 1975):

$$V_{ILmax} = 0.8 \text{ V} \qquad V_{IHmin} = 2.1 \text{ V}$$

$$V_{OLmax} = 0.4 \text{ V} \qquad V_{OHmin} = 2.8 \text{ V}.$$

Substituting these values into the noise immunity equations,

$$N_L = V_{ILmax} - V_{OLmax} = 0.8 \text{ V} - 0.4 \text{ V} = 0.4 \text{ V},$$

and

$$N_H = V_{OHmin} - V_{IHmin} = 2.8 \text{ V} - 2.1 \text{ V} = 0.7 \text{ V}.$$

These values indicate that for reliable operation, the dc noise on the signal lines should not exceed 0.4 V when the signal is LOW, nor 0.7 V when the signal is HIGH.

It should be noted that these values of noise immunity are valid only for the test conditions under which the four parameters, V_{ILmax},

V_{OLmax}, V_{IHmin} and V_{OHmin}, were obtained. For the computation of the worst case dc noise immunity, the worst case values of the four parameters should be entered in the calculations.

The noise immunity of digital circuits is a function of temperature, power-supply voltage, and fan-out. Fan-out is a measure of the number of logic circuits an output can drive. The graphs in Figure 4.5 show that noise immunity decreases (a) when the fan-out increases, (b) when the temperature deviates from $25^{0}C$ in either direction, and (c) when the power-supply voltage deviates in either direction from the nominal level of 5 V.

The inherent input capacitance of digital circuits favorably contributes to the suppression of ac noise, especially that of small pulse width. This capacitance can be increased externally, if improvement in ac noise immunity may be obtained at the expense of high-frequency response.

The ac noise immunity is expressed in terms of amplitude and pulse width, because it is the amplitude-pulse-width product to which digital circuits respond (Kostopoulos, 1975). Figure 4.6 is a typical graphical presentation of noise immunity. The shaded area is the region where noise immunity exists. The figure indicates that as the pulse width of the noise increases, the noise amplitude to which the circuit is immune reaches the dc noise immunity of that circuit.

The ability to drive capacitive loads is an important characteristic in digital integrated circuits, especially when long cables are driven by the output of these circuits. This ability is directly dependent on the output impedance of the circuit. The lower the impedance, the higher the ability of the circuit to drive capacitive loads.

When a circuit drives a capacitive load, the rise and fall times of its output greatly depend on that load. A capacitive load increases the propagation delay of the circuit in a way proportional to the increase in the output time constant of the circuit determined by the capacitive load. Figure 4.7 is typical of the effect capacitive loads have on

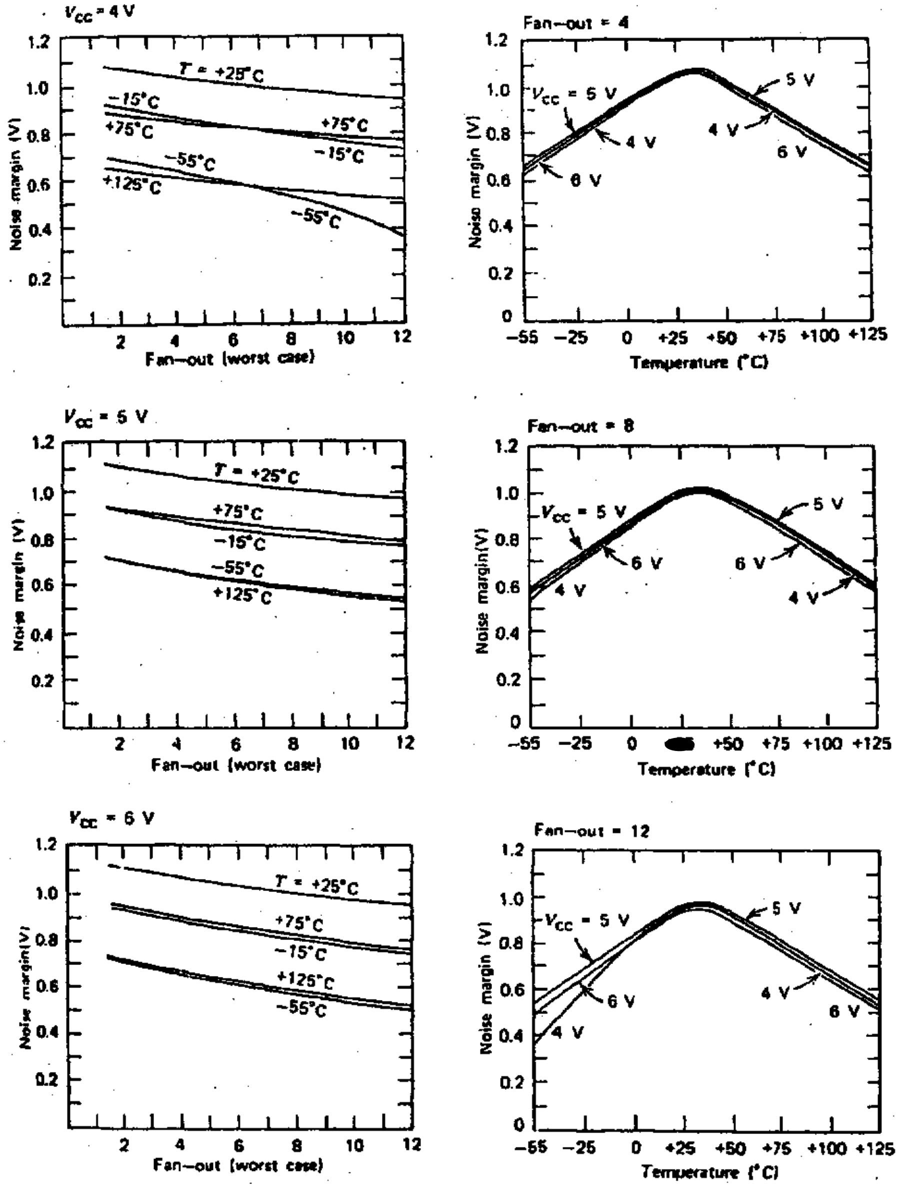


Figure 4.5 Noise Immunity as a Function of Temperature, Power-Supply Voltage, and Fan-out (After Kostopoulos, 1975) (Reprinted with permission, John Wiley and Sons, Inc., New York, NY, 1975).

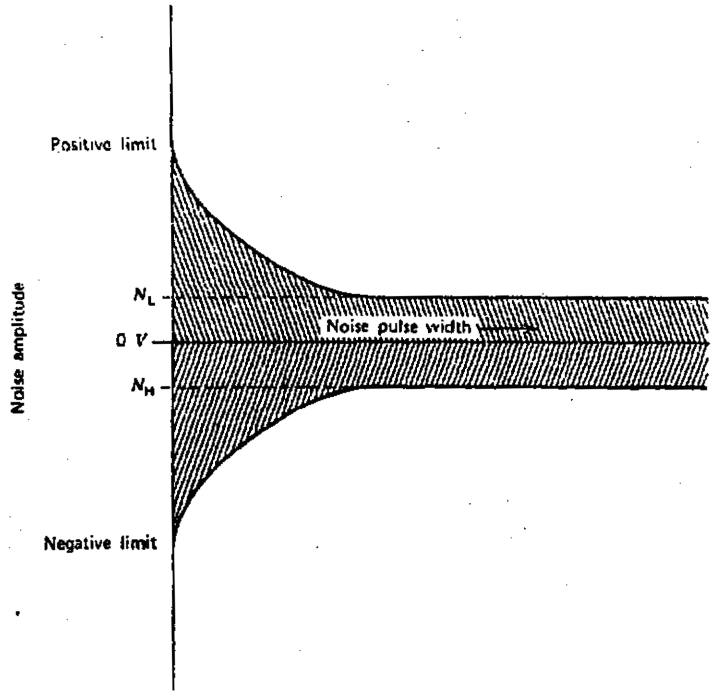


Figure 4.6 Amplitude Vs. Pulse Width of Noise (After Kostopoulos, 1975) (Reprinted with permission, John Wiley and Sons, Inc., New York, NY, 1975).

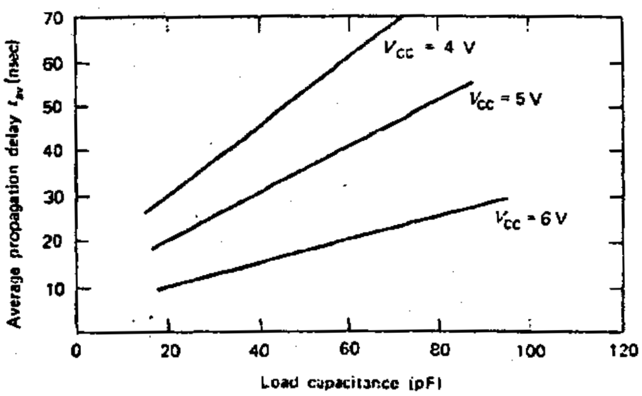


Figure 4.7 Average Propagation Delay (t_{av}) vs. Load Capacitance (After Kostopoulos, 1975) (Reprinted with permission, John Wiley and Sons, Inc., New York, NY, 1975).

propagation delay.

A table of typical output impedances as a function of state is given in Figure 4.8. Two other tables are shown in Figures 4.9 and 4.10. These tables present comparisons of the basic characteristics of the six major logic families.

4.2 Technological Development

The automobile is a harsh machine in which to place sensitive sophisticated electronic circuits. Not only does it present a rugged physical environment, but its electrical systems are subject to severe variations in voltage, loading, and coupled signals.

Recognizing the requirements for successful use of electronic circuits in motor vehicles, the component design industry (electronics industry) and automotive industry have developed or adapted some techniques to ruggedize and improve components to better fit in the automotive environment. This section discusses some of the techniques proposed and used and reviews some of the characteristics of semiconductors best suited for automotive electronics.

Requirements and applications of some automotive interface electronics are similar to those used in industrial control. Thus it is possible that developments for industry will have application in motor vehicles. Some of the new products described here serve both industries. The motivation for this development has been to overcome some of the environmental problems, to reduce costs and to improve reliability. This discussion does not exhaustively cover all possibilities because some techniques require a total system approach. The following paragraphs describe some of the new products used in automotive electronics.

4.2.1 Operational Amplifiers

An advance in the state-of-the-art of operational amplifiers extends the use of this device to many automotive electronic applications. Sensing, timing, buffering and control circuits are among the functions for which operational amplifiers may be used. A combination

Logic type	"0" Output impedance (ohms)	"1" Output impedance (ohms)
ECL (MECL II)	15	15
TTL (54/74)	12	140
HTL	35	1,500
RTL	25	640
DTL	25	2,000
CMOS	1,500	1,500

Figure 4.8. Typical Output Impedances for Six Logic Types (After Peatman, 1972) (Reprinted with permission, copyright © 1972, McGraw-Hill Book Co.).

Logic type		Specific logic line (second-sourced by many companies)		Relative speed (worst-case flipflop toggling rate) (MHz)	Noise immunity: Internal	Noise immunity: External	Logical flexibility: Gate fanout capability	Logical flexibility: Dot AND/OR capability	Gate power dissipation at 50% duty cycle (mW)	Power-supply voltage (V)
CMOS	Complementary metal-oxide semiconductor	RCA COS/MOS		2	Excellent	Good	50	No	3* (at 1 MHz)	+10
HTL	High-threshold logic	Motorola MC660 series		2	Excellent	Excellent	10	For some gates	28	+15
RTL	Resistor-transistor logic	Fairchild 900 series		4	Fair	Fair	5	No	12	+3.6
DTL	Diode-transistor logic	Fairchild 930 series		8	Good	Good	7	Yes	14	+5
TTL or T²L	Transistor-transistor logic	Texas Instruments	54L/74L (low power)	3	Good*	Good	10	For some gates	1	+5
			54/74	15			10	For some gates	10	+5
			54H/74H (high speed)	25			10	For some gates	23	+5
ECL	Emitter-coupled logic	Motorola	MECL II	70	Excellent	Fair	25	Yes	32	-5.2
			MECL III	300			7	Yes	240	-5.2

* TTL logic achieves good internal noise immunity only if switching transients on the power supply line are locally suppressed with one 0.01-μF capacitor per eight integrated circuit packages

*Power dissipation proportional to frequency down to 2 μs

Figure 4.9 Characteristics of Different Logic Lines (After Peatman, 1972) (Reprinted with permission, copyright © 1972, McGraw-Hill Book Co.).

