DOT HS-801 737

5/4 5/10

INVESTIGATION OF ELECTROMAGNETIC INTERFERENCE EFFECTS ON MOTOR VEHICLE ELECTRONIC CONTROL AND SAFETY DEVICES

Contract No. DOT-HS-4-00918
October 1975
Final Report

PREPARED FOR:

U.S. DEPARTMENT OF TRANSPORTATION
NATIONAL HIGHWAY TRAFFIC SAFETY ADMINISTRATION
WASHINGTON, D.C. 20590

Technical Report Documentation Page

1. Report No. DOT HS -801 737	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle
Investigation of Electromagnetic Interference Effects on Motor Vehicle Electronic Control and Safety Devices

5. Report Date
October 1975

6. Performing Organization Code

7. Author(s) R.H. Espeland, L.A. Jacobsen, L.R. Teters, E.L. Morrison, Jr.

8. Performing Organization Report No.

9. Performing Organization Name and Address
U.S. Dept. of Commerce
Office of Telecommunications
Inst. for Telecommunication Sciences
Boulder, Colorado 80302

10. Work Unit No. (TRAIS)

11. Contract or Grant No.
DOT-HS-4-00918

12. Sponsoring Agency Name and Address
U.S. Department of Transportation
National Highway Traffic Safety Administration
400 Seventh Street S.W.
Washington D.C. 20590

13. Type of Report and Period Covered
Final Report of Period
June 10, 1974
June 1, 1975

14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

This report describes the results of a study to investigate, identify, and analyze the potential problems of electromagnetic interference from all sources (internal and external to the vehicle) that may cause malfunction of motor vehicle electronic control and electronically actuated safety devices.

This program accomplishes an analysis of inter- and intra-vehicle energy transfer and coupling by computer simulation, utilizing DOD developed modeling techniques that have been employed for a wide range of EMC/EMI design and evaluation support problems. These applications have included aircraft, spacecraft, and advanced surface ships.

A computerized circuit analysis model adapted from the IBM Electronic Circuit Analysis Program (ECAP) is used to assess susceptibility of representative types of electronic components and subsystems typically used in automotive electronic applications.

A preliminary EM environmental source file is provided based on a literature search of vehicular internal noise sources and worst case external electromagnetic field descriptions.

Validation test plans and preliminary EMC guidelines for automotive electronics are summarized.

17. Key Words Electromagnetic interference, automotive electronics, automotive safety, EMC guidelines, noise immunity

18. Distribution Statement
Document is available to the public through the National Technical Information Service, Springfield, Virginia 22161

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages	22. Price

Form DOT F 1700.7 (8-72)

Reproduction of completed page authorized

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

INVESTIGATION OF ELECTROMAGNETIC INTERFERENCE EFFECTS ON MOTOR VEHICLE ELECTRONIC CONTROL AND SAFETY DEVICES

R. H. Espeland, L. A. Jacobsen,

L. R. Teters, and E. L. Morrison, Jr.*

ABSTRACT

This report describes the results of a study to investigate, identify, and analyze the potential problems of electromagnetic interference from all sources (internal and external to the vehicle) that may cause malfunction of motor vehicle electronic control and electronically actuated safety devices.

This program accomplishes an analysis of inter- and intra-vehicle energy transfer and coupling by computer simulation, utilizing DoD developed modeling techniques that have been employed for a wide range of EMC/EMI design and evaluation support problems. These applications have included aircraft, spacecraft, and advanced surface ships.

A computerized circuit analysis model adapted from the IBM Electronic Circuit Analysis Program (ECAP) is used to assess susceptability of representative types of electronic components and subsystems typically used in automotive electronic applications.

A preliminary EM environmental source file is provided based on a literature search of vehicular internal noise sources and worst case external electromagnetic field descriptions.

Validation test plans and preliminary EMC guidelines for automotive electronics are summarized.

Key Words: Electromagnetic interference, automotive electronics, automotive safety, EMC guidelines, noise immunity.

---

*The authors are with the Institute for Telecommunication Sciences, Office of Telecommunications, U. S. Department of Commerce, Boulder, Colorado 80302

1. INTRODUCTION

The number and performance characteristics of commercial and pleasure (passenger) road vehicles have increased significantly over the previous two decades. Regulatory actions have evolved during this period, primarily at the state government level, resulting from higher vehicle speeds and greater population densities. State imposed vehicle inspection procedures attempt to insure a minimum safety and control capability for vehicles licensed to operate on public roadways. Inspection standards and acceptance criteria are different for automobiles and small commercial vehicles (e.g., panel and pickup trucks) than for the larger buses and multiple-axle trucks.

With increased vehicle performance, recently imposed emission regulations, and the current fuel economy emphasis, the potential for utilization of electronic control techniques for various energy management and safety functions is well recognized. The former application (control) includes fuel distribution and engine carburetion and exhaust operations. The latter (safety) includes radar and acceleration-controlled braking, speed control, passenger restraint and safety device actuation (e.g., air bags and door locks), light control and internal power management. Implied functional operations include analog and digital computations and control, with energy conversion devices used for sensing and actuation.

These electronic systems must be integrated into vehicles where control requirements have been satisfied by mechanical and hydraulic devices. With these devices, the vehicle environment considerations have primarily concerned such characteristics as temperature, moisture, and vibration. With increased sophistication in control and safety areas, electronic devices present cost-effective alternatives to the competing mechanical, hydraulic, and pneumatic systems. Electronic systems used could vary in complexity from the simple comparator amplifier to a micro-processor (digital) with interface input/output and/or conversion devices.

Electronic applications in motor vehicles have generally included entertainment (AM/FM radio and stereo tape decks), amateur transmitter and receiver equipment, mobile telephone systems, and electronic fuel injection and ignition devices. A number of imported passenger automobiles also utilize electronic circuitry in emission control functions.

Some possible types of electronic devices that may be included in passenger automobiles are depicted in Figure 1.1.

This introduction of electronic circuitry into the control and safety functions of road vehicles requires consideration of an additional environmental element, namely, the internal electromagnetic fields and the currents circulating on structural components that are used for mounting and circuit grounding. The internal electromagnetic environment derives from the operation of switches, electro-mechanical devices, and ignition action within the vehicle, as well as from the penetration of external fields through non-metallic areas of the vehicle body and from currents induced into the metal frame by low external frequency field components (e.g., utility power lines and lightning). These environmental components are discussed for various internal and external sources for the Electromagnetic Compatibility/Electromagnetic Interference (EMC/EMI) problem areas and for the principal radiative and conductive coupling modes. In recognition of the potential EMC/EMI problems which accompany the introduction of electronic systems into the control and safety functions of road vehicles, the Highway Safety Institute of the U. S. Department of Transportation initiated an investigation to determine the range of possible problems and to develop preliminary design guidelines in order to assist equipment and system designers in circuit and configuration selection and control. Possible circuit variations include discrete components as well as integrated circuits. Configuration factors are considered which relate to

