TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. TX -99/7-4936-1	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Development of Guidelines for Control of Radio-Frequency Interference in Vehicles — Phase II: Final Report		5. Report Date March, 2001 6. Performing Organization Code TechMRT
7. Author(s) Thomas Trost		8. Performing Organization Report No. 4936-1
9. Performing Organization Name and Address Texas Tech University Center for Multidisciplinary Research in Transportation Box 41023 Lubbock, Texas 79409-1023		10. Work Unit No. (TRAIS) 11. Contract or Grant No. Project 7-4936
12. Sponsoring Agency Name and Address Texas Department of Transportation Research and Technology P. O. Box 5080 Austin, TX 78763-5080		13. Type of Report and Period Cover Final Report 14. Sponsoring Agency Code

15. Supplementary Notes
Study conducted in cooperation with the Texas Department of Transportation.
Research Project Title: "Development of Guidelines for Control of Radio-Frequency Interference in Vehicles — Phase II"

16. Abstract

This report describes the second and final phase of a study of vehicle-generated radio interference in Texas Department of Transportation vehicles. The results of the first phase are contained in a 1998 report. The emphasis throughout the study has been on the test methods used to characterize the interference. The second phase took place over the 16-month period from May 1, 1999 to August 31, 2000. Three faculty members and three students carried out the research at Texas Tech University. The Main results of the study were the formulation of an expanded version of the TxDOT Tex-899-B test, worked out in cooperation with the vehicle manufacturers, and the determination that other versions are possible, but while more precise, suffer the drawback of added complexity.

17. Key Words radio interference, noise interference, vehicle generated interference	18. Distribution Statement No restrictions. This 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 198	22. Price

Form DOT F 1700.7 (8-72)

Development of Guidelines for Control of Radio-Frequency Interference in Vehicles — Phase II: Final Report

by

Thomas F. Trost
Department of Electrical Engineering
Texas Tech University
Lubbock, Texas

Research Report Number 7-4936

conducted for

Texas Department of Transportation

by the

CENTER FOR MULTICISIPLINARY RESEARCH IN TRANSPORTATION

TEXAS TECH UNIVERSITY

March 2001

IMPLEMENTATION STATEMENT

Included among the results of the present study is a newly expanded version of the TxDOT Tex-899-B radio-interference test. This version includes several improvements to the original, which serve to make a good test even better. It is recommended that a test document based on this expanded version be included in TxDOT procurement specifications for new motor vehicles.

Time will be required to judge the effectiveness of the expanded test in reducing the incidence of interference problems in new vehicles. At some point, consultation with the vehicle manufacturers to discuss the progress in this regard would seem advisable.

The survey indicates that some other states suffer radio-interference problems similar to those of TxDOT. The test document mentioned above should be sent to these states, so they can benefit from TxDOT's experience. It may also be a good idea to arrange some type of forum with these states, e.g. a special session at a national meeting, to facilitate continued exchange of information on vehicle-generated radio interference.

Prepared in cooperation with the Texas Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: Volumes greater than 1000 l shall be shown in m^3.				
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate

(Revised September 1993)

ACKNOWLEDGMENT

The TxDOT Project Director for this project was Don Lewis, Fleet Manager, General Services Division, Austin, Texas.

Research performed in cooperation with the Texas Department of Transportation.

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I. INTRODUCTION

"... an important part of that fundamental problem of producing a desired effect is simultaneously preventing undesired effects"– Ronold W.P. King, *Transmission Lines, Antennas, and Wave Guides*, 1945

A. Motivation

The Texas Department of Transportation (TxDOT) sometimes finds that radio interference or noise is generated by the electrical system of a new fleet vehicle at such a level that it degrades the performance of the receiver in the two-way FM radio carried in the vehicle. The problem has persisted, in varying degree, over a period of years. In response, TxDOT has developed a test method to identify offending vehicles before they are put into service. And a procedure has been adopted whereby offending vehicles are modified so that they will pass the test and thus may enter the fleet.