	Logic families					
Characteristics	RTL	DTL	TTL	HTL	ECL	MOS
Propagation delay	Medium (12 nsec)	High (20 nsec)	Medium (6 nsec)	Medium (10 nsec)	Low (5 nsec)	High (30 nsec)
Maximum clock frequency	Low (7 MHz)	Medium (20 MHz)	High (50 MHz)	Medium (20 MHz)	High (150 MHz)	High (25 MHz)
Power dissipation	Medium (24 mW)	Low (5 mW)	Medium (20 mW)	High (40 mW)	High (35 mW)	Low (2 mW)
Noise immunity	Low (0.25 V)	Medium (1.0 V)	Medium (1.0 V)	High (4.0 V)	Low (0.12 V)	High (0.45 V_{DD})
Fan-out	Low (5)	Medium (10)	Medium (10)	Medium (10)	Medium (10)	High (50)
Power-supply voltage	3.6-5.0 V	5 V	5 V	15 V	5.2 V	3.0-18.0 V
Tolerance of power supply	Low (15%)	Medium (20%)	Medium (20%)	Medium (20%)	Low (10%)	High (50%)
Cost	Low	Low	Medium	High	High	Medium

Figure 4.10 Comparision of the Basic Characteristics of the Six Major Logic Families (After Kostopoulos, 1975) (Reprinted with permission, John Wiley and Sons, Inc., New York, NY, 1975).

of technologies (Cohen, 1975) which combines metal oxide semiconductor (MOS) and bipolar devices on the same chip, provides the high impedance input of the MOS process and the high current gain and inherent stability of the bipolar devices. Its high gain, coupled with fast response time and normal circuit versatility, makes it an interesting new component. It also offers diode-gate protection to reduce its susceptibility to damage by electrostatic discharge and low-energy transients. This type of circuit is very suitable for the single-supply applications found in automotive electrical systems.

4.2.2 Improved Encapsulation of IC's

An improvement in the reliability level of plastic-encapsulated integrated circuits exposed to extremely severe temperature and humidity cycling has been achieved in the development of a hermetically sealed chip (Cohen, 1975). One integrated circuit (IC), a high-current NPN transistor array, consists of four separate transistors, each of which is capable of handling up to 1A and is rated for a collector-to-base voltage of 80 V under cut-off conditions.

4.2.3 Displays

As electronic subsystems and electronic monitoring and diagnostic capabilities are added, the desirability and need for visual displays increases. Among the technologies for small and medium displays which are now commercially available are (Nolan, 1975):

1) light emitting diodes,
2) planar gas discharge,
3) vacuum fluorescent,
4) incandescent,
5) electroluminescent, and
6) liquid crystal.

Thus far, no single type of display device has proven to be clearly superior for all applications, and this has led to continuing examination of the new technologies. The decision as to which type of display is most suitable for a given application involves such factors as brightness, color, contrast, voltage, power, response time, operating life, cost of display, cost of driving circuit and resistance to shock, vibration and ambient temperature changes. Such considerations as adaptibility to shared applications or "display-on-demand" functions are also important.

4.2.4 Microprocessors

It has been shown (Jones, 1975) that by effective system engineering, microprocessors can be used to perform on a time-shared basis, multiple-control and monitoring functions. Although the feasibility has been shown, areas exist where further work must be done. Among these is the interface circuitry necessary to communicate between the vehicle and the microprocessor. The basic function of the microprocessor is data processing and, as such, is not actually tailored to the variety of automobile problems.

Some advantages of microprocessors are (Boufaissal, 1975):

1. Flexibility - which allows redefinition of the function without costly redesign. Many changes are possible through reprogramming.
2. Short design cycles - allows for rapid design once a basic set of boards and input-output interfaces have been developed.
3. Low cost - can result for moderate sized systems.

Two technologies that are suited for high-density microprocessor chips are MOS and current injected logic. Additional considerations in selecting technologies for microprocessor design are low power consumption and possibly zero power consumption in stand-by.

4.2.5 Power Devices

Two areas that are as important to increased utilization of electronics in automobiles as the design of control and signal processing devices, are power devices and sensors. All the sophistication of electronic devices is useless unless it can be related to the electrical and mechanical hardware of the automobile, which means an interface with the final control, such as a solenoid, relay, or ignition system. Most of these devices are inductive and generate voltage spikes and transients. Further, since significant current is required, the final control element cannot economically be buffered from the raw voltage supply and must be able to withstand the load devices, inductive switching, alternator field transients, and abnormal power supply variation.

Several devices with high energy handling capability have been developed. Voltages of 50 V, current levels of 5 A, and power handling capabilities to 35 W are typical.

The multiple-epitaxial-base structure and the monolithic Darlington junction will provide ample capability for automotive applications. The recent advance of epitaxial devices into the high-voltage area results from continued development of high-resistivity epitaxial layers and the ability to control both resistivity and thickness to produce a device that can support the high fields (Vanderschmitt, 1974).

4.2.6 Sensors and Transducers

Such systems as fuel injection, emission control, automatic transmission control, spark timing and duration control and others will depend heavily on highly reliable and accurate sensors for input (Zeisler, 1973). A great number of sensors exist to measure such parameters as temperature, pressure, velocity, acceleration, air flow, fuel flow, position, quantity, etc. Many of these devices were not designed for the size, power limits, and environmental demands of the automobile, and a suitable interface between the sensor and the electronic control system which it must address was not part of the design.

Recent developments which approach the transduction as a systems concept have done much to overcome the above described deficiency (Patstone, 1974). Within a single package are provided an input modifier (buffer) if necessary, the sensor and a signal conditioner. A single package of compatible units that requires no additional interface is used in place of two or three units on a breadboard.

4.3 Design Practices

A number of areas are discussed as candidates for consideration in establishing design practices and standards to meet the performance and safety requirements of electronic subsystems in motor vehicles. These areas are discussed keeping in mind the particular environment and conditions of use - namely the privately owned and operated automobile. Contributing factors are the normal and abnormal electrical and electromagnetic environments, the severe physical environment, the range of skills of the vehicle operators, the range of skills and facilities of maintenance personnel (both professional and amateur), and the implications of malfunctions on safety and convenience.

4.3.1 Component and Circuit Selection

In the preceding sections, noise immunity levels of various logic families are discussed regarding temperature, power supply voltage, and fan-out. Other characteristics of these logic devices are also compared. Rather than to specify one family as a most likely candidate for automotive electronics, these families have features that should be considered in each application. The following guides are given for this phase of system design:

a. Components and devices should be selected to achieve the highest degree of built-in immunity consistent with the other circuit requirements (operating frequency, loads, etc.).

b. A safe operation range needs to be designed into the circuit considering noise margin variations as a function of temperature (approximately 50%), and fan-out (approximately 10 to 20%). See Figure 4.5.

c. A single power supply is desirable for many electronic subsystem applications. Because such factors as component density and cost must be considered, special purpose dual supplies or multi-level supplies should not be ruled out. (This is discussed further in the section on Cabling and Wiring Installation).

d. As a general rule, a particular module should be designed to operate at as low a frequency as is consistent with the system requirements. As an example, the upper frequency of the sensor from the antiskid module that was tested is 4kHz. A practical application here would be to suppress frequencies above 4 kHz. This practice affords some high-frequency noise immunity. The input shunt capacitance of digital circuits favorably suppresses ac noise. This capacitance can be increased externally to improve ac noise immunity, but at the expense of high-frequency response.

e. Most electronic subsystems are packaged in a case or box. Consideration should be given to using metal cases to afford electromagnetic shielding. Factors that would govern these decisions are the vulnerability of the circuits and the intended location of the design within the automobile.

f. Consideration should be given to noise suppression input techniques, such as a "differential line driver" or a "Schmitt trigger" circuit that have the effect of cancelling certain types of noise input or rendering the added noise ineffective. Using a differential line drive can result in cancellation of noise signals coupled to signal transmission lines. These techniques would be very useful for clocking or timing applications.

g. In addition to the general good practices described above and discussions available in digital design and application references (see References), many industrial and aerospace applications are confronted with environments and conditions not unlike those of the automobile. Thus, much can be learned from the precautions taken in these designs.

4.3.2 Modular Design

With the advent of the integrated circuit, many functions can be performed by a single semiconductor chip. The following factors stress the importance of plug-in modular design for many applications of automotive electronics:

a. There are several levels of modular design. The module could be as simple as a single amplifier or inverter (buffer) or as complex as a microprocessor. The degree of modularity must be governed by several factors: size, cost, its function in the system, etc. Modular design is highly recommended, because it reduces interface requirements and the number of power and signal cables and lines needed to perform a specific function.

b. The modules should have a plug-in feature that is readily accessible, but is also securely retained. The modules should be keyed so as to prevent improper installation or should be designed so that improper installation will not only avoid damage to the module and its associated circuitry, but will indicate such improper installation. To a large part, the integrity of EMC system design is assured through proper installation and maintenance.

c. Modular design lends itself favorably to a replacement philosophy of field repair. It can be designed to be more than a "cut-and-try" trouble-shooting technique. This approach would be highly desirable with the more complex modules. A certain degree of part standardization can be easily attained by modular design. This could, in part, help to reduce the required inventory for garages and parts stores.

4.3.3 Use of Proven Devices and Techniques

Semiconductors have established a good record of long and reliable (maintenance free) service in systems that are properly engineered and in situations of normal intended use. An important part of EMC is to maintain the design as originally conceived. The use of EMC proven devices and techniques reduces the need for design change or redesign. Several factors impact upon this consideration as a good guide to electronics design for automotive electronics:

a. In the fast developing electronics industry, new offerings are always just around the corner. However, the compound risk of a new application resulting, in part, from a new technology may not be advisable. Such an addition could result in consumer dissatisfaction and general non-acceptance of an otherwise highly desirable and useful electronics application.

b. The availability and proven acceptance of candidate technologies should be considered in writing safety legislation. This also could have impact on the general acceptance and implementation of desired safety goals.

c. The use of circuit redundancy and/or default modes of operation will be very important. This could be automatic with appropriate warning or a conversion to manual override. The extent to which this is necessary depends upon the primary function of the electronic device and cost and safety factors involved.

d. The use of proven techniques can be extended to the use of software in control systems. It may be a less critical requirement because, in all but major changes, the use of programmable digital logic will permit application changes.

5. GUIDELINES FOR INSTALLATION

Equally important to good design practices for EMC in automotive electronics are good practices for the installation and maintenance of these electronic systems. Of course, the most practical approach is to consider the design, testing (pre-installation and post-installation) and installation factors as a coordinated effort. Five topics are discussed in relation to the subject of system installations. These are:

1. shielding,
2. grounding and bonding,
3. wiring and transmission lines,
4. filtering,
5. interference source reduction.

In each category, general information and considerations are reviewed followed by specific practices and possibilities for application in the automobile environment.

5.1 Shielding Techniques

A shield is an enclosure which prevents the electromagnetic energy within it from escaping and, conversely, the electromagnetic energy exterior to it from entering. The isolation between the interior and exterior of most shields is less than perfect. In fact, it does not often exceed 100 dB. The degree of isolation between the interior and exterior of the shield may be called isolation loss or shielding effectiveness (Everett, 1972).