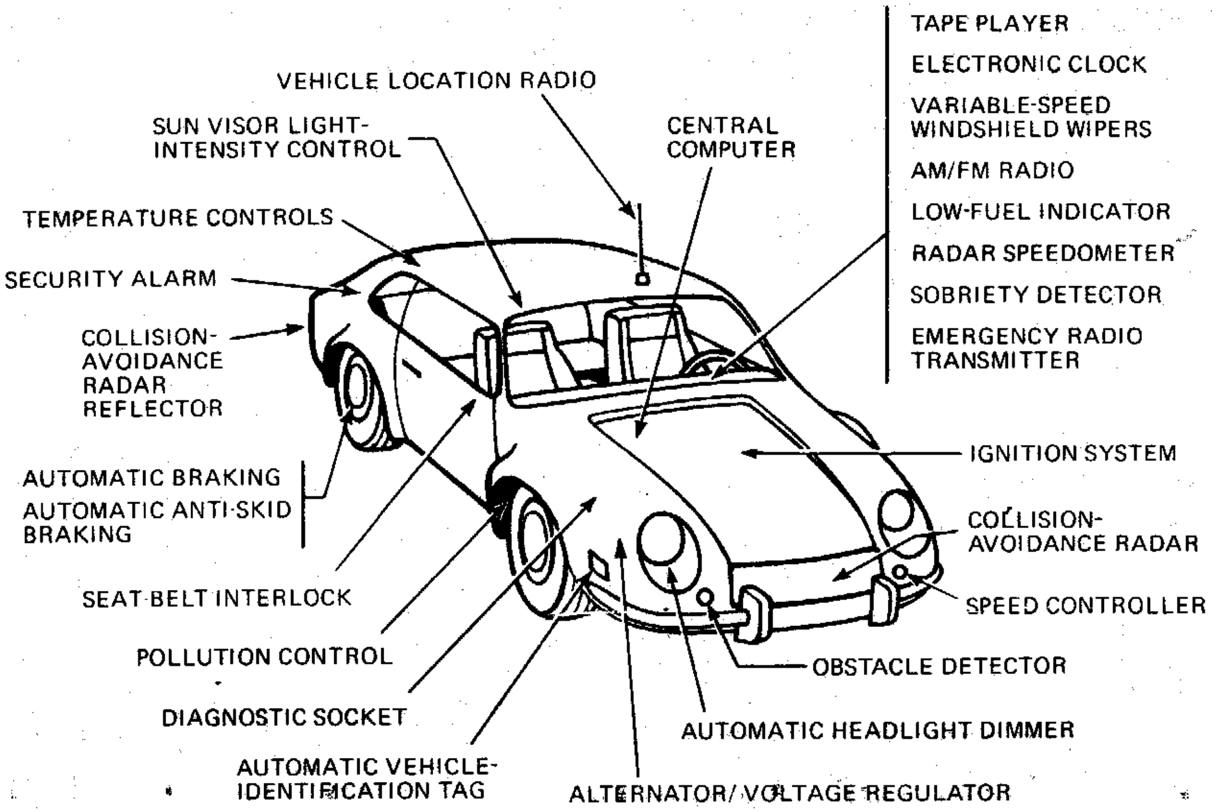


Figure 1.1 Automotive Electronic Devices (After Walker, 1973)

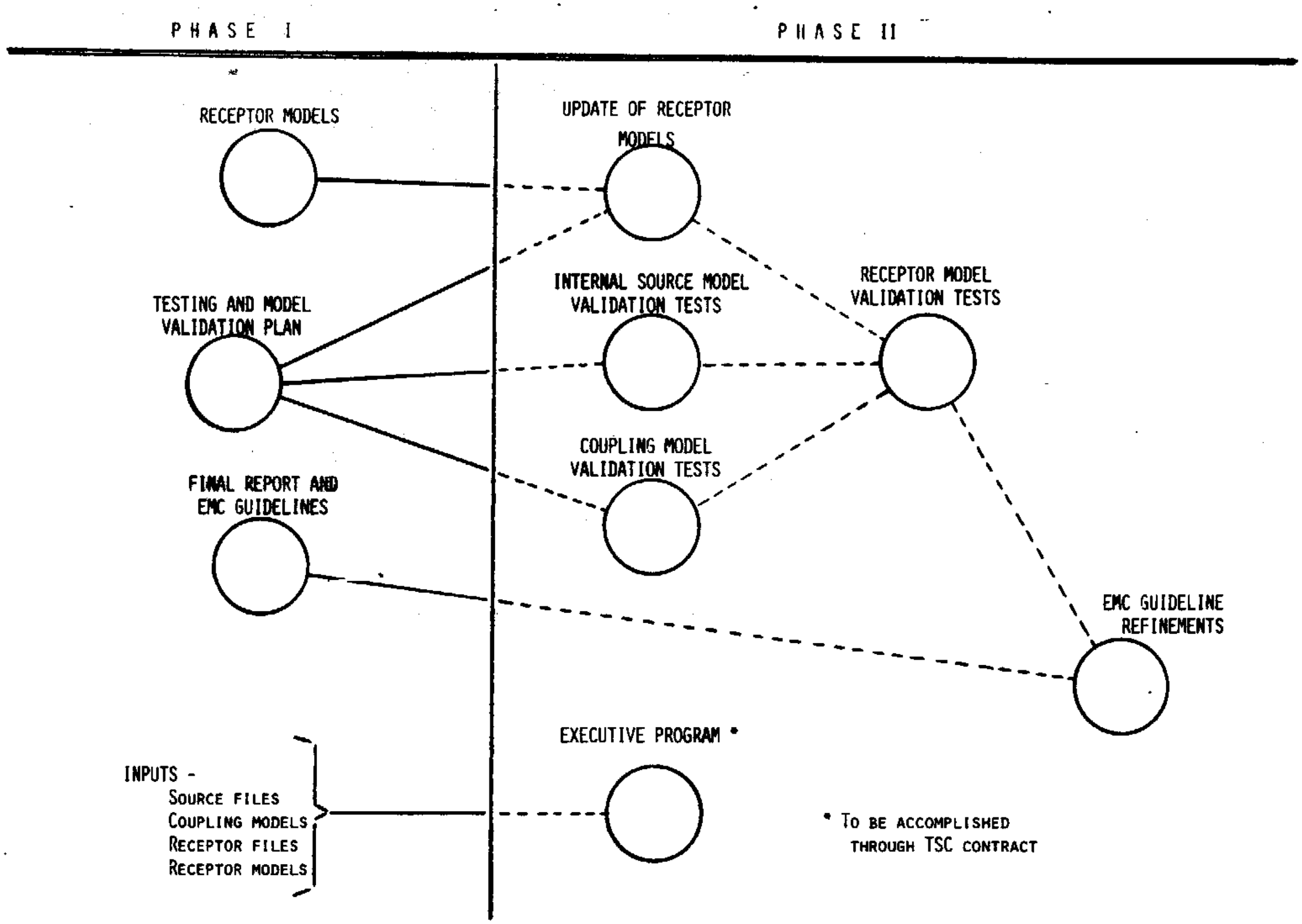
physical arrangement, shielding, and grounding. As indicated previously, these circuit applications include analog and digital computational and control (e.g., switching, amplifications, comparison) functions.