In an effort to move away from this cumbersome test-and-fix activity, TxDOT initiated the present research project as an independent investigation of the problem, focusing on testing methodologies and on cooperation with the vehicle manufacturers. The first phase of the project was completed in 1998 [1], and the second and final phase is now also complete.

B. Definition of Noise

The term "noise" (or interference) as used throughout this report refers to any electromagnetic disturbance which is picked up by a TxDOT radio and, if strong enough, can interfere with the reception of signals by the radio. The sound of this "noise" in the radio speaker can take the form of random clicks or pops, a tone, distortion of the desired signal, or a quieting of the desired signal.

C. Project Personnel

The following faculty members and students conducted the Phase II research; they were all members of the Department of Electrical Engineering at Texas Tech University (TTU).

Faculty members:
- Thomas F. Trost, Principal Investigator
- David J. Mehrl
- Thomas F. Krile

Graduate students:
- Prasanna Bahukudumbi (MSEE degree, 2000)
- Jongsin Yun (MSEE degree, 2000)

Undergraduate student:
- Chad Bonner (BSEE degree, 2000)

D. Equipment Support

Our primary instrument for the measurement of radio-frequency (RF) noise, a Rohde & Schwarz ESVP receiver, was loaned to us from the electromagnetic compatibility (EMC) laboratory at Dell Computer Corp. by David Staggs. Other instrumentation was supplied by the TTU Department of Electrical Engineering or was rented.

Jackie Anderson of the TxDOT Ft. Worth office kindly supplied two Dodge trucks for radio-frequency interference (RFI) testing.

Lucinda Martin of the Texas Tech University motor pool kindly supplied a Chevrolet, a Dodge, and a Ford truck for RFI testing.

E. TxDOT Staff Support

Information on the history of TxDOT radio-frequency interference problems and good suggestions for the current project were supplied by members of the TxDOT radio engineering staff, Leonard Bryan (Lubbock), Richard Herndon, Robert Packert, and Pat Warsham (Austin), and by Curtis Reinert and Don Lewis of the Purchasing and Equipment Sections (GSA, Austin).

Bradford Rehm of Professional Testing, Inc., in Round Rock, who is under contract to TxDOT for RFI testing, was also very helpful.

F. Interaction with the TEAM

During the course of the project, Principal Investigator Thomas Trost together with Project Director and TxDOT Fleet Manager Don Lewis delivered periodic briefings to the SAE Electromagnetic Radiation (EMR) Committee in Detroit. The members of this committee were the TEAM— the Technical Expert Advisory Members for the project; and they provided many good comments and suggestions during the briefings. Among the TEAM were EMC engineers from DaimlerChrysler, Ford, and General Motors, all major suppliers of TxDOT vehicles; and thus the briefings also provided an opportunity for discussions between Mr. Lewis and his suppliers regarding specific concerns on the subject of vehicle radio interference. These engineers were Poul Andersen of DaimlerChrysler, Keith Frazier and Richard Kautz from Ford, and Donald Seyerle from General Motors.

The dates of the briefings were March 5, 1999, September 10, 1999, January 14, 2000, and January 19, 2001. Prof. Trost also held discussions with several of the TEAM individually while attending the international IEEE (Institute of Electrical and Electronics Engineers) EMC meeting in Washington, D.C., on August 21–25, 2000.

G. Pulsed Electric Currents

In the early days of radio the first transmitters used spark gaps to generate their radio-frequency signals. Thus we should not be surprised to find that any sparking device in use nowadays is a potential source of radio noise or interference to nearby electronic equipment.

More generally, not only sparks but any pulsed electric current can be a noise source because of its inherent broad frequency spectrum. In order to understand the basic nature of this spectrum, we can mathematically model the waveform of a current pulse as trapezoidal. We then find from Fourier analysis that the envelope of the spectrum first falls off slowly, as f^{-1} or 20 dB per decade, with increasing frequency and then more rapidly, as f^{-2} or 40 dB per decade.