Regarding automobiles and automotive electronics, shielding effectiveness is accomplished in several ways. First, the metal body isolates the interior from external fields. The potential effectiveness of this shield is greatly reduced by openings such as the radiator grill, the openings around the hood and doors, and, of course, the windows. A second means of effecting shielding is with metal enclosures for electronic components and packages, and a third is to provide a shield or enclosure for the signal transmission lines or wiring. Until recently, very little concern has been given to applying or improving upon any of these ways of shielding effectiveness for automotive electronics.

There are several good references (White, 1973; Everett, 1972; and AFSC DH-4, 1973) that treat the general topic of shielding. It is not within the scope of these guidelines to develop the topic, but rather to present material appropriate as a general aid in considering shielding applications. The material in the next several paragraphs is of this nature. This material is directed to applications regarding the body shielding and shielding through packaging. Shielding associated with wiring and cabling is discussed in that section.

Shielding effectiveness (SE) is defined by the following general equation:

$$SE = A + R + C$$

where

- A = Absorption loss in the wall material in dB,
- R = Reflection loss for both sides in dB,
- C = Correction term for multiple reflections in the material in dB. This factor is usually insignificant for metal walls of enough practical thickness to support their own weight.

Calculations have been made to determine the shielding effectiveness due to absorption, reflection, and multiple reflections as a function of frequency, barrier thickness, metal used, and signal source. These data are presented in table and figure formats (Everett, 1972). These references would be useful in assessing effectiveness of existing shielding and/or of estimating shielding requirements for given environments.

An equally important factor in evaluating shielding requirements is shielding integrity. This loss of shielding integrity results from improper care in dealing with openings, seams and joints associated with the shield. The illustrations in Figure 5.1 show proper and improper treatment of typical shielded compartment discontinuities.

The following list provides general guidance for shielding (AFSC, 1973):

1. Design shielded wires and enclosures to provide maximum shielding efficiency.
2. Use a minimum number of joints, seams, gasket seals, and openings.
3. Use conductive material for gasket seals.
4. Compress all rf gaskets.
5. Use a minimum number of inspection plates, adjustment holes, and screened ventilation parts.
6. Check equipment enclosure for rf leaks through:
    a) meters,
    b) toggle switches,
    c) indicator lamps,
    d) fuse holders,
    e) handles,
    f) access doors, and
    g) any other such openings.
7. Electrically bond screens and honeycomb material to its frame.
8. Whenever possible, electrically bond all discontinuities.

5.2 Shielding Practices

The following paragraphs specify those factors which influence shielding decisions regarding automotive electronics:

a. Basic mechanical considerations for radiation shielding should be designed into the enclosure at the drawing board phase. It's almost useless and too expensive after the box is designed and built to provide EMI shielding. This condition holds for ordinary cabinets and consoles and would be of even greater importance in the often cramped and restricted automotive areas and compartments.

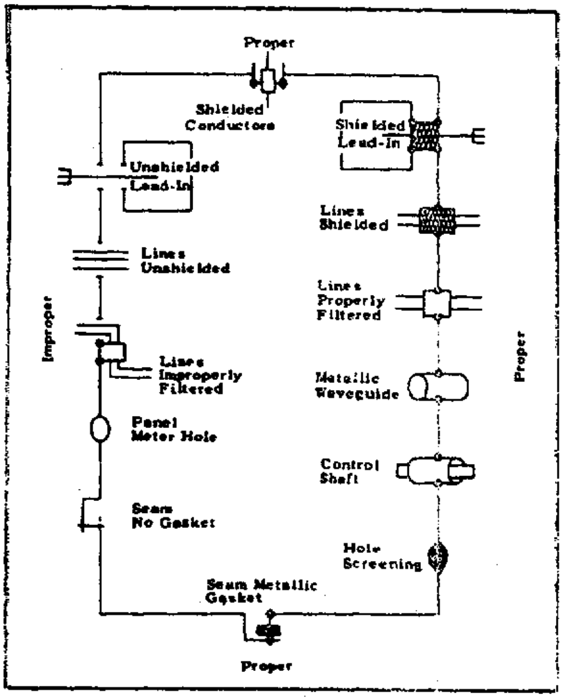


Figure 5.1 Typical Shielding Compartment Discontinuities (After SAE, 1973)

b. Requirements for shielding are determined by comparing the immunity of a circuit as a function of frequency to the potential interference levels expected, also as a function of frequency. Shielding will be required to the extent that the interference exceeds the immunity levels. Immunity levels can be specified from the logic family data presented in Section 4.1 or from data obtained in a test series such as discussed in Volume 1 of this report (Section 4). Data on potential interference levels are included in the summary tables of Section 3 of this volume. The need for shielding and the effectiveness of the shield is deduced from the circuit immunity and interference level data discussed above.

c. The industry must be alert to the potential interference that can result when non-metallic materials are used in the body of a vehicle to reduce the overall weight. Unless other measures are taken, such as use of internal conductive coating or impregnated mesh, to duplicate the body shielding, additional component and system shielding may be required. Cable routing to affect maximum shielding should be employed within the constraints of other system requirements.

d. It has been shown that the greatest loss in intrinsic shielding ability in an enclosure is due to the first largest opening. As an example, the first of equal sized openings may contribute a loss exceeding 100 dB, the second opening approximately 6 dB and a third, 3.5 dB. It is not the number of openings, then, that is of greatest importance. To ensure the integrity of the shield, there should be no openings. Also, the most important parameter is the length or diagonal and not the area. In other words, a long, thin crack could be worse than a small hole. This points out the importance of proper and careful maintenance when shielding and shielding enclosures are involved.

5.3 Grounding and Bonding

Grounding and bonding are generaly concerned with the same problem, that of establishing a low-impedance path to a reference, to which power and signal voltages may be compared. The basic principle is to maintain all portions of a system - electrical (electronic), mechanical, or structural - at the same potential by providing low-impedance paths at all frequencies for the energy to equalize throughout the system. The grounding system usually refers to the fairly extensive network of conductors which tie the various elements of a system to some common point or to a common potential, depending on the system involved. Also, an electrical system may consist of several networks such as a signal network, a control network, and a power network (Everett, 1972).

There are three basic grounding concepts: 1) single-point grounding, 2) multi-point grounding, and 3) hybrid grounding. A brief description of these techniques follows.

5.3.1 Single-Point Grounding

When using this grounding scheme, the ground leads from all subsystems are connected to a common point. The method of single-point ground is illustrated in Figure 5.2. The only common path is in the earth ground (reference ground), but this usually consists of a substantial conductor of very low-impedance. This avoids common mode (common path) impedance coupling problems.

The problem of implementing the single point grounding scheme comes about when interconnecting cables are used, especially ones with cable shield which have sources and receptors of lengths greater than about 1/20 of a wavelength, and when parasitic capacitance exists between subsystems. This situation is illustrated in Figure 5.3. Unless certain precautions are taken, common-impedance ground currents could flow. At high frequencies, the parasitic capacitive reactance represents low-impedance paths, and the bond inductance of a subsystem-to-ground point results in higher impedances. Thus, again common-mode currents may flow or an unequal potential may develop among subsystems.

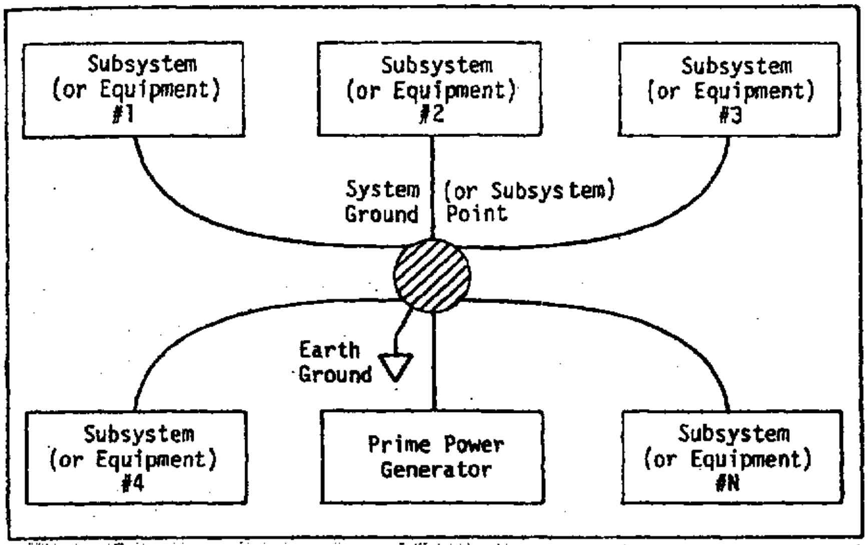


Figure 5.2 Single-Point or Star Grounding Arrangement (After White, 1973) (Courtesy Don White Consultants, Inc., Germantown, MD, Vol. 3, EMI Control Methods and Techniques.)

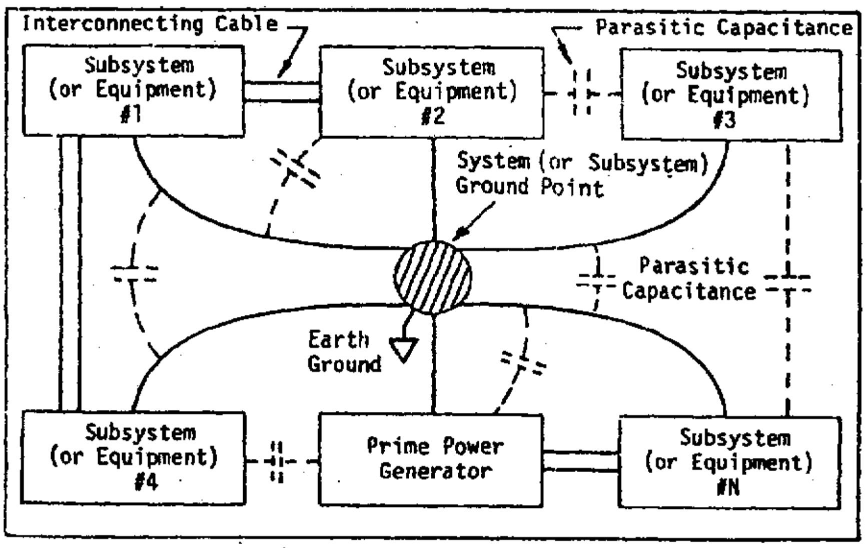


Figure 5.3 Degeneration of Single-Point Ground (After White, 1973) (Courtesy Don White Consultants, Inc., Germantown, MD, Vol. 3, EMI Control Methods and Techniques.)

The condition shown in Figure 5.3 could soon develop in an automobile as new subsystems are arbitrarily added to the network.

5.3.2 Multi-Point Grounding

Supporters of multi-point grounding argue that the situation shown in Figure 5.3 exists in real life despite the concept of ideal single-point grounding shown in Figure 5.2. Thus, rather than the uncontrolled situation in Figure 5.3, if everything were heavily bonded to a solid ground conducting plane to form a homogeneous low-impedance path, common mode currents and other EMI problems would be minimized. A diagram illustrating the multi-point concept is shown in Figure 5.4. Note in this scheme that a ground plane replaces the ground point and many good ground lugs or bonds are used to connect the subsystem ground points to the ground plane.

The facts are that a single-point grounding scheme operates better at low frequencies than at high frequencies (White, 1973). As might be expected, there is not a sharp demarcation between low and high frequency. Rather, a transition band exists. This is illustrated in Figure 5.5. Desirable regions for single-point, multi-point, and hybrid grounding are defined as a function of the largest effective ground plane dimension and the highest low-level operating frequency of the system.

Some general rules that should be considered in system design follow. These are, in general, directed toward signal circuits which may span the frequency range from zero to the gigahertz region. In addition, in the same equipment, signal circuits may be present at both very low and very high power levels. These rules are (Everett, 1972):

1. Supply power to low-frequency and high-frequency circuitry from separate dc supplies.
2. Supply power to low-signal-level and high-signal-level circuitry from separate dc supplies.
3. Connect the dc power ground at one point to the system ground point or ground plane.
4. Run separate grounds to the dc power ground from each module or critical stage.