This investigation included a determination of the general character of the intervehicle electromagnetic (EM) environment from various internal and external sources. In this investigation, the following topics were studied: device energy coupling magnitudes based upon estimates of the effective apertures for cabling and devices, transfer magnitudes for cabling and grounding elements, and degradation characteristics for basic analog and digital functional elements (with the undesired signal or noise components coupled through the signal, control, and power connections for the test circuits). In order to provide maximum utility for device or system designers, a parametric investigation was performed to determine the sensitivities in relation to such characteristics as cable length and bundle arrangement, termination impedances, circuit configuration and operational mode, and vehicle functional state (e.g., starting, parked, moving, and day-night and related variations). Device and system design decisions also considered shielding, grounding and waveform specifications.

The EMC/EMI guidelines have advisory impact on design, and, therefore, must indicate constraints on the physical arrangement and placement of vehicle cabling and on the mounting, grounding, and connector integrity aspects involved in maintenance and measurements required to insure compliance with specifications. These specifications dictate the type of measurements and the amplitude or waveform parameters that define the undesired signal or noise spectrum constraints, coupling magnitudes, and shielding and grounding effectiveness required.

This investigation relied primarily upon simulation and modeling techniques in order to define the ranges of coupling and degradation for the conductive and radiative transfer and circuit responses. Such procedures are considered necessary in an initial investigative effort in order to indicate parametric and configuration sensitivities, and to provide a basis for planning subsequent measurements which are designed to validate the simulation predictions and to quantify the coupling and degradation parameter variances. The vehicle configuration variations (device location and cable bundles), the source device arrangement and operational mode differences, and the different analog and digital circuits available are typical justifications for employing simulation and modeling for sensitivity analysis, measurement planning, and as the basis for the initial design and application guidelines relative to coupling and degradation characteristics. The general time-phase relationships between modeling and measurement are diagrammed in Figure 1.2. For this EMC/EMI program, the modeling effort was completed in Phase I, and the validation and noise source measurements, will be accomplished in Phase II. Such a relationship between modeling and measurement activities has proven invaluable to many military system development and performance, or measurement specification quantification requirements. A coordinated measurement program with performance-related data and identifiable characteristic relationships is to be expected. These relationships concern the functional connection between coupling, circuit parameters, and degradation. This includes problems relating to the intra-system (vehicle or site) EMC/EMI analysis for aircraft, space vehicles, sites involving co-located electronic equipments (computers, radars, communications, electro-optical devices), and naval ships. Modeling developments and supporting validation measurements in these problem areas over the previous 10-15 year period have produced a simulation technology with an established credibility.

For this program, models have been utilized which treat conductive and radiative energy transfer, bonding and grounding resources, and circuit performance. These have been employed extensively in the EM intra-systems analysis areas previously cited, thus assuring credibility for the parametric analysis performed here. These models are described in Sections 3 and 4.



* To be accomplished through TSC contract

Figure 1.2 Automotive EMI Research

As mentioned previously, the model data will guide the measurement operational modes and the form of data analysis necessary. This procedure follows the proven experience of previous EMC design support or performance evaluation programs.

In addition to the model prediction-validation relationship and source file refinement, the organization of the coupling and degradation models into an integrated program under the control of a set of executive routines is indicated in Figure 1.2. This integrated system will provide the Department of Transportation with a "user-oriented" simulation capability to support future design or test specification development and evaluation of advanced vehicle control or computational system concepts or configurations. Upon completion of Phase II, this integrated modeling system would include the updated source models, coupling model parameters, and degradation descriptors derived from the measurement tasks. Previous experience organizing such integrated model systems in relation to file structures, retrieval methods, and model configuration will be applicable to this task.

Subsequent sections of this report discuss the energy coupling and transfer models, and the circuit model simulation procedures utilized for this investigation. The validation and model-updating measurements will be accomplished during Phase II. The preliminary guidelines regard the EMC/EMI aspects of circuitry design, selection and placement, and the cable bundling and routing within a vehicle. These guidelines also indicate grounding, bonding, and shielding specifications in relation to interference sources, spectral content, circuit type (discrete component or integrated circuits), and functional application.

though the non-differential output noise amplitudes are .4 V and .15 V respectively. Thus the differential output noise is smaller than the single ended output noise by more than 60 dB. These numbers will vary considerably as the matching in beta of the transistor pairs vary. In this example the input betas were matched exactly, while those of the output stage were purposely mismatched by about 1.5%.

Preliminary ECAP analysis has shown that this particular operational amplifier has high inherent power supply noise immunity. Also since induced pick-up noise tends to have high positive correlation, this amplifier will eliminate most of this type noise due to its high common-mode rejection. The main noise problem will result from single ended input noise or asymmetric input noise.

6. TEST PROGRAM

6.1 Introduction

The program reported herein has concerned an analysis of energy transfer and coupling phenomena within a road vehicle, and the susceptibility of various types of analog and digital circuitry to impulsive and continuous forms of interference components. This analysis has been based on computer modeling of wiring harness segments and the various types of receptor circuits, with the vehicle operational mode constraining the inter-harness energy coupling (e.g., switch, light, and device condition in relation to vehicle operation) parameters. Cable termination impedances and the effective apertures for internal sources and receptors have obvious model sensitivities. These computer model exercises have provided a range of parametric and configuration dependent transfer, coupling, and degradation definitions which allow the development of preliminary EMC related design and applications guide-lines for road vehicle electronic equipments.

This modeling effort has also employed a wide band impulsive form of stimuli to maximize the resolution of the transfer and coupling analysis. Utilization of the EMC guidelines by equipment and vehicle designers also requires specification of the relative spectral density characteristics of the conductive and radiative components of actual internal sources (e.g., ignition, electromechanical devices, switches). A measurement program to develop such a source file is included in the Phase II effort. Subsequent paragraphs discuss these two measurement efforts.

6.2 Validation Rationale

This research and analysis effort (Automotive EMI RESEARCH - PHASE I) produced a preliminary EM environment file (internal and external) germane to a typical motor vehicle, a computer model for analyzing the signal coupling properties within the vehicle, and a computer model to evaluate the sensitivities and susceptibilities of electronic circuits and subsystems.

The internal environment files were developed from reports and studies conducted primarily by groups in the automotive and electronics industries. The coupling functions for the wiring harness and grounding elements were derived through the wire-to-wire coupling module of the "Intrasystem Electromagnetic Compatibility Analysis Program (IEMCAP) as originally developed for the U.S. Air Force, and the receptor analysis capability was evolved from the IBM "ELECTRONIC CIRCUIT ANALYSIS PROGRAM" (ECAP).

Although computer modeling in EMC/EMI analysis and evaluation applications has received wide acceptance and confidence for nearly a decade, the necessity of validating model predictions must always be recognized. This model-measurement relationship provides parameter uncertainty resolution and establishes confidence in simulator predictions. In general, simulation is a principal vehicle in designing measurement programs through identification of parameter or configuration sensitivities indicating <u>what</u> factors are to be measured, guidance regarding <u>how</u> the measurements are to be accomplished, and the data analysis and interpretation methods. This model-measurement relationship is a consideration when parameter or configuration variations are such as to cause an unacceptable confidence level in model data.