The frequency at which the transition between slopes occurs is approximately equal to $1/(\pi\delta)$, where δ is the risetime of the trapezoid [2]. Thus if the risetime were 5 ns, the transition frequency would be 64 MHz. If the current pulse repeats in time at a slow rate, then there are many closely spaced frequency components under the envelope. If the pulse repeats rapidly, then there are just a few widely spaced components under the envelope.

Nearly all the electromagnetic noise sources found in a motor vehicle are the result of pulsed electric currents. There are the sparks at the electrodes of the spark plugs and the sparks occurring on the commutators of the DC motors that run the HVAC fan, fuel pump, etc. The vehicle's electronic modules also produce noise from pulses because the clocks in the microcontrollers generate pulsed signals and all the digital information is pulsed. In addition, pulse-width-modulated DC power is used to drive some motors, actuators, and injectors.

The transition-frequency value of 64 MHz stated above is a realistic one for motor-vehicle sources. Since the primary TxDOT communication band is located at 47 MHz, it lies within the slowly falling portion of the noise spectrum, where the noise may still be strong enough to cause significant interference in the TxDOT radio receivers. Thus on the basis of this simple mathematical model we are alerted to a potential problem. Of course, good design of vehicle systems can mitigate noise radiation. For readers who may be interested, some design handbooks are listed in the references [3,4,5].

H. Vehicle EMC Tests

The branch of electrical engineering which deals with problems of interference between electrical devices, like that addressed in the present project, is known as electromagnetic compatibility (EMC); and numerous EMC test and certification procedures have been developed over the years.

Two EMC test standards were of primary interest in this project, the TxDOT test referred to above in Section A, Tex-899-B [6], and a Society of Automotive Engineers test, SAE J551/4 [7]. Both of these tests are concerned with placing limits on the radio-frequency (RF) noise emissions of a motor vehicle, but they are fundamentally different in nature. J551/4 involves the measurement of RF emissions received by an antenna on the vehicle. Tex-899-B involves the measurement of the effect on the audio-frequency (AF) output of a radio in the vehicle from the emissions received by the antenna, when a signal is also present. J551/4 is an RF noise amplitude test, and Tex-899-B is an AF SINAD test (measuring the AF signal-to-noise-and-distortion ratio) [8].

The Tex-899-B test in fact contains two parts. One of them deals with vehicle RF emissions, as discussed above, and was the one of primary interest to us; it is referred to as the "egress" test [6]. The other part, the so-called "ingress" test, deals with the susceptibility of the various vehicle systems to upset from radiation from the TxDOT radio transmitter. In this report, as we refer to Tex-899-B, unless otherwise noted, we will mean just the egress part.

I. Project Objective and Method

Tex-899-B is a specialized test well suited to uncovering potential TxDOT interference problems because it employs a radio like that used in the TxDOT fleet. In contrast, J551/4 is a more general industry standard, and, as we learned in Phase I, J551/4 is not useful, as it stands, for testing vehicles for TxDOT service.

Our objective in Phase II was to determine whether some modified form of the J551/4 test could be found that would be as effective as Tex-899-B and that the automakers would be willing to perform to qualify their vehicles for TxDOT service. J551/4 seemed like a better candidate than Tex-899-B for use by the automakers primarily because it appeared to be less time-consuming to carry out.

The range of frequencies in which most TxDOT radios operate, and where the noise problem exists, lies in the two-way radio low-band VHF range and extends from 47.02 MHz to 47.34 MHz. This is the range the project concentrated on.

Our approach in Phase II had several components. First, we performed bench-top tests related to J551/4 and Tex-899-B using TxDOT radios. The testing was done in a laboratory at TTU. Second, we wrote a computer program to provide a theoretical baseline for the laboratory tests. Third, we performed outdoor whole-vehicle tests on TxDOT trucks. This testing was done at a low-noise location several miles outside of Lubbock, and five trucks were tested. Fourth, we conducted a survey of other state DOTs around the country. And finally, we applied all of the information gained to arrive at a number of conclusions and to propose a new version of Tex-899-B in which the option of using a modified form of J551/4 is included [Appendix A].