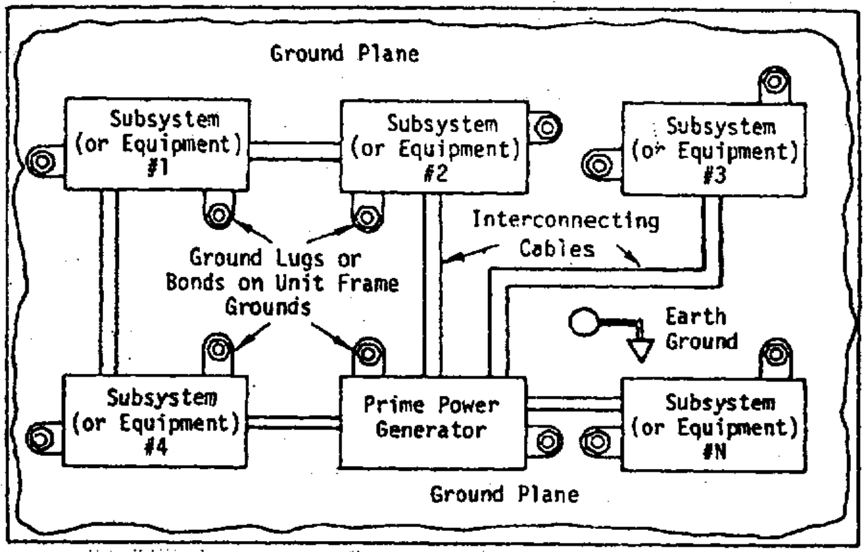


Figure 5.4 Multi-Point Grounding System (After White, 1973) (Courtesy Don White Consultants, Inc., Germantown, MD, Vol. 3, EMI Control Methods and Techniques.)

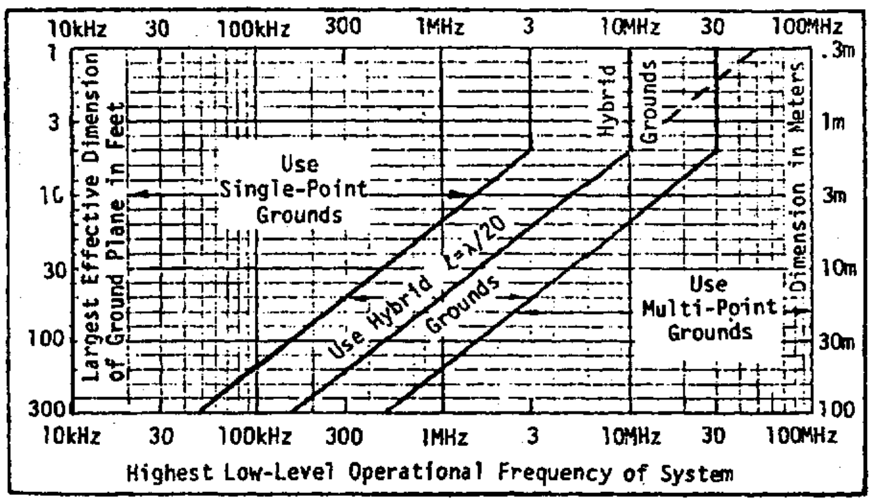


Figure 5.5 Cross-Over Regions of Single-Point vs. Multi-Point Grounding (After White, 1973) (Courtesy Don White Consultants, Inc., Germantown, MD, Vol. 3, EMI Control Methods and Techniques.)

5. For rf circuits, the circuit parts and interconnecting wiring are often mounted on (and close to) a ground plane formed by a copper sheet and grounded directly to the system ground plane.

6. When coaxial cable is used for signal transmission in high-frequency circuitry, the outer conductor is connected to the circuit grounds at both ends. If both circuits are also separately grounded to their dc power grounds or returns, a ground loop is formed into which low-frequency current can be induced from an outside source. In many cases, this may not affect the high-frequency circuitry, but the loop can transmit the low-frequency energy to another susceptible circuit. It may be necessary to open the loop. Again, the area enclosed by the loop should be reduced to reduce coupling. In difficult situations, shielding and triax, rather than coax, cable should be used.

5.3.3 Bonding

It is possible to degrade or reduce the desired benefits of good practices in shielding, grounding, and wiring or cabling, if no attention is given to effective bonding. Good bonding assures low-impedance connections between conducting parts independent of time and adverse environments. Good bonding ensures the integrity of good installation practices.

The literature on bonding covers types of bonds such as permanent and semipermanent, and such topics as choices of metal, protective finishes, conductive adhesives, and conductive parts. This material has been omitted because the detail necessary to cover these topics is not warranted in this report. However, a brief discussion on general bonding practices is given. The effectiveness of the bond depends on its applications, frequency range, magnitude of current, and environmental conditions such as vibration, temperature, humidity, fungus, and salt content. The following points should be observed (Everett, 1972):

1. Bonding must never cause damage to the two surfaces that are

to be joined.

2. Bonds are always best made with the joining of similar metals.
3. Bonding jumpers are only substitutes for direct bonds. If the jumpers are kept short and are higher in the electrochemical series than the bonded members, they can be considered a reasonable substitute.
4. Since bonds are subject to corrosion and are susceptibile to mechanical shock and vibration problems, their accessibility for preventive and unscheduled maintenance is a key design consideration.
5. It is always important in the broadest types of bonding application that the bonding jumper or direct bond is sufficiently large to be able to carry the currents that may be required to flow through it. This is particularly true in bonding to the ground system, where appreciable currents may flow and also in bonding for protection of equipment against lightning surges.

5.4 Grounding and Bonding Practices

The automotive electrical-electronic system departs in nature from most ground-based stationary sites in two significant ways: 1) it does not obtain its power from a high-voltage ac transmission network, and 2) it is not physically grounded in the sense that stationary systems can be.

An example of an electrical network is the primary power supply system of an automobile. It consists of the battery, generator-regulator, and distribution and switching circuits. These systems have most generally used the automobile chassis and frame as the ground return path. Although these paths are low-impedance for electrical circuits (light, motors, etc.) with the automobile, they may not appear so to some electronic subsystems, necessitating other considerations to establish proper grounding and return paths.

The following paragraphs suggest considerations which can guide bonding decisions regarding automotive electronics:

a. Although the entire body and frame of an automobile may be considered as a ground plane for electronic installation and operation purposes, this is not a good practice. This assumption is highly dependent upon construction practices and methods of jointing and insulating the several body components. It may be a better practice to consider smaller, one-piece segments as ground planes, or in special design and in high-frequency applications, provide a special ground plane.

b. To apply the single-point vs. multi-point grounding philosophy to an automobile, a practical largest dimension would not exceed 12 to 16 ft. This limitation is set by the length of the average passenger vehicle. Assuming the entire chassis as ground plane and the length as the largest dimension, the data in Figure 5.5 would indicate that single-point grounding would be appropriate if the highest operating frequencies and frequencies of ambient signals did not exceed 1 MHz. A hybrid ground is suggested for frequencies from 1 MHz to 30 MHz and multi-point ground for frequencies above 30 MHz. Even if smaller planes are considered, the frequency range for single-point grounding extends only to about 3 MHz.

c. An area of consideration in the design and use of bonds is that, particularly in the automobile, equipment maintenance and interchange will be performed by mechanics, both skilled and unskilled. It may be possible to design "fool-proof" arrangements for installation and reassembly where good bonding is critical.

d. Bonding jumpers should be connected directly to the basic structure rather than through adjacent parts. Bonds should be installed so that vibration or motion will not severely affect the impedance of the bonding path.

5.5 Wiring and Transmission Lines

Undesired proximity coupling among wires and cables interconnecting networks, chassis, and equipments is one of the principle causes of EMI. This is in addition to the direct coupling that can occur and which is discussed in Section 2 of Volume 1 of this report. Section 3 of the earlier report (Espeland, et al., 1975) presents a technical discussion of a coupling model and its adaptation for automobile wiring harness coupling analysis, and the reference literature adequately discusses the physics of magnetic-field coupling and electric-field coupling. Also, coupling reduction techniques are discussed (White, 1973).

The following material discusses classes of wiring (grouping) and techniques and rules to reduce EMI.

5.5.1 Wiring Classes

In general, industrial application signal levels within cables range from +70 dBm (10 kW) of 60 Hz, ac power or +90 dBm (1 MW) of VHF/UHF peak rf transmitter power at the high end to -120 dBm (an antenna lead to a sensitive receiver) at the low end. This range of 210 dB (which could be less for automobiles) presents an enormous EMI coupling threat to low-level circuits from high-level emission sources. Various classifications and groupings of wiring and cabling have been developed to reduce range of power level exposure between cables. The one shown in Figure 5.6 classifies power levels into 30 dB groups. This has the advantage that EMI sources and receptors tend to be grouped separately with a division at about -20 dBm. Also, if no classes are mixed in a cable or bundle, power levels in adjacent wires would not exceed a 30 dB spread.

The application that can result from wire classification is that whenever possible and practical, source and receptor or victim wires should be isolated. Some general rules to follow are (AFSC, 1973):

1. Separate power wires from signal wires and input lines from output lines (do not install in the same wire bundle or connectors;

Class	Power Range	Identification
A	>40 dBm	High Power DC/AC and R-F Sources
B	+10 to +40 dBm	Low Power DC/AC and R-F Sources
C	-20 to +10 dBm	Pulse and Digital Sources Video output circuits
D	-50 to -20 dBm	Audio and sensor susceptible circuits Video input circuits
E	-80 to -50 dBm	RF and IF input circuits Safety Circuits
F	<-80 dBm	Antenna and RF Circuits

Figure 5.6 Wiring Classification by 30 dB Power-Level Groupings (After White, 1973) (Courtesy Don White Consultants, Inc., Germantown, MD, Vol. 3, EMI Control Methods and Techniques.)

2. Route susceptible wires away from power supplies and other high power devices;
3. Use twisted pairs instead of shielding power cables.

It is generally established that magnetic-field coupling between wire pairs is more significant for low-impedance circuits and that electric-field coupling is the more significant for high-impedance circuits. Also, above about 10 MHz, electric-field coupling will almost always predominate.

5.5.2 Cable and Wiring Installation

Magnetic coupling is greatly affected by the size of the loop formed between wire pairs or a signal wire and ground. A method of reducing loop area in magnetically-susceptible circuits is shown in Figure 5.7. Figure 5.7(a) shows the formation of a large loop area which is highly susceptible to magnetic coupling. In Figure 5.7(b), this area is reduced by placing the insulated signal lead near the ground plane. A better practice, Figure 5.7(c), is to not ground either end to the ground plane, but to use a dedicated return wire. In Figure 5.7(d), the same circuit is used as in Figure 5.7(c), except that a twisted pair replaces the parallel pair. The twist tends to make local environmental EMI contributions cancel since the induced voltage in each incremental twist area is approximately equal and opposite to its neighbor.