The models employed for this program have attained a high degree of credibility because of the extensive application to aircraft and space vehicle EMC/EMI problems. Because of the large possible variances in cable characteristics and arrangements and the effectiveness of structural and metal case shielding in commercial road vehicles, a validation and parameter definition measurement program is required. The demonstration is also important to establish confidence in a community that is not so oriented toward modeling as those concerned with military EMC problems. This is also important in the evolving utilization of simulation techniques for vehicle and equipment life cycle management support (design, testing, maintenance phases).

6.3 Test Plans

A significant part of the Phase II-Automotive EMI Research effort will be devoted to the source measurement and validation test program. The specific test categories defined are: 1) internal source (environment) measurement, 2) signal coupling and transfer model validation test, and 3) the receptor model validation and subsystem susceptibility tests. For planning purposes these tests fall into two areas: 1) those to be preformed primarily on a test vehicle and 2) those to be preformed in a laboratory or laboratory test situation. The test philosophy, facilities, types of measurements, and methodology of these areas will be discussed in the following paragraphs.

ON-VEHICLE TESTS

Internal source characteristics must generally be measured while operated on a conventional vehicle with all interconnections. The filtering and shielding factors afforded by structural components and device interconnections (including switch actions) must be reflected in the source emission definition. Isolated device measurements are useful but must be modified when utilized for environment specification by the effects imposed by the normal modes of employment. In the vehicle, both normal and abnormal operating conditions can be created which generate the signals to be measured under normal loading, filtering, and coupling conditions. Also such parameters as engine speed, motor loading, primary electrical power line loading, open and closed switches, and component failures can be varied to determine the environmental effects.

A list of typical internal automotive devices that can produce interfering signals is given below:

1. ignition systems,
2. generator and regulator systems,
3. switches,
4. motors,

5. soleniods and relays,
6. flashers,
7. sensors (electronic, magnetic),
8. static dischargers,
9. entertainment systems,
10. mobile transmitters (telephone, amateur),
11. automotive radar,
12. air-conditioning clutches,
13. garage door openers (transmitters).

This list suggests that three basic classes of interfering signals could be generated by the various sources: periodic related to engine speed, periodic related to motors, etc., and aperiodic related to the random actuation of switches, solenoids, etc. It is generally known that the potential interfering signals can range from a few volts to well over 100V amplitude. In addition, some of the aperiodic signals appearing on the power supply lines have a polarity opposite to that of normal supply voltage.

Equipment to be used for these vehicle measurements will include an oscilloscope with both high-impedance voltage probes and clamp-on current probes, wideband radiation probes, and a spectrum analyzer. The amplitude and duration of pulse-type signals will be determined, as well as the spectral content of the background noise. A display of proposed tests to measure the source signals and their distribution is shown in Table 6.1. This table is in matrix form showing the vehicle operating conditions, the test points, and the test code. An explanation of the test code and intended equipments is on the second page. The use of additional test points will be considered as the results of these tests may dictate.

Radiation measurements will include discrete frequency and energy densities in the regions of the front grill, rear bumper and axle, passenger and driver areas, and primary vehicle body gaps (hood-fender, hood-cowl).

Table 6.1 Proposed Test for Source Signals and Distribution

TEST POINTS	OPERATING CONDITIONS	ENGINE RUNNING			DIRECTIONAL SIGNALS		EMERGENCY FLASHER	WINDSHIELD WIPER (ELECTRIC)		WARNING BUZZER	HEATER & AIR COND FAN			AIR COND CLUTCH		STARTER CRANKING	ALTERNATOR	HEADLAMP SWITCHING		MAXIMUM LAMP LOAD	
		IDLE	2,000	4,000	LEFT	RIGHT		START	RUN		START	RUN	STOP	START	STOP			TO ON	TO OFF	TO ON	TO OFF
SCOPE SYNC		DISTRIBUTOR			O.S. FLASHER		EMERG. FLASH.	WIPER SWITCH	INT.	INT.	FAN SWITCH	INT	FAN SWITCH	TEMPERATURE CONTROL		INT.	INT.	HEADLAMP SWITCH		INT.	
MAIN BUS		1, 3			1, 3	—	1, 3							1, 3							1, 3
IGNITION SWITCH TERMINALS	ACCESS	1, 3	1, 3	1, 3	1, 3 4, 6	—	1, 3	1, 3 4, 6							1, 3 4, 6	—	—	—	—	—	—
	COIL	1, 3, 4,5,6	1, 3 4,5,6	1, 3 4,5,6	1, 3								1, 3								1, 3
FRONT DIRECTION SIGNAL	LEFT	1, 2, 3	1, 2, 3	1, 2, 3	1, 2, 3 4, 6	1, 2, 3	1, 2, 3 4, 6	1, 2, 3						1, 2, 3							1, 2, 3
	RIGHT	1, 2, 3	1, 2, 3	1, 2, 3	1, 2, 3	1, 2, 3 4, 6	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
FRONT PARKING LAMP	LEFT	1, 2, 3										1, 2, 3									1, 2, 3
	RIGHT	1, 2, 3				1, 2, 3	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
REAR DIRECTION SIGNAL	LEFT	1, 2, 3		1, 2, 3	1, 2, 3 4, 6	1, 2, 3	1, 2, 3 4, 6	1, 2, 3						1, 2, 3							1, 2, 3
	RIGHT	1, 2, 3		1, 2, 3	1, 2, 3	1, 2, 3 4, 6	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
REAR TAIL LAMP	LEFT	1, 2, 3		1, 2, 3	1, 2, 3 4, 6	1, 2, 3															1, 2, 3
	RIGHT	1, 2, 3			1, 2, 3	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
WINDSHIELD WIPER MOTOR		1, 2, 3					1, 2, 3	1, 2, 3 4, 5, 6	1, 2, 3 4, 5, 6	1, 2, 3						1, 2, 3					1, 2, 3
AIR CONDITIONER CLUTCH		1, 2, 3					1, 2, 3						1, 2, 3	1, 2, 3 4, 6	1, 2, 3 4, 6	1, 2, 3					1, 2, 3
O.S. FLASHER OUTPUT		1, 2, 3		1, 2, 3	1, 2, 3 4, 6	1, 2, 3 4, 6	1, 2, 3 4,	—	—	—	—	—	—	—	—	—	—	—	—	—	—
EMERGENCY FLASHER OUTPUT		—	—	—	—	—	1, 2, 3 4, 5, 6	—	—	—	—	—	—	—	—	—	—	—	—	—	—
IGNITION COIL POSITIVE TERMINAL		1, 3 4, 5, 6		1, 3 4, 5, 6	1, 3								1, 3								1, 3
WARNING BUZZER		1, 3								1, 3 4, 6											
HEADLAMP TERMINALS	HIGH	1, 3								1, 3							1, 3	1, 3 4, 5, 6	1, 3 4, 5, 6	1, 3	1, 3
	LOW	1, 3										1, 3									1, 3
BATTERY		1, 3	1, 3 4, 4	1, 3						1, 3,6						1, 3,6	1, 3				1, 3
ALTERNATOR	FIELD	1, 3	1, 3	1, 3	1, 3											1, 3	1, 3 4, 6	1, 3			1, 3
	BATT.	1, 3	1, 3	1, 3	1, 3											1, 3	1, 3 4, 6	1, 3			1, 3