J. Typical Testing Sequence

Figure 1 shows a flow chart that graphically illustrates several of the ideas discussed in the sections above. The chart traces the progress of a new motor vehicle through the steps of testing by the automaker, delivery by a dealer to TxDOT, and testing for TxDOT by Professional Testing, Inc. The box labeled INPUT FROM THIS PROJECT shows the main point of application of our research results. The hope is that our new version of the Tex-899-B test will provide the automakers with a valuable tool to help them develop vehicles suitable for TxDOT service, thus obviating the need for the path labeled BACK TO DEALER.

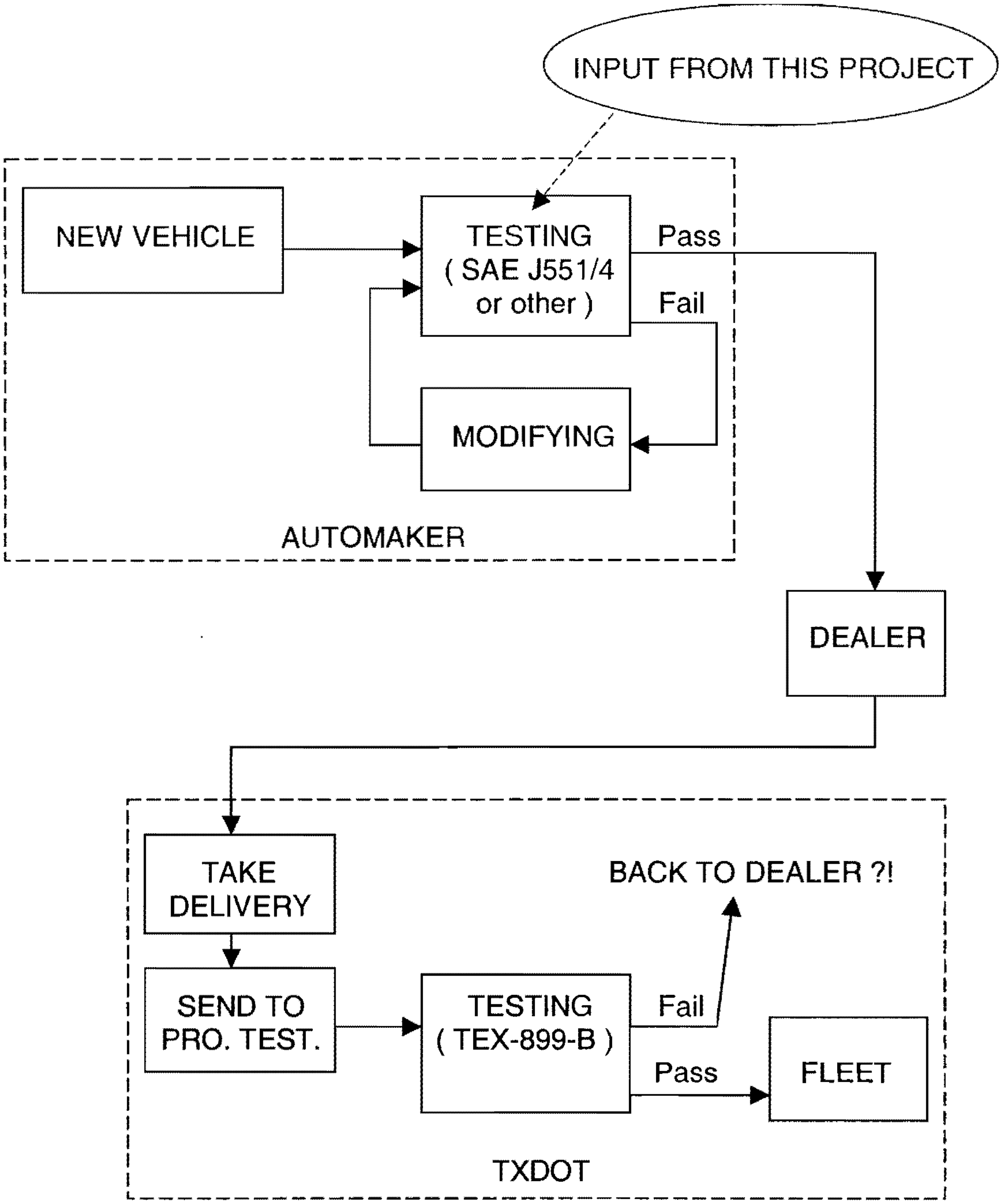


Figure 1. EMC testing of new TxDOT vehicles

II. LABORATORY EXPERIMENTS

A. Simulation of Multiple Noise Sources

Our main laboratory activities during Phase II were the simulation of multiple noise sources, the characterization of the noise blanker circuits in TxDOT radios, and a performance comparison of the average detectors in our EMI (electromagnetic interference) receiver and spectrum analyzer.

In Phase I of the project, motor-vehicle noise sources were simulated one at a time in our laboratory [9]. A block diagram of our laboratory apparatus is shown if Figure 2 and a photograph in Figure 3. A J551/4 type of measurement was obtained with the EMI receiver, which was set for peak detection; and a Tex-899-B measurement was made with the FM radio, FM signal generator, and SINAD meter.