Shielding can be used to reduce coupling between wires in a cable. The shield needs to be grounded at only one end to prevent any low-

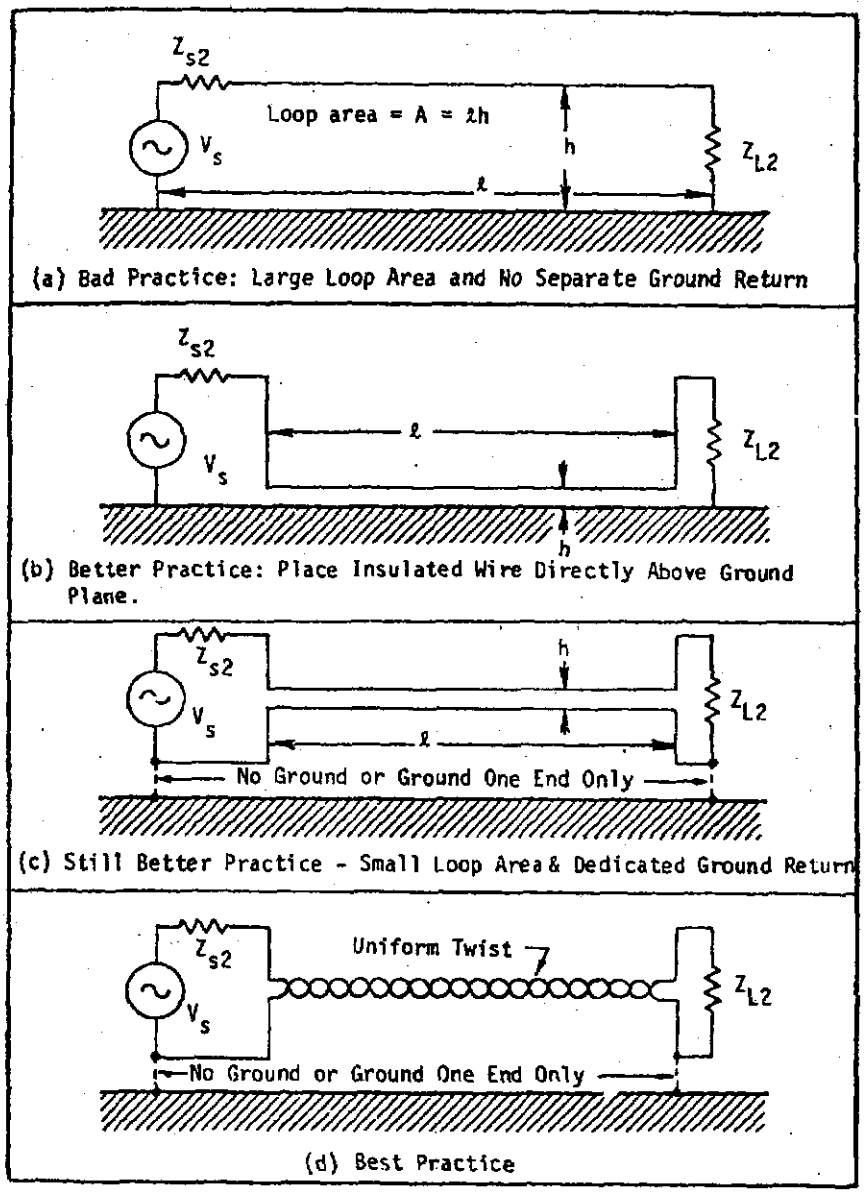


Figure 5.7 Evolution of Reducing Loop Area in Magnetically Susceptible Circuits (After White, 1973) (Courtesy Don White Consultants, Inc., Vol. 3, EMI Control Methods and Techniques.)

frequency interference. In some cases of potential EMI, shielded cable should be used to protect against electric fields and, in severe situations, against magnetic fields. Grounded coaxial cable installations generally perform well and are typically used from 20 kHz to 10 GHZ for many installations. Coaxial lines, if subjected to strong interference, may not adequately protect the desired signal. More sophisticated cable and de-coupling techniques must then be used, depending upon the frequency and impedance levels of EMI and how it enters the cable system. Types of cable that are specially designed to protect against radiated noise signals are triax, which is a coaxial cable with an additional outer copper braid, and twinax, which is a two-conductor, twisted, balanced-wire line with a grounded shielding braid around both wires.

5.6 Wiring and Cabling Practices

In much of the signal wiring used in today's automobiles, little attention is given to applying the general suggestions outlined in Section 5.5. Most wires and cables are strapped into a convenient bundle and routed along the shortest inobtrusive path available. Essentially no separation by class is employed, and the potential for large loop areas exists. These arrangements are tolerable with dc signals and insensitive circuits. However, with the advent of more complex, high-frequency electronics and the potential of signal level ranges of 100-150 dB, it will make sense to isolate or separate the high level signal cables from the low level signal cables and to employ some of the other practices described.

a. Further practice of isolating low-level signals from high-level and power signals will be required as modular and central-control systems such as those discussed in Section 2.2 become widely used. Examples of separate and isolated signal lines in use today include the coaxial lines that are used to connect radio antennas to receivers and noise suppression techniques used with ignition systems and attenuators.

b. In applying the wiring classifications in Figure 5.6, automobile type signals would yield the following groupings:

1. Most power control (motors, lights, etc.) would be in Class B.
2. Central processor (digital and command) signals and sensor or transponder derived signals are in Class C.
3. Most rf and radio or video control or command (propagated signals) would fall in Class D or lower. Thus, it appears reasonable to consider at least three potential groupings of signal bundles for future signal transmissions.

c. One further consideration is the utilization of multiplexing techniques for fast and efficient distribution of data between the many sensors, computer functions, and command circuits that may some day be utilized in automotive electronics. Network signaling techniques would come in to play in this concept, and separate system design approaches should be utilized.

5.7 Filtering and Suppression Techniques

Filters provide a very effective means for reducing and suppressing EMI. They attenuate undesired signals outside their pass-band and pass the desired signals within the band, and, of course, undesired signals within the pass-band are unaffected. The application of a filter to a subsystem requires careful consideration of a variety of factors such as insertion loss, impedance, power handling capability, signal distortion, tunability, cost, weight, size, and rejection of undesired signals. Of the practices discussed (shielding, grounding, filtering, wiring, etc.), filtering and suppression costs must be fully justified on the basis of improved performance only. Most of the other techniques or practices are based on good implementation of necessary interconnections. The difference between good and poor or questionable practices is an incremental cost.

The design and use of filters is an art as well as a science, since much depends on the judgement and techniques or options used. The purpose of this discussion is to provide some guidance to selection, application, and installation of filter circuits. Several useful references (White, 1973; AFSC DH-4, 1973) are available and suggested for further reading.

Filters are classified according to the band of frequencies to be transmitted or transferred such as: low-pass, high-pass, and band-pass or band-reject. Figure 5.8 shows examples of these filter types and their frequency characteristics. Other techniques employ operational amplifiers and ferrite beads.

In addition to the cost of filters, mentioned above, another factor is size and weight. Filters are realizable at any impedance level for cut-off frequencies in the 3 kHz to 3 MHz frequency range.

5.8 Specific Interference Source Reduction Techniques

In most instances, reduction of noise and interference is most successful if sensitive circuits can be physically removed as far as possible from the interfering sources. Application of noise suppression techniques at the sources, as described below for specific examples, provides an additional means of reducing noise and interference (Coombs, 1972):

<u>Relays, Controllers, Switching Devices</u>

1. Shunt relay or switch contacts with a capacitor to reduce current surges. In general, a current-limiting resistor should be placed in series with the capacitor to prevent deterioration of the switching contacts.
2. Enclose switching device in a shield.

<u>Electromechanical Vibrators</u>

1. Shield the vibrator.
2. Use feedthrough capacitors or, if necessary more elaborate filters for power leads passing through the shield. Filter components should all be within the shield, with leads passing through the shield via feedthrough capacitors.

<u>Vibrating-Type DC Voltage Regulators</u>

1. Shield the regulator.
2. Locate the regulator as near the generator as possible.

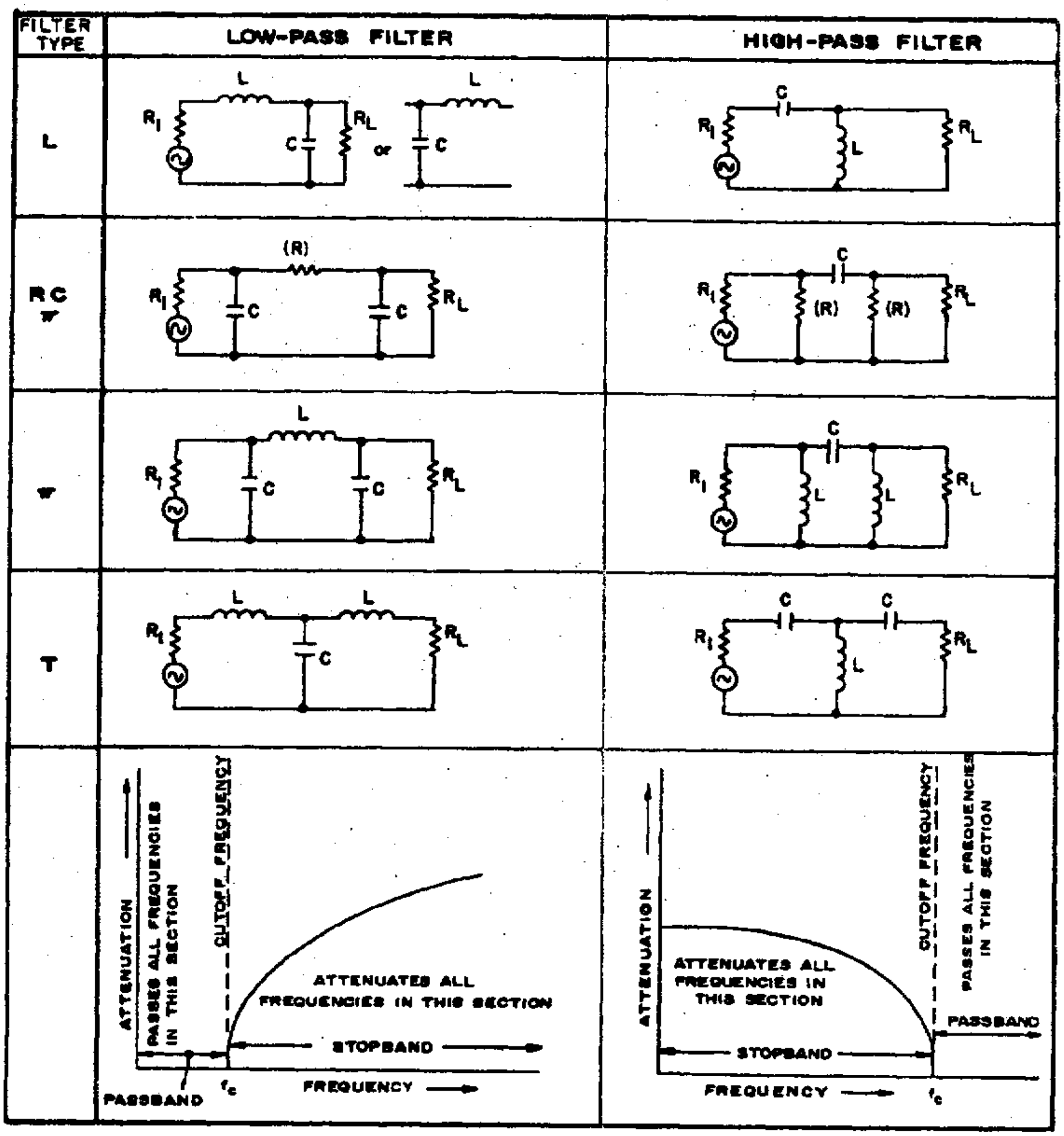


Figure 5.8 Low-Pass, High-Pass, Band-Pass, and Band-Reject Filter Configurations (After AFSC, 1973)