Table 6.1 (Continued). Proposed Test for Source Signals and Distribution

Tests:	Equipment:
1. Voltage waveform reference to device ground to show voltage transients under as many operating conditions as possible.	H. P. 1207 B Scope
2. Voltage waveform from battery ground to device ground to detect ground differential voltages in a possible ground loop condition.	H. P. 1207 B Scope
3. Spectrum measurement of voltage waveform to determine the frequency/power content of the device load.	UA - 6A Spectrum Analyzer (Federal Scientific)
4. Current probe measurement of device current.	H. P. 1207 B Scope H. P. 456 A Current Probe
5. Battery and terminal to device and lead to examine effects of line drop.	H. P. 1207 B Scope
6. Power spectrum of device current. (This test would be expected to be the same as the voltage spectrum. It may prove effective in isolating device analysis from outside interference.)	UA - 6A Spectrum Analyzer H. P. 456 A Current Probe with Adaptor

LABORATORY TEST

These tests are concerned with the cited parametric updating for model enhancement and validation of predicted coupling magnitudes. This phase concerns sensitivity tests of components and subsystems and a number of coupling measurements on the wiring harness. The advantages of a laboratory environment are the controlled experimental conditions thus enhancing the ability to isolate specific stimuli and transfer mechanisms in the absence of normal vehicle background noise. A controlled environment with adequate diagnostic instrumentation allows close correlation with model exercises. Receptor devices to be included in these tests include discrete component and integrated circuit functional elements of the type modelled, and various electronic safety and control subsystems that could be individually procured. The functional circuits, as previously indicated in Section 4, are listed:

1. gates (AND, OR),
2. flip-flops,
3. counters (Binary and Decade),
4. decoders,
5. encoders,
6. drivers and buffers,
7. adders,
8. shift registers,
9. core storage modules,
10. operational amplifier.

Commercial modules will be utilized, functionally similar to the circuitry included in the model exercises.

Safety and control circuitry will be tested as available. Since these devices include varying combinations of the previous functional circuitry, correlation in EMC characteristics (considering configuration dependencies) will be demonstrated. Candidate control elements are listed:

1. ignition systems,
2. radar braking,

3. speed control,
4. voltage regulation,
5. anti-lock braking,
6. electronic fuel injection,
7. passive restraint air bags,
8. seat belt interlock,
9. headlight dimmer,
10. exhaust emission control.

These lists suggest the choice of subsystems and component functions that can be included in the test plans. Availability and diversity will govern which devices will be actually tested. These will be specified in the test plans being completed for Phase II.

The facilities for testing discrete devices, integrated circuits, and electronic subsystems developed and operated by the Air Force Weapons Laboratory (AFWL) Electronics Division at Kirtland, AFB New Mexico will be used to perform the circuit and subsystem tests.

Even though the emphasis at AFWL has been measurement of the EMP susceptibility of components and subsystems, the facilities and the measurements techniques, analysis procedures, and data handling methods are directly applicable to this EMC program. As cited previously, the impulse stimulus is uniquely compatible with that employed for the computer coupling and circuitry models.

The AFWL Direct Drive Laboratory will be utilized for the harness coupling and circuit upset testing.

"Direct Drive" refers to hard coupling of the interference signal into the circuit/subsystem. For these tests, the impulse source would be coupled into a cable harness with appropriate termination switches and load, and to the power, control, and ground lines or terminals of the indicated circuitry modules.

Direct drive includes four types of test:

(1) <u>Direct Injection</u> to determine damage or upset thresholds at subsystem interfaces.

(2) Component Testing to obtain failure or response parameters for individual components.

(3) Nondestructive Pulse Tests to detect spurious coupling paths.

(4) Continous Wave (CW) Measurements to define transfer functions and input and output impedances.

Any or all of these tests may be employed as part of an impulse upset or damage assessment. Their relative importance will depend on the individual system. All direct drive tests are characterized by tight coupling between the environment source and the test specimen. This coupling may be resistive, inductive, or capacitive and coupler requirements are a significant test design consideration. Since the coupling is efficienct, the environment source tends to be relatively inexpensive (compared to the environment source for system level testing).

The AFWL Direct Drive Laboratory includes the complete range of equipment required for subsystem testing. This includes environment sources, transient instrumentation, and data processing. The major equipment items available in the Direct Drive Laboratory are categorized as follows:

(1) The Automatic Test System (ATA) 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, frequencies, 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.

(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. One particularly useful combination consists of the ATS, the Distribution System, and the Linear Amplifier. This combination is referred to as the Programmable Universal Direct Drive (PUDD). The PUDD provides for complete automation of subsystem direct injection testing, as is depicted in Figure 6.1. The Distribution System provides sufficient interface capability so that the ATS computer can control the operation of the test subsystem and the operation of a number of auxiliary equipment items.

Radiation testing involves illumination of harness and the circuit subsystems with wideband pulse and discrete frequency sources. Sequential testing of a harness with switched terminations, and circuit modules with appropriate shielding and cable connectors will be accomplished. These tests would be conducted in AFWL facilities, and possibly limited circuit and functional level measurements in NBS TEM cells.

Diagnostic measurements for the wideband tests would include pulse-time waveforms, wave front flatness, and the direct and reflected component ratios. Instrumentation for this