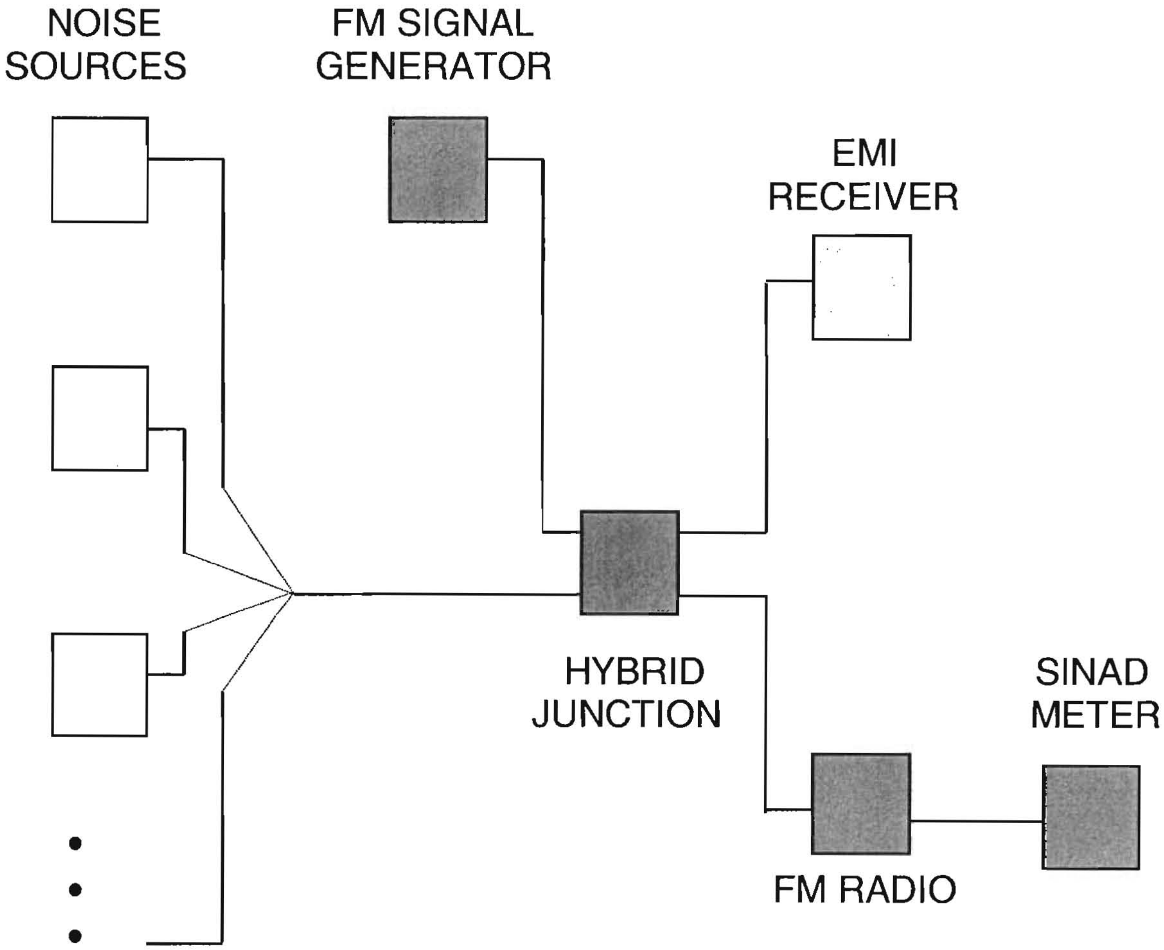


Figure 2. Block diagram of bench-top test system

Figure 3. Laboratory evaluation of RF noise with EMI receiver and FM radio

In Phase II the apparatus was similar, but we operated two or three of the noise sources simultaneously. Our results are detailed in the Master's thesis by J. Yun [Appendix B], and they are summarized in a paper written by Prof. Trost in February 2000 and presented at the 2000 International IEEE EMC Symposium [Appendix C]. The primary conclusion of the symposium paper is that a degree of correlation can be achieved between the TxDOT Tex-899-B test and the SAE J551/4 test if certain changes are made in the J551/4 limits. For the convenience of the reader, a copy of the table from the paper containing the new limits is reproduced here as Table 1. The abbreviation BW stands for bandwidth, and NB stands for narrow-band (< 15 kHz).

This table represented our best estimate of a suitable J551/4 type of test as of early 2000. Subsequently, during the spring and summer of 2000, we conducted additional laboratory tests and whole-vehicle tests on five vehicles. We gained further insight into J551/4 testing, especially in regard to the use of average rather than peak detection and in regard to the characteristics of electronic-module noise. However the procedure in Table 1 continues to represent a suitable test, if one change is made: the removal of the restriction NB on the module noise, so that all module noise is included.

The additional laboratory tests in 2000 were carried out by P. Bahukudumbi [Appendix D]. He used the setup in Figure 2 to study DC-motor noise, employing the Rohde & Schwarz ESVP with average detection as the EMI receiver. He determined that the Tex-899-B limit corresponds to a J551/4 average limit of 3 dBμV, and he suggested that this limit could be used rather than the J551/4 peak limit of 40 dBμV shown in Table 1. This possibility is further discussed in Chapter III, Section B.