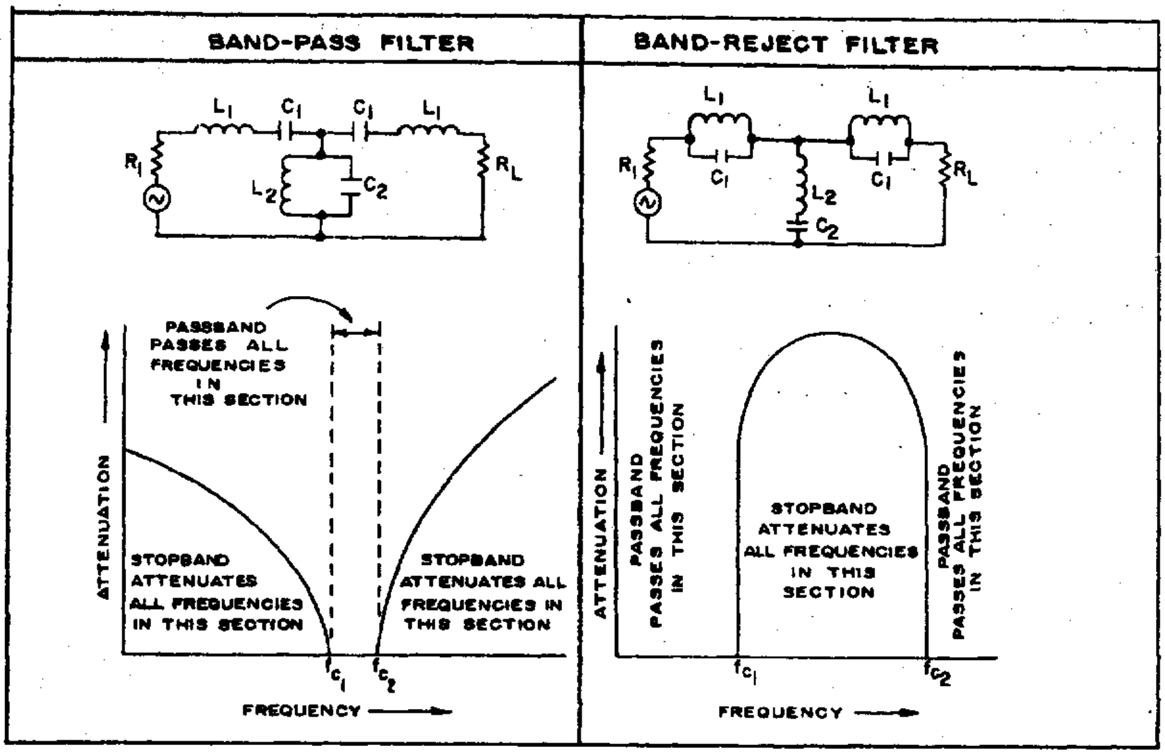


Figure 5.8 (cont.) Low-Pass, High-Pass, Band-Pass, and Band-Reject Filter Configurations (After AFSC, 1973)

3. Shield leads between regulator and generator.

4. Bypass input dc leads inside the shield with a capacitor, preferably a feedthrough capacitor.

DC-DC Converters and Inverters

1. Shield the unit.

2. Use low-pass filters on all leads passing through the shield (at least, use feedthrough capacitors).

Electric Motors and Generators

1. Use a good shielded housing.
2. Bond housing to ground.
3. Use bypass capacitors at brushes.
4. Use a feedthrough capacitor at the armature terminal.
5. Shield terminals and interconnecting wiring.
6. Keep brushes in good condition.

Ignition Noise (Internal-Combustion Engine)

1. Place resistor (10 KΩ) in high-voltage leads near the coil, or use resistive ignition leads.
2. Use shielded internal-resistor spark plugs.
3. Shield the coil.
4. Use shielded ignition wires.
5. Use bypass capacitors on the dc lines into the coil and distributor.

5.9 Filtering and Suppression Practices

The following paragraphs outline some filtering and source suppression considerations:

a. Redundant filtering may result in an uncoordinated effort by two or more separate design groups. This could easily occur with the use of stand-alone and add-on automotive electronic subsystems, where each subsystem is designed for adequate protection. In add-on philosophy of electronics application, the source of interference may not be suppressed or filtered at all, thus overlooking a potential for improved system EMC.

b. If shielded enclosures are used, such as discussed in Sections 5.1 and 5.2, then filters may be required at the signal input connectors to keep conducted signals from entering the enclosure. Single-element filters (series inductor or shunt capacitor) should be used only between equal source and load impedances. A shunt capacitor is effective where both the source and load impedance are large with respect to the capacitor reactance. A series inductor is effective where these impedances are both small compared to the inductor reactance. Symmetrical T and π filters should also be used only between equal source and load impedances. A T network is effective where these impedances are capacitive, and a π network is used where these impedances are inductive in nature. For unequal source and load impedances that differ by an order of magnitude or more, an LC filter should be used. The series inductor is connected to the lower of the source and load impedances.

c. Many of the devices described in Section 5.8 are used on automobiles, and several of these noise reduction techniques have been employed to protect and improve performance of entertainment radio and communication systems. Most of the aids are directed toward high-frequency radiation of energy. In addition to these good practices, attention should be given to the reduction of some of the high-level transients that contribute to the potential of conducted interference signals. Electronically controlled loading and switching of these sources may be feasible and relatively inexpensive.

6. GUIDELINES FOR TESTING

Physical measurements of a circuit or system are fundamental to adequate diagnostics for determination of functional capability, including EM susceptibility. Cost considerations dictate an integrated measurement procedure for operational equipments. This implies that susceptibility testing be an element of the measurement specifications for original installation, and maintenance and inspection operations.

In this section, procedural and functional guidelines will be indicated with regard to defining the specific measurement requirements and the relationships to normal "dealer and service station" maintenance activities. With proper assurance through specifications for equipment design and installation planning, the complexity and variability of the measurement instrumentation and procedures imposed on the vehicle and system maintenance facilities are reduced. These considerations are important to the capital and operating expense of dealerships and service garages. The incremental skills for mechanics because of the vehicle electronics equipment must also be minimized. Previous experience with relatively complex engine control "computers" has demonstrated the necessity of employing exchange modules, with repair effected at particular manufacturer operated service centers. Unfortunately, operational reliability problems (some EMC related) caused abandonment of the electronic engine control system after less than two years of service. Recent experiences with anti-skid devices on commercial trucks also indicates probable EMC problems. Such difficulties with serious safety implications are compelling reasons for implementing an EMC management function within DoT and vehicle manufacturer organizations.

Testing involves different functional considerations, depending on the candidate system life cycle status. The areas of application are as listed:

1) Validation of model predictions for circuit, equipment/system, or integrated vehicle susceptibility. These models and supportive

measurements would be utilized to define functional susceptibilities for advanced circuits and devices, develop modularity and configuration requirements. Intravehicle radiative and conductive coupling, extravehicle aperture penetration and cable or bond aperture coupling, and induced modal degradation are included.

2) Performance certification measurements by equipment manufacturers. This primarily involves coupling of simulated signal and noise components into signal, control, and power connections; and illuminating the equipment with normal shielding and cables attached. Signal and input noise characteristics would be derived from the source data files (electromechanical devices, ignition, electrostatics, external components), and simulation and validation test excercised to identify source and functional sensitivities relative to system operational modes (e.g., initiation, signal tracking, termination).

3) Performance testing as one element of vehicle or system inspection or associated with maintenance operations. This operation would involve a form of automatic test equipment to measure specific test point responses while injecting synthesized waveforms to circuit terminal points and connecting terminals on the vehicle cable distribution bundle(s) during operation of the engine and selected electromechanical devices. For these measurements, specific test points on the electronic equipment would be utilized. These EMC tests would be integrated with the basic performance test systems. Test points should be selected so as to allow identification of EMC problem sources (e.g., cable bundle, power line, ground bond or ground circuit noise inputs). Shield integrity would be determined by manual inspection. Ground circuit resistance measurements, probably separate from the integrated instrumentation, would also be required. These measurements would determine equipment shield to vehicle chassis resistance at more than a single chassis point.

The cited measurement categories indicate a system life cycle component relationship, consisting of development, installation and vehicle system design, and operations and maintenance. A summary of the basic measurement methods is presented in subsequent paragraphs.

The following data are required to determine the operability of a system in the EMC environment or a number of systems in their composite environment, and provide design guidance relative to circuit, device, and configuration design:

1) a description of the radiative and conductive EM environment in which the system is intended to operate,
2) a definition of the operational modes and modal performance criteria for the system, and
3) a data base of circuit device, and module susceptibility characteristics.

A survey of the electromagnetic interference sources external to a motor vehicle during normal use was prepared in an earlier study (Espeland, et al., 1975), and a summary is included in Section 3 of this report. A typical composite summary of signals generated internal to a vehicle was also included in Section 3. The two sets of data present a reasonably accurate estimate of the total electrical and electromagnetic environment of a typical motor vehicle. For application to EMC design problems, the environment specifications must obviously be related to any subsystem through the aperture penetration and internal radiative and conductive coupling modes.

The intended operating modes and procedures and parameter characterizations of a proposed system are part of the design information. Usually the functional requirements are well specified and the design conservatively accomodates the physical environment (thermal, vibration, humidity, dust, etc.), and power source variations. Testing in a controlled chamber for physical environment susceptibility is usually necessary; EM susceptibility testing must receive a similar priority.

The general methods of determining the electromagnetic susceptibility of a system or subsystem involve testing in an actual or simulated operating mode, while being subjected to interference signals. The range, character, and level of the interference signals can be determined from an estimate of the system susceptibility as a function of frequency, signal character, system port impedance, etc., and an estimate of the environment. The testing can be confined to those limits of suspected susceptibility for the operating modes, with emphasis on functions that relate to safety and control.

6.1 Testing Techniques

Three testing and evaluation concepts are discussed: 1) modeling programs and analysis aids, 2) subsystem and component evaluation, and 3) entire system testing. Each of these techniques is related to life cycle EMC management and control. As mentioned, all must be utilized in an integrated management program to maximize operability and cost effectiveness in EMC assurance.

6.2 Models for Analysis and Evaluation

A number of models exist for such applications as circuit design (ECAP and SCEPTRE), systems analysis (WTWCAP and FTWCAP), and network analysis (SOLVENET). ECAP, WTWCAP and FTWCAP have been used in this project for coupling and transfer prediction and circuit degradation prediction. Models have varying degrees of compromise in resolution and functional accuracies. For this road vehicle EMC application, with a limited scope coordinated measurements program, the approximations in ECAP, WTWCAP, and FTWCAP represent no compromises in application. These models allow parametric and configuration variation so as to accomodate circuit, device, and coupling sensitivity analyses. This aspect is particularly important in the equipment design and configuration planning phases.

An example of the use of the FTWCAP program is to generate an EMI margin for tested equipment when exposed to predicted external fields. The upset levels determined from the test procedures in Section 4 of Volume 2 provide susceptibility level inputs as a function of frequency for the specific equipment tested. The FTWCAP model can be programmed to simulate prescribed fields at the vehicle apertures. The resultant EMI margin, which is a standard program output, evaluates the test equipment in the presence of prescribed fields and shows those portions of the spectrum where upset might occur or a margin of safety might be expected.

The procedures to employ WTWCAP for cable bundle coupling prediction were described in the first technical report (Espeland, et al., 1975), and the utilization of the FTWCAP to derive aperture penetration have been presented in Section 3, Volume 2 of this report. The basic relationships in utilizing these models for sensitivity analysis, developing details of manufacturer and maintenance test procedures, and developing general application guidelines for advanced circuit modules or devices functions are indicated herein.

The general process for application guideline support is diagrammed in Figure 6.1. The utilization of measurement planning is indicated in Figure 6.2.

6.3 Subsystem Evaluation

The Society of Automotive Engineers, Inc. (SAE, 1975) has approved recommended practices to establish uniform laboratory techniques for the measurement and determination of the susceptibility to electromagnetic interference of electrical, electronic and electromechanical ground vehicle components. This has been published as "SAE Recommended Practice," SAE J1113. It is intended to serve as a guideline for testing vehicle components for specified EMI levels.

The major sections in SAE J1113 are:

1) Introduction.
2) Conducted Susceptibility, 30 Hz-50 kHz.
3) Equipment Conducted Susceptibility, 50 kHz to 300 MHz, All Input Leads, including dc and ac Power.
4) Conducted Susceptibility, Repetitive Spike, Power Leads.
5) Conducted Susceptibility, Load Dump and Field Decay Transients, Power Leads.
6) Radiated Susceptibility, 30 Hz to 15 kHz, Magnetic Field.
7) Radiated Susceptibility, 14 kHz to 200 MHz, Electric Field.
8) Radiated Susceptibility, 200 MHz to 1000 MHz, Electric Field.