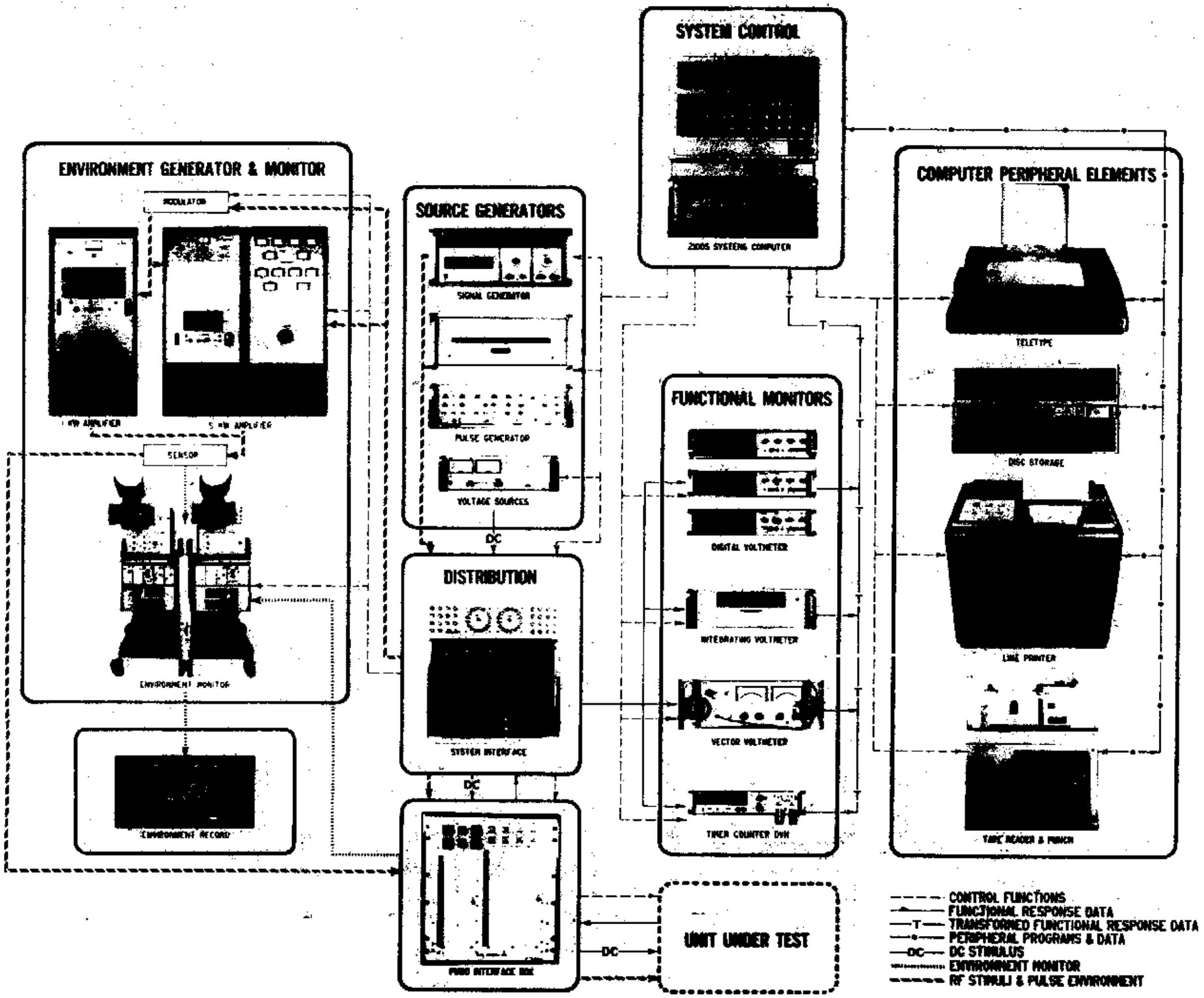


Figure 6.1. Programable Universal Direct Drive System (PUDD) (After U.S. AFWL, 1974)

requirement is available at both facilities. Experiment configuration is important relative to sensor and data transfer cable arrangement and connections to the test device to remove secondary current effects. Procedures have been developed and certified as elements of standard test methodology for control of test cell arrangements and methods of testing to assure minimal experimental bias.

Measurements in the radiative test phase will include inter-wire coupling within a harness with mode related termination switching, and circuit and subsystem functional degradation. Data to be recorded for analysis for the harness coupling include induced time waveforms and in some cases a direct spectral display in relation to termination conditions, and circuit module responses as related to the magnitude and form of the interference signal and mode of coupling.

Circuit module operation with interference from radiative and/or conductive sources will be generally measured from the general functional considerations listed:

a. Flip-flop circuit - Turnover delays, failures to operate, false operation, output noise level.
b. Gates - Failures to operate, response delays, false operation, output noise level and form.
c. Adders - Sum errors in relation to word rates.
d. Counters - Sum errors in relation to input rates.
e. Shift registers - Bit or word position errors as function of command rate.
f. Storage Modules - Failure to accept or retain bits or words, unintended readout, induced destructive read-out, output noise level and form.
g. Operational Amplifier - Output noise level and form, transfer function error.

For the digital and pulse operated circuits and modules, the amplitude of the impulse and continuous mode interference, and the phase differences between impulse interference and control and signal pulses must be varied to develop multi-variant response descriptors. For these functions the amplitude and time phase of the interference component, and the entry mode must be included in the degradation (noise immunity plot) description.

With discrete component circuits and modules, diagnostic data may also be recorded to assist in understanding of the indicated functional performance characteristics. Waveform recordings at specific internal points present unique problems, however, in experimental bias potential; and must therefore be carefully considered in the instrumentation and analysis planning for data validation.

7. CONCLUSIONS AND GUIDELINES

7.1 Introduction

The electromagnetic compatibility considerations for road vehicle electronic systems concern the design, fabrication, and maintenance phases of the life cycle. All phases have nearly equal importance if desired or required operability criteria are to be assured. Success in the EMC aspects of vehicle operations ultimately requires coherent management procedures. These procedures should detail the simulation and measurement requirements and the techniques that have some commonality in methodology and data support files. Regulations and supporting technical and operational documentation which are "user oriented" should also accompany these EMC analysis and measurement elements. The simulation system should provide a modularized set of radiative and conductive coupling models (field-to-wire, wire-to-wire, bond resonance), numerical circuit and subsystem scoring (S/I_i; S/I_j ...) model files, internal and external source files, sets of empirically based aperture penetration discriptors, as well as an executive program to manage and control the computational, data base organization and operation, inter model data exchange, and I/O operations. Programs (computational and control routines) in tape or card form, selected files, and the Technical and User Manual documentation could be available at a central computer or furnished to a designer or manufacturer for use at a separate computer facility. This type of simulation capability assures commonality in procedures and equipment characteristic files for all design and manufacturing requirements. It allows a direct comparison in data output from independent exercises with a common system configuration. This mode of operation represents significant cost savings for industry subsystem and vehicle manufacturers, and for agencies of DOT with EMC and equipment certification responsibilities.

The measurement procedures should accommodate computer model validation, as well as the development of vehicle device and equipment emissions for the Source File updating, and instrumentation techniques useable by maintenance groups associated with sales and service organizations. Basic measurement requirements concern emission and coupled spectral densities (radiation and conduction components) and time waveforms for the various internal aperiodic energy functions. Instrumentation components would include connectors and impedance converters for direct coupling to wiring and circuit test points, wideband radiation sensors with impedance transformers, signal converters and conditioning filters, spectral density extraction (comb filters or FFT micro processor), and recording and display devices. For maintenance and service facility applications, the inter connections, control mechanisms, and display devices must operate with procedures not too dissimilar from current diagnostic instruments. Utilization and data interpretation procedures must impose a minimal special training and education requirement for service personnel.

These simulation and measurement applications will be detailed in Phase II of this EMC/EMI program and incorporated into the revised guidelines. As mentioned, these technical support elements are important to effective management and quality assurance.

The preliminary EMC/EMI guidelines summarized in this section relate to the harness arrangements, shielding methods, circuit types, and operational modes. These guidelines result from the simulation exercises and application reviews of the Phase I program, and will, as indicated previously, be refined through the validation and source measurements of the Phase II effort. These initial guidelines address basic methods for controlling interference through specification of source emission and wiring arrangements, shielding practice, and recognition of the immunity properties of various types of analog and digital circuits that would be employed in vehicle electronic systems. Subsequent paragraphs discuss these control areas.

7.2 Internal Source Control

The control of both radiative and conductive emissions from devices and subsystems within a vehicle is problem oriented (in application) since the cost effectiveness of such a solution depends upon the specific character of the devices and their method of employment. The guidelines for source control should, however, generally follow the experience of the aircraft industry in establishing sets of procedures for control of the basic waveform generated, the utilization of filtering devices in the conductive leads, and shielding techniques to reduce the radiative component to an acceptable level. As cited previously, cost effective considerations prevent a direct extrapolation of specifications applicable to the aircraft industry into the road vehicle arena.