No limit is stated in Table 1 for the spark-ignition noise that exists when a vehicle engine is running. This noise can achieve high peak values. However in our laboratory simulations of this noise, the noise blanker circuits in the TxDOT radios very effectively eliminated it even when it was adjusted to be much stronger than on the vehicles. It is not thought to be a threat.

Table 1. Modified J551/4 RF-emissions test for new TxDOT vehicles

Test Configuration	Measurement BW (kHz)	Limit (dBμV)	Comment
1. Run engine until warm			
2. All OFF	9	– 9	Ambient
3. All OFF	120	34	Ambient
4. Engine OFF, key ON	9	– 3	NB electronic-module emissions
5. Engine OFF, key ON, DC motors ON	120	40	DC-motor emissions

B. Characterization of Noise Blankers

The noise blankers, or extenders as they are sometimes called, in the TxDOT FM radios perform the extremely valuable function of removing spark-ignition noise and reducing DC-motor noise from the radio output. The blankers in the two primary TxDOT radios, the *MaraTrac* and the RANGR™, perform somewhat differently; and a number of their characteristics are given in Tables 2, 3, and 4.

Table 2. Noise blankers in TxDOT radios: general data

Blanker Characteristic	Radio	
	Motorola *MaraTrac*	General Electric RANGR™
Type of circuit	IF detect and IF blank	IF detect and IF blank
Blanking disable/enable	Push button	Internal jumpers

Table 3. Laboratory test of noise blanker performance of TxDOT radios: part I

Pulse length of noise pulses = 10 ns
Various pulse rates and amplitudes

Blanker Characteristic	Radio *MaraTrac*	 RANGR™
Length of blanking pulses	8 µs	2 µs
Minimum amplitude of noise pulses for blanking	3 mV	2 mV
Maximum amplitude of noise pulses for blanking	> 7 V	> 7 V
Pulse-rate shut down	300 kpps	250 kpps