In each of the sections, guidelines are provided regarding measurement philosophy, grounding and shielding techniques, suggested test

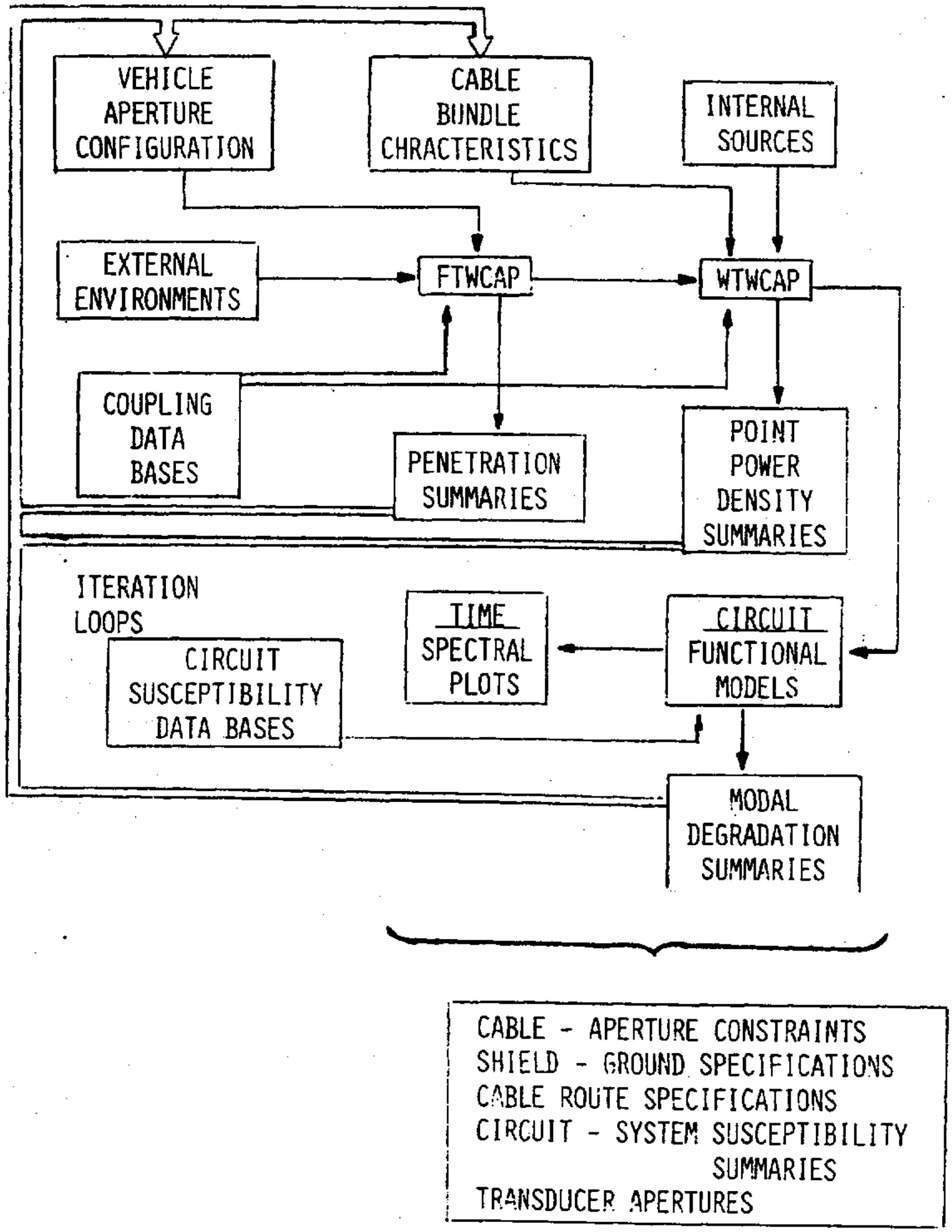


Figure 6.1 Model Guideline Support

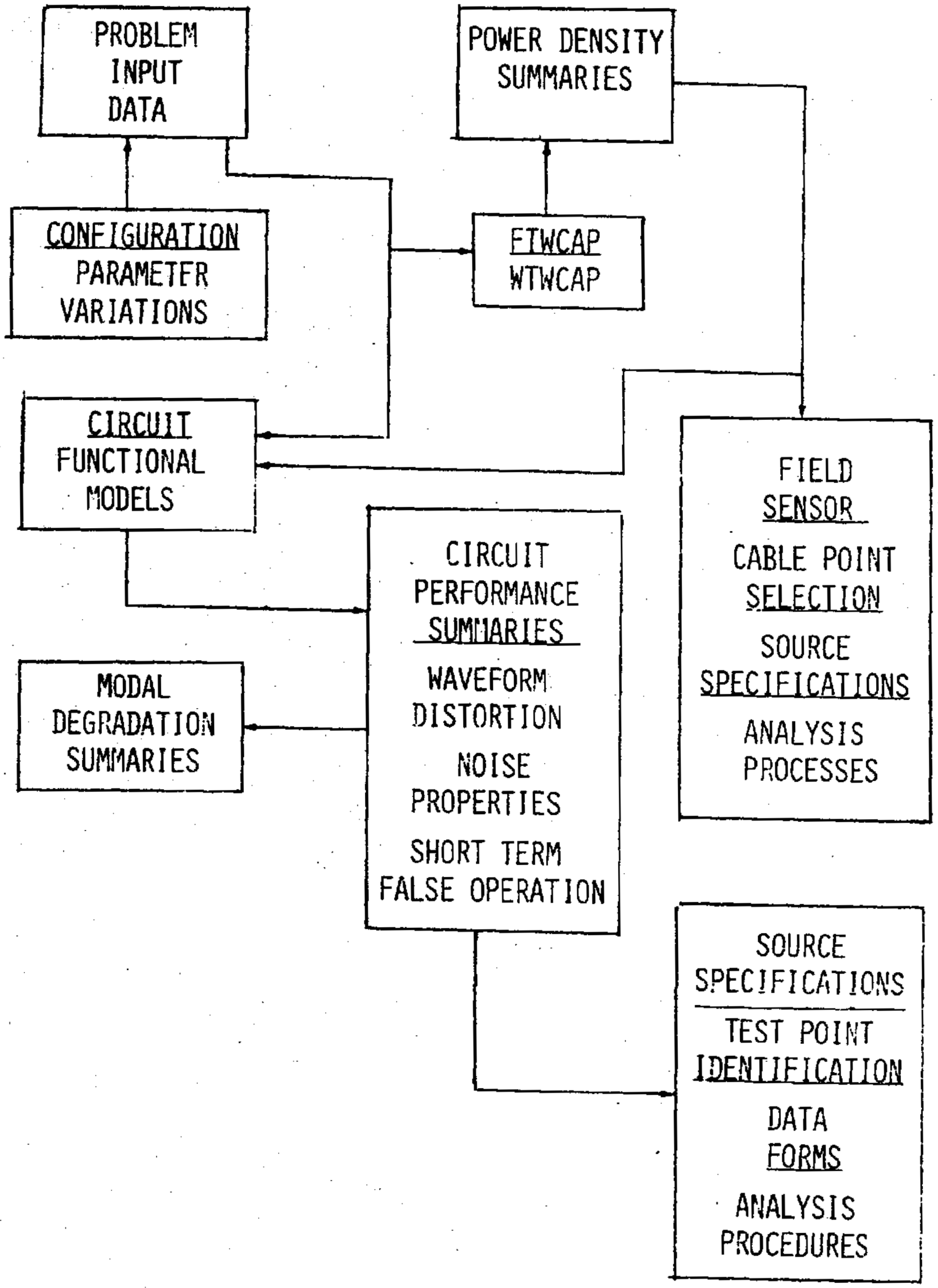


Figure 6.2 Model Applications to Measurement Planning

apparatus, test setup and procedures, and typical equipment. Impedance, power and frequency ranges are included in the equipment data.

An example of the use of these guidelines for testing is a current program of the National Bureau of Standards (NBS) (Wu, 1975) in which electronic subsystems, similar to those tested in Section 4 of Volume 1, are being tested for radiated susceptibility due to electric fields. This project includes developmental work on an electromagnetic enclosure called the transverse electromagnetic (TEM) transmission cell, and measurements of electric fields at points in a vehicle resulting from mobile band radio emissions.

A second technique, available for subsystem testing, is a special test facility such as the Direct Drive Unit (Greaves, et al., 1975) used to perform a series of upset tests on a speed control system and an antiskid control module. These tests were conducted at Air Force Weapons Laboratory (AFWL) at Kirtland Air Force Base, New Mexico. This testing project, including preparation, testing and analysis, is reported in Section 4, Volume 2 of this report. The philosophy of operation is to inject signals of specified character (cw, dc, pulse, etc.) at selected input leads over a range of levels. Upset criteria (degraded functional response) are included in the test specifications. With this input information, the system automatically ranges from a low to high interference signal, level and when an upset is reached, an output is printed, and the system cycles again at a new frequency or other appropriate parameter change. This facility can readily perform tests similar to those specified in the SAE J1113 guidelines. The uniqueness of the facility is its programmability.

The Direct Drive Laboratory includes a complete range of equipment required for subsystem testing, such as environment sources, transient instrumentation, and data processing. The major equipment items available in the Direct Drive Laboratory are listed below:

1) The Automatic Test System (ATS) which provides a range of diagnostic instrumentation and pulse and dc sources under computer control,

2) The Environment Generators which provide a variety of pulse and continuous wave environments with a range of pulse shapes, fre-

quencies, and output levels. Three types of generators are available: the Linear Amplifier, the Damped Sinusoid Pulse Set (DSPS), and the Rectangular Pulse System,

3) The Distribution System which interconnects the test specimen, the environment generator, and the ATS,

4) The Automatic Network Analyzers which provide wide band frequency domain analysis of components and circuits under computer control,

5) The Data Reduction System which is used for processing both diagnostic and transient response data, and

6) Other test equipment, including oscilloscopes, oscillators, impedance bridges, etc.

This equipment can be employed either separately or in various combinations to meet the test objectives.

As utilized for this program, the facility represented the most cost effective method of developing coupling and equipment degradation data for conductive interference. The flexibility in parameter variation of the excitation signals (pulse shape parameters, pulse repetition frequency) for discrete frequency and baseband excitation, the computer control capabilities, and the integrated on-line data analysis and display functions afforded benefits to test execution.

For radiative cable, device, and equipment EMI testing, the ARIES facility at AFWL or the TEM cells at NBS could be utilized. The former would be advantageous for large volume testing because of the extensive computer control and data analysis capabilities available. This facility has also a sufficient experiment volume to accomodate individual or integrated testing of cable bundles, sensors and actuators, electronic functional modules, and vehicle chassis or frame elements. Pulse cw, and baseband illumination is available with source modifications required between discrete frequency and baseband modes.

These types of facilities would be applicable to model validation and equipment and configuration certification support testing. As indicated previously, such testing should be related to model excercise through the utilization of models for experiment specification. In this context, the tests provide validation in parametric verification and performance data base validation. These relationships are indicated in Figure 6.3.

Radiative and conductive testing of the character discussed is appropriate for engineering and design certification support. Specific functional problems would include penetration by discrete signals and wide or narrow band noise through vehicle body apertures, cable and bonding coupling and transfer, and circuit or module degradation validation.

Included in support to the design phase, measurements specifications for dealer and service station maintenance are developed from the simulation and supportive measurements. These specifications would include sensing points to indentify cable coupling and circuit performance, and the character of synthesized signals and points of connection to the cables and circuit modules. Measurement standardization and minimal complexity are necessary for the service center environment.