Typical of the problems are the measurements of transients that can occur on the vehicle power wires. During starting action, for example, the 12V power bus may be subjected to voltages that reduce to approximately 5V with peaks extending to ± 24 volts. Transients where high inductive loads may be transferred momentarily on or off the power line may result in magnitudes of 75 to 130 volts. These pulse signals will vary in width from the millisecond range to several microsecond range. Previous measurements of RF noise components has demonstrated amplitudes of ± 20V over the frequency range of 100 kHz to 7 MHz. These components generally originate from switching transients on top of rotating device noises, as well as spurious emissions from the ignition system. If a vehicle has a radio telephone system with improper grounding, the RF noise could originate from such a source. This is particularly true where the improper grounding also includes a corroded joint. This "diode" action has been demonstrated on shipboard as the "rusty bolt" effect. The nonlinear properties generate a wide bandwidth of emissions when illuminated by a discrete frequency.

External sources to which the vehicle may be exposed include commercial broadcast stations with a possible maximum exposure of

10V/m to 70V/m, and radar installations of the type employed at airports that may illuminate a vehicle with fields of 1000 V/m. Lightning transient fields can well be of the same integrated magnitude as that cited for an airport radar. These broadcast and radar signal amplitudes are obviously pessimistic occurring when the radiators are in close proximity to a roadway.

As indicated previously, the control of internally generated noise components includes parameter selection and design to minimize extraneous components in the generated waveform, the employment of filtering devices to reduce extraneous components to an acceptable level, and proper shielding to prevent the unintentional escape of spurious spectral components. The specific application of any technique is obviously governed by cost and the usage of the source device. As an example of the latter, passive filters employed in a high current line present serious component cost and packaging implications. Impedance and power loss considerations here would probably dictate other techniques of source waveform control and shielding technique. For a low-current source, however, passive filtering represents generally a very cost effective spurious component eliminator. The R, L, and C components can be small with very low cost as contrasted to the fabrication expense of shields and the component expense associated with coaxial cables and special purpose connectors.

Waveform control within the output circuitry of any functional device would involve functions such as time gating or limiting, these utilizing active circuitry with the attendant expense.

Undesired components can also be removed or suppressed by the employment of proper grounding techniques. Resonances in the grounding bonding straps, and the provision for clean joints with the frame or grounding buses are important in radiative coupling and assuring shielding effectiveness. Resonances are of obvious importance where a high number spurious or harmonic components of a wideband pulse is present. A significant aperture can be provided by a ground or bond strap, and is therefore a potential problem for DTL and TTL logic and high gain operational amplifiers. For the latter, the wideband interative operations have the highest susceptibility.

7.3 Power and Signal Transmission

Current wiring practices for road vehicles involve a harness configuration that connects instrument and control panel areas to the engine compartment and forward lighting, the transmission controls, and the rear lights. This harness generally appears as a Y and is fastened to the inner frame along of the length of the car and passes into the passenger compartment near the steering column. This harness generally comprises only bundles of insulated wires which provide virtually no protection from wire-to-wire transient transfer. Noises induced onto wiring in the engine compartment or large switching transients associated with, for example, the horn relay or turn signal operation can also couple through the bundle with little impedance. Because these bundles connect generally to lights or other low impedance loads, one end is terminated relatively close to ground level. With electronic circuits connected to such a wiring arrangement, however, the impedance relationships would not be advantageous from the viewpoint of wire-to-wire energy coupling. These wires are also unshielded, and except for those regions where they are mounted close to the longitudinal structure, limited shielding from radiation is available. This radiation problem can be particularly severe because of the length of the wires and the consequent large effective aperture. For electronic circuits with a significant input impedance, therefore, severe problems are to be expected from the radiative environment internal to the car.

Consideration of cable configuration should therefore include separation of power and signal distribution bundles. Coaxial cables may be necessary for many of the signal lines where, for example, FET on time-controlled digital logic are the types of receptors connected. Wide bandwidth digital type signals present particular problems because of the limited utility for standard filtering schemes. Time gating is useful, but for interference having high periodicity rates, the potential for significant improvement by time gating is very limited. Coaxial cables are therefore almost mandatory for pulse-information-transfer applications. Where a CW carrier with AM or FM modulation is employed in a control function, spectral filtering techniques provide significant improvements in noise immunity because of the limited bandwidth of the receptor device. Modulation components are significantly less vulnerable than pulse waveforms. For continuous modulation formats, further noise immunity is accrued through coherent detection which generally adds little in cost to circuit development or fabrication.

Coaxial cables admittedly represent a significant cost impact in the wiring system for a road vehicle. This is obviously most sensitive with passenger automobiles. Commercial vehicles would be much less effected because of the higher total cost.

Assuming cost factors could be reconciled, the future employment of multiplexed data bus configurations provides significant EMC/EMI enhancement capabilities for multifunctional vehicular control. A single shielded wire could be routed throughout the vehicle with signal sources and receptors coupled through appropriate multiplex-demultiplex equipments. Time or frequency-multiplexing schemes would be employed with only minor differences in immunity for the road vehicle type of environment. These data transfer techniques have found a significant application in aircraft systems where a high degree of noise immunity was necessary and cost-space considerations prevented the employment of bundles of coaxial cables. With integrated circuit technology the multiplex-demultiplex cost considerations are nearly negligible. Since such integrated circuitry can readily be fabricated to tolerate the temperature and other physical environment of a road vehicle, the life time of this circuitry should readily exceed that of other automobile accessories, assuming normal usage.

The previously cited EMI reduction procedure of separating signal and power cabling represents a recognizable disadvantage in fabrication and maintenance of a road vehicle. These cables cannot always have large physical separation because of the close proximities that will be necessary in such areas as the engine compartment, instrument panel, and the connections to transmission control and sensor devices.

7.4 Circuit Selection and Design

The previous chapters of this report presented immunity and degradation data for a variety of integrated and discrete component analog and digital functional circuitry. Basic elements were modeled and functional modules were also evaluated, particularly for families of logic. Salient characteristics of the operational considerations of this logic include operating levels, noise immunity, noise generation, fan-out/ fan-in, and power dissipation.

For logic element, the analysis of the presented data indicates that for noise pulses exceeding 200-300 ns, the propagation delay and rise-times and fall-times are important. Evidence also indicates that the sensitivity to power supply voltages is affected by the noise on the signal and control lines. This is particularly aggravated when the noise on the signal and power lines are correlated. (See Sections 4 and 5).

The operational amplifier has a limited vulnerability for noise on the power supply lines. With a balanced input circuit, uncorrelated noise on both inputs is amplified as an unbalance signal. Uncorrelated noise on the positive and negative supply lines is reflected in the output as a vector addition, with transients less than 10% of the supply voltage. Spectral modification is directly related to the bandwidth limiting properties of the transfer function in the operational feedback circuit. The direct input connection is particularly sensitive because of the high impedance. In normal operation this circuit point would always be protected by shielding and the connections through the feedback and driving operational components. Noise on the ground line presents more effective coupling than the same magnitudes on the power lines because of the additive connections in the input balanced amplifier. Operational amplifier utilization therefore requires shielding of the amplifier device, short grounding lines connected to a common bus, or a single chassis location.