Table 4. Laboratory test of noise blanker performance of TxDOT radios: part II

Pulse rate of noise pulses = 1500 pps
Various pulse lengths and carrier frequencies

Type of Noise Pulse	Radio *MaraTrac*	 RANGR™
Short (50 ns) DC	Blanked	Blanked
Long (50 µs) DC	Blanked	Blanked
Short (50 ns) RF	Blanked	Blanked
Long (50 µs) RF	Blanked	Not blanked

The characteristics listed in Table 3 show the two radios to perform about the same except that the *MaraTrac* has longer blanking pulses. This gives the *MaraTrac* increased blanking capability.

The noise pulses labeled "DC" in Table 4 are approximately rectangular voltage pulses. The pulses labeled "RF" are approximately rectangular AM voltage pulses with a carrier frequency set equal to the frequency to which the radios are tuned, typically 47.18 MHz. Our laboratory testing has revealed the following information: For the short DC, long DC, and short RF pulses, both radios provide effective blanking. However the radios respond differently to the long RF pulses.

The short DC and short RF noise pulses are successfully blanked because they are shorter than the length of the radio blanking pulses. For the long DC pulses, the low-frequency cutoff characteristic of the radios removes the middle portion of the pulses, converting each long pulse into two short ones, which are then readily blanked.

For the case of the long RF noise pulses, the *MaraTrac*'s blanking pulse increases in length to match the noise pulse while the RANGR™'s blanking pulse remains short. Thus the *MaraTrac* blanks the long RF pulses while the RANGR™ does not. This gives the *MaraTrac* some advantage in blanking.

In addition to the noise-blanker testing described above, we also carried out the test procedure used by TxDOT in the acceptance testing of new radios [10]. This procedure involves using an HP 222A pulse generator to provide 100 ns 10 kHz pulses. We verified that the *MaraTrac* and RANGR™ radios both passed this test. Also of interest in regard to noise-blanker testing is the relevant section in TIA/EIA-603 [11].

C. Comparison of Average Detectors

1. Average or peak?

In considering the use of a test like J551/4 for TxDOT vehicles, the idea of employing average rather than peak detection seems worth exploring. The appeal of average detection stems from the fact that the noise blanker in a TxDOT radio removes the sharp peaks in the noise, and therefore to get a result from a J551/4 test that correlates well with the response of the radio, peak detection would seem much less desirable than average (or perhaps RMS) detection. Here are some of the pros and cons of average detection.

Advantages of measuring average rather than peak values:

(i) Can uncover narrow-band emissions in presence of broad-band noise

(ii) Allows testing various vehicle noise sources with engine running by suppressing spark-ignition pulses

(iii) Can be expected to give better correlation with Tex-899-B for impulsive noise sources because it acts somewhat like the noise blanker in a TxDOT radio

(iv) Can supply insight into noise mechanisms when used together with peak measurements

Disadvantages of measuring average rather than peak values:

(i) Some spectrum analyzers do not measure average values

(ii) EMI receivers may not have enough dynamic range to measure average values of some noise sources

(iii) The limits of accuracy of average detectors may not be well established in the EMC community

Based on the advantages listed above, we investigated average detection in the laboratory and employed it in our vehicle tests. From our results we determined average-detection limits on vehicle noise emissions. No such limits exist in SAE J551/4; only peak and quasi-peak are given. Our laboratory work is discussed in the next section, and the vehicle tests are described in Chapter III.