6.4 Vehicle Testing

Complete system testing, including electronics, cabling, and electromechanical devices, configured in a production type of road vehicle will be necessary, on occasion. Principally, such testing will provide conformation of total environment predictions (external illumination sources, ignition noise, electromechanical device noise), cable coupling, and equipment degradation. Such testing requires an illumination facility with sufficient volume to accomodate an automobile or medium size truck, and in the extreme circumstances, allow illumination of a tractor or trailer commercial vehicle.

Test facilities currently available for this purpose at AFWL include the ALECS test center that can accomodate 707 and 747 class of aircraft. Proposals have been advanced to develop large volume TEM chambers where a greater usage emphasis would involve measurement standards development and application. For the 1976-80 period, the AFWL facilities could readily satisfy vehicle test requirements.

This road vehicle test application will utilize a facility having the test volume sufficient for automobiles, medium trucks, and at least

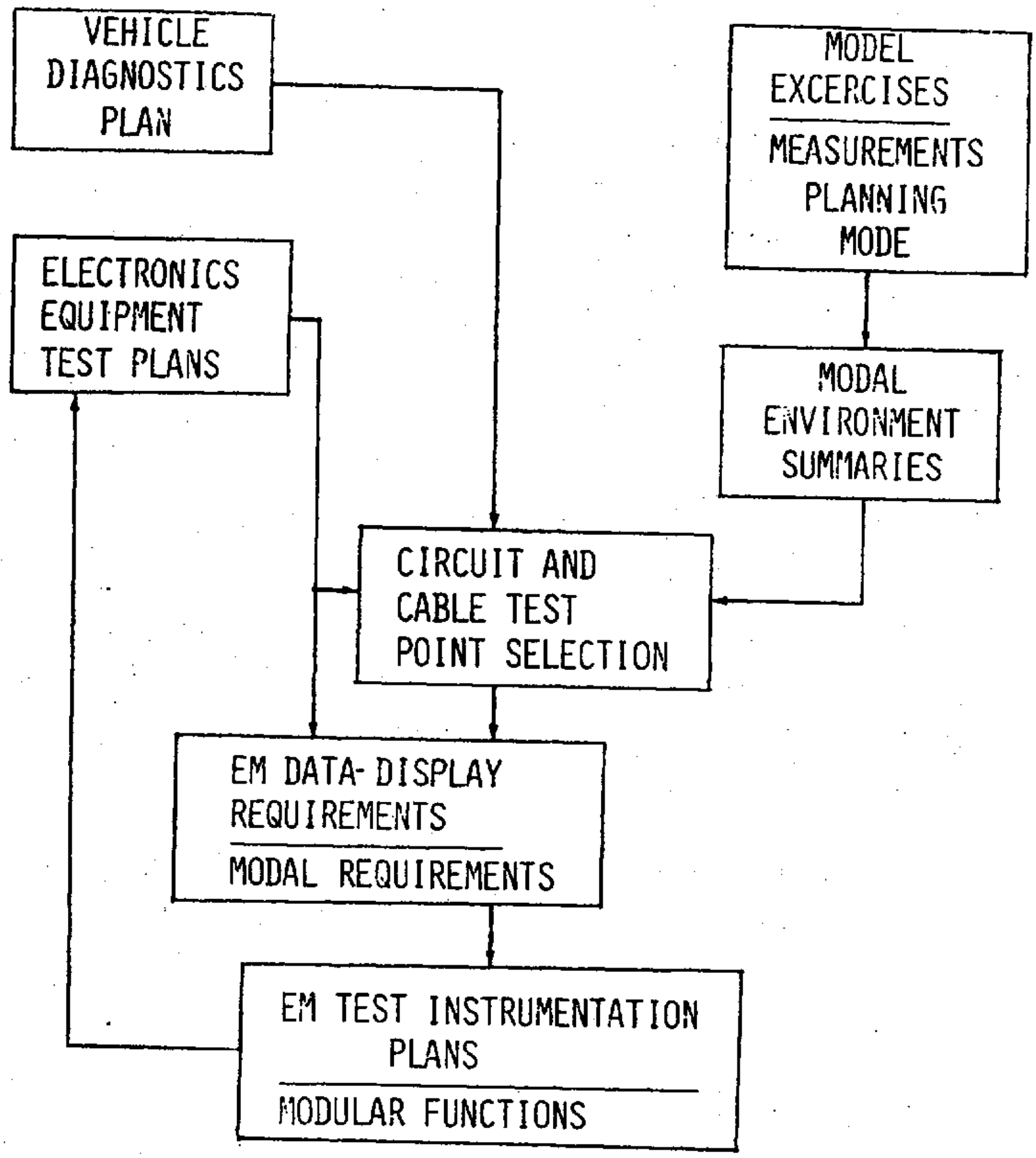


Figure 6.3 Specification Support to Service Area Testing

the tractor or trailer sections of multiaxle trucks; provide cw, pulsed single frequency, and baseband illumination with a maximum frequency of about 30 GHz and maximum power density to the vehicle skin of about 100 V/m^2; and the capability of varying rise time and width for the pulse modes. Field probes, voltage/current sensors with isolated telemetry links, and diagnostic instrumentation must also be available in the test volume.

The volume of data available from these large scale tests, and the probabilities of multiple parameter interactions require stringent test planning procedures. Planning for these tests should include computer simulation exercises to indicate probable signal or noise amplitudes or spectral densities, penetration or coupling and the character of induced degradation, and parametric or configuration sensitivities. Subsystem testing for specific validation requirements can be accommodated in the Direct Drive Facility, available TEM cells, or an ARIES type facility.

Generally, vehicle testing will emphasize three axis illumination; bottom, front, and top. Rear exposure would be necessary if electronics subsystems or exposed cabling were in the areas of the trunk or rear bumpers of an automobile. This is generally contrary to current trends.

7. SUMMARY

These guidelines will serve to emphasize and highlight those factors in the use of electronics for automotive safety and control that are important to the accomplishment of EMC among the various subsystems. In considering rules or standards for electronics in automobiles, it is important to remember that the applications of electronics for these purposes are in their infancy and that the trend for greater application is most certainly toward a modular or central processor concept. The EMC implication is that a modular concept can augment compatibility using overall system design practices. At the same time, it could create a condition of increased susceptibility due to the increased use of digital components and an increase in demand for signal transmission within the vehicle in order to utilize a central control device.

The automotive and electronic industries are very much alert to the challenge of using electronics systems in automobiles. New ruggedized electronic components have been designed to meet the demands of the severe automobile physical environment. Single package sensors and transducers are being designed to simplify the interface of signal sources and reference devices to the digital control systems. Several of the major automobile industries have supported research of an overall (central processor) control system which, when implemented, affords an economy in multiple use of sensor functions and multiplexing capabilities of the computer (processor). These research efforts indicate central control system feasibility.

The summary of the automotive electrical and electromagnetic environment in Section 3 describes the range and character of potential interfering signals (both conducted and radiated) that may be encountered by electronic systems. These data provide a useful reference to testing and modeling exercises for determined regions of system susceptibility.

The guidelines for design, installation, and testing in Sections 4, 5, and 6, respectively, describe the several factors of importance to general EMC in each of these areas and also specific practices and considerations pertinent to automotive electronics. Shielding, bonding, packaging, filtering and signal transmission requirements should be an integral part of the system design. Also, there needs to be a concern for overall vehicle compatibility in the application of electronics, not just system by system consideration.

Testing for susceptibility at the component and subsystem level can be very useful for design and installation purposes. However, it is impossible, or at least very difficult, to simulate completely the automobile environment and the interaction between the electrical and electronic systems outside the vehicle itself. This problem calls for some means of effecting testing on a vehicle. Testing for conducted susceptibility is not too difficult to perform. Similar testing for radiated signals requires the types of special facilities cited.

Susceptibility analysis for EMC/EMI assurance requires integrated environment evaluation, realistic assessments of conductive and radiative components with operationally related variations, coupling modes to electronic modules, and the induced degradation related to operating modes. This philisophy is demonstrated in Figures 6.1 and 6.2.

8. ACKNOWLEDGEMENTS

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9. REFERENCES

AFSC DH 1-4, (1973), Electromagnetic Compatibility, Dept. of the Air Force, Headquarters 4950th Test Wing (AFSC), Wright-Patterson AFB, Second Edition.

Boaen, V. (1973), Designing Logic Circuits for High Noise Immunity, IEEE Spectrum, 10, No. 1, pp. 55-59.

Boufaissal, J. (1975), What's a Microprocessor?, Automotive Electronics II, (Society of Automotive Engineers), p. 51.

Caiati, F.P. and J.F. Thompson (1973), The Feasibility of a Car Central Computer, Society of Automotive Engineers, SAE 730126, Jan.

Cohen, R.M. (1975), Auto Electronics: A Semiconductor Suppliers' Viewpoint, Automotive Electronics II, (Society of Automotive Engineers), p. 43.

Coombs, C.F., Jr. (1972), Basic Electronic Instrument Handbook, (McGraw-Hill Book Co., New York, NY.)

Espeland, R.H., L.A. Jacobsen, L.R. Teters and E.L. Morrison, Jr. (1975), Investigation of Electromagnetic Interference Effects on Motor Vehicle Electronic Control and Safety Devices, (DoT, HS-801 737), U.S. Dept. of Transportation, NHTSA, Washington, DC 20590.

Everett, W.W., Jr. (1972), Topics in Intersystem Electromagnetic Compatibility, (Holt, Rinehart and Winston, Inc., New York) p. 502.

Greaves, L.D., J.J. Schwarz, H.J. Wagnon, and G.W. Wilson (1975), Subsystem Test Methodology for the AFWL Direct Drive Laboratory, D224-13057-1, AFWL, Kirtland AFB, NM.

Hood, R.B. (1974), Sensors, Displays, and Signal Conditioning, Automotive Electronics, (Society of Automotive Engineers), SAE SP-388, p. 107.

Jones, T.O. (1975), The Challenge of Automotive Electronics in the USA, Society of Automotive Engineers, SAE P-57, p. 33.

Jones, T.O., T.R. Schlax, and R.L. Colling (1975), Application of Microprocessors to the Automobile, Automotive Electronics II, (Society of Automotive Engineers), p. 65.

Jurgen, R.K. (1975), The Microprocessor in the Driver's Seat?, IEEE Spectrum, June.

Kostopoulos, G.K. (1975), Digital Engineering, (John Wiley & Sons, New York, NY).

McCarter, O.T. (1974), What Electronic Devices Face in the Automobile Environment, EDN, January 5, pp. 28-34.

Nolan, J.R. (1975), Survey of Electronic Displays, Automotive Electronics II, (Society of Automotive Entineers), p. 87.

Oswald, R.S., N.L. Laurance, and S.S. Devlin (1975), Design Consideration for an On-Board Computer System, Society of Automotive Engineers, SAE 750434, p. 79.

Patstone, W. (1974), Sensors and Transducers: An Update on the IC Invasion, EDN, July 20, p. 32.

Peatman, J.B. (1972), The Design of Digital Systems, (McGraw-Hill Book Co., New York, NY).

Society of Automotive Engineers (1974), Preliminary Recommended Environmental Practices for Electronic Equipment Design (Proposed), International Colloquium on Automotive Electronic Technology, Oct, pp. 28-30.

Society of Automotive Engineers J1113 (1975), Electromagnetic Susceptibility Test Procedures for Vehicle Components (Except Aircraft).

Vonderschmitt, B.V. (1974), A Long-Range Look at Semiconductor Development and its Impact on Automotive Electronics, Automotive Electronic Technology, SAE P-57, p. 137.

White, D.R.J. (1973), A Handbook on EMI Control Methods and Techniques, Don White Consultants, Inc., Germantown, MD, Vol. 3.

Wu, Yung-Kuang (1975), Private Communication, National Hwy Traffic Safety Administration, Dept. of Transportation, Washington, DC.

Zeisler, F.L. (1973), Transducers for Automotive Control Systems, Society of Automotive Engineers, Jan.

Ziomek, J.F. (1973), Single Wire Syste, Society of Automotive Engineers, SAE 730132, Jan.