The Darlington amplifier requires similar considerations in the shielding and input line protection. Noise on the power lines in the range of 5% to 15% supply voltage presents little problem in operation of the circuit. Analog circuitry generally present much less problem in signal filtering than digital elements because of the reduced signal bandwidth. The major exception would be a relative comparison between a high speed repetitive analog element and lower bit rate serial digital systems. Repetitive analog computers have found limited application in motor vehicles because of the sensitivity to power supply regulation and with the higher stability operational amplifiers a problem in noise immunity relative to low to intermediate digital computation elements. Advantages in maintenance, cost, and functional effeciency also accrue to digital computation.

The increased utilization of micro-processors also presents significant advantages in the digital area in respect to noise immunity. These devices can be colocated with sensors, thus affording reduced susceptibility because of impedance and signal form conversions. Difficulties with micro-processors in the motor vehicle application relate to the maintenance of proper grounds over extended operating periods and through service cycles. A tendency will probably emerge towards single element or distributed computation in only two or three interval models in order to mimimize service costs and complexity.

Shielding, grounding, and cable protection will therefore be the principal EMC/ EMI problems. The relative comparisons of TTL, DTL, ECL, and CMOS logic were indicated in this report (Section 5). With the forthcoming test program these sensitivities will be verified and the subsequent guidelines (Phase II) will indicate a range of environmental and parametric sensitivities for various pulse control and digital computation applications. Supply voltage sensitivities for the noise immunity data were presented. At the higher supply levels (∿ 15V) CMOS and ECL have significant advantages relative to other logic types. For the latter, the current drive and low input impedance affords appreciable protection to wire-wire induced noise.

7.5 Receptor Packaging and Placement

This section discusses considerations relative to the shielding and physical configuration for mounting subsystems and electronic circuits within a motor vehicle, and the placement of these circuit elements within a vehicle relative to structure and noise sources. Integrated circuits will, for cost and maintenance reasons find an accelerating application for digital and analog functional requirements. Packaging considerations relative to volume are also important. Maintenance of IC circuitry would therefore be relagated to module replacement. Discrete component circuit boards will find application for the next few years with maintenance in the eschelon category, but at the local service facilities, complete replacement will still be necessary. Training for service personnel and diagnostic equipment dictate this replacement philosophy.

Packaging considerations require that all electronic circuitry be assembled in a shielded container. Power transistors that must be exposed to free air flow can follow the same procedures as currently employed for ignition control and light control devices where the shielded cover and radiator fins protrude external to the box and therefore afford necessary heat transfer. This consideration is of importance primarily for power converter circuitry.

Integrated circuit elements are generally assembled in a shielded container. These organized in modular structure within a second shielded container connected into shielded signal lines and power and control lines with passive filtering devices as necessary could be utilized in any area of the motor vehicle.

Grounding should be accomplished through single point or star techniques, where a common connection through a bonding strap or a mounting lug is provided. This single point grounding removes the possibility of circulating currents in the frame from causing interfering effects within the circuitry. The grounding strap should be shorter than 5 cm with a net resistivity of less than .01 ohm per cm to minimize potential for resonances where high frequencies (> 100MHz) fields may be present. The only potential sources within a commercial road vehicle that have components within this range are the ignition and power solenoids and relays. The ignition problem results principally from badly worn points and defective by-pass capacitor. This data has been verified by previous measurements of the ignition spectral densities from various types of automobiles, with allowances for different ignition conditions. Noisy power relays, such as the type that operate headlights and horns, can also produce this range of higher frequencies.

7.6 Operational Control Techniques

This section concerns exploiting the variation in operational procedures of electronic systems in accordance with mode of operation of the vehicle. For example, the speed controller could be deactivated when the car is not moving. If, under conditions imposed by a nonmoving vehicle, the speed controller had a serious EMI problem when the car is not moving, deactivation of the circuit may be the least costly approach to solving the interference problem. Such a circumstance could exist with certain classes of electronic ignition control because of pulsing characteristics of power transistors and the inductive load of the ignition coil. An overlaping pulse rise and decay characteristic which may have radiative additive components could exist at higher engine speeds. The solution with electronic techniques would involve perhaps some expensive shielding procedures, but with deactivation of the speed controller, a significant cost savings in EMI assurance would be evident. This type of EMI solution must receive extremely careful consideration in the circuit design because of the direct implication to safety where, for example, in the situation cited, the speed controller was not activated at the speed level required. The cost of assuring reliable operation of the circuit in relation to the automobile mode must be weighted against other more conventional EMI solutions. This serious problem in assuring a reliable activation signal from one or more sensors relegates this general technique to secondary consideration. This discussion is included here, however, for completeness since some success has been achieved in previous systems through deactivation of susceptibility circuits or sensors. Generally in aircraft or military vehicles where such methods have been employed a manual "override" has been provided with warning so that the function is assured of availability even if manually activated. Such procedures are, however, not tractable for commerical passenger vehicles because of driver burden.

8. ACKNOWLEDGEMENTS

The authors wish to express appreciation to Mr. William B. Grant, Mr. Donald H. Layton, and Mr. Bill D. Warner for their valuable contributions and suggestions to this study.

Figure 1.1 reprinted from Electronics, June 21, 1973; Copyright © McGraw-Hill, Inc., 1973.

Figures 2.1 through 2.7, 2.11 and tables 2.1, 2.2, and 2.4 reprinted with permission, "Copyright © Society of Automotive Engineers, Inc., 1974, All rights reserved."

Figure 2.8 reprinted with permission from IEEE Transaction on Vehicular Technology, May 1974; Copyright © Institute of Electrical and Electronics Engineers, Inc., 1974. All rights reserved.

Figure 2.9 and tables 2.3, 2.5, and 2.7 reprinted with permission, "Copyright © Society of Automotive Engineers, Inc., 1974, All rights reserved."

Figure 2.10 and table 2.6 reprinted with permission, "Copyright © Society of Automotive Engineers, Inc., 1973, All rights reserved."

Figures 2.12 through 2.14 reprinted with permission from IEEE Spectrum, August 1974; Copyright © Institute of Electrical and Electronic Engineers, Inc., 1974. All rights reserved.

Figures 2.15 through 2.19 reprinted with permission from Don White Consultants, Inc., Copyright 1972.

Figure 2.20 reprinted from Journal of Geophysical Research Volume 78, No. 18, page 3525, June 1973; Copyright 1973, American Geophysical Union.

Figures 4.1 and 5.1 through 5.4 reprinted with permission from IEEE Spectrum, January 1973; Copyright © Institute of Electrical and Electronics Engineers, Inc., 1973.

Figures 4.2 through 4.4 and 5.5 reprinted with permission from IEEE Spectrum, October 1970; Copyright © Institute of Electrical and Electronics Engineers, Inc., 1970.

Figure 4.5 reprinted with permission from IEEE Spectrum, November 1970; Copyright © Institute of Electrical and Electronics Engineers, Inc., 1970.

Figures 4.6 through 4.8 and tables 4.1 and 4.2 reprinted with permission from IEEE Spectrum, December 1970; Copyright © Institute of Electrical and Electronics Engineers, Inc., 1970.

Figures 4.10 and 5.15 reprinted with permission from RCA Solid State Divison; Copyright © RCA Corporation, 1974.

Figures 4.12 and 4.13 reprinted by permission from 1620 Electronic Circuit Analysis Program (ECAP). Copyright © 1965 by International Business Machines Corporation.