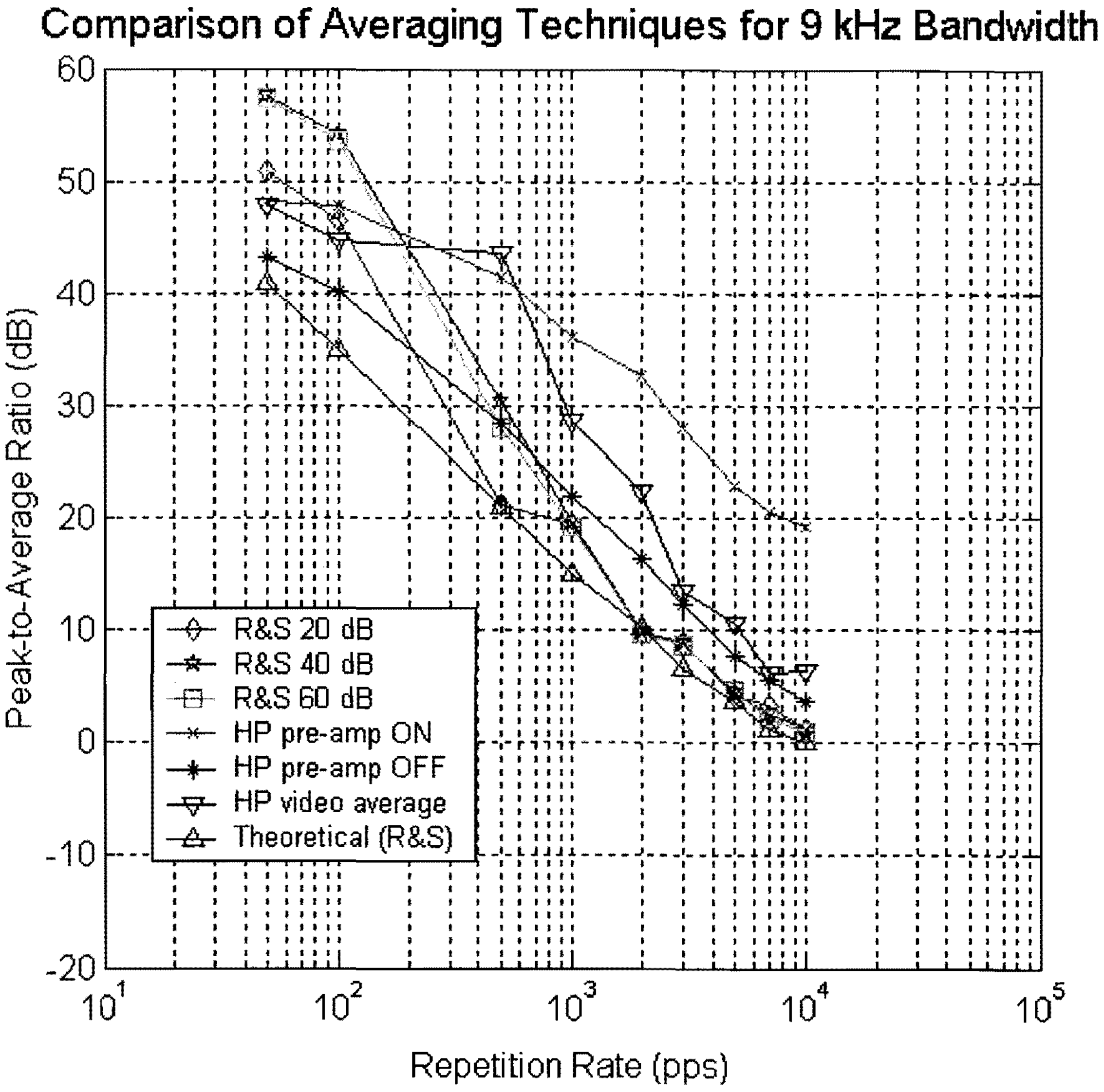
2. Laboratory measurements

In the laboratory we characterized the average detectors in two instruments, an R&S ESVP receiver and a Hewlett-Packard E7401A EMC analyzer. The HP analyzer is a spectrum analyzer with some additional features, including a built-in low-noise preamplifier and an average detector.

Figures 4 and 5 show our results for the two instruments. The figures are duplicates of those contained in the Master's thesis of P. Bahukudumbi [Appendix D]. The noise source connected to the instruments was a pulse generator adjusted to give varying repetition rate and constant amplitude and pulse length. Plotted out in the figures is the measured peak-to-average ratio (sometimes called the crest factor) versus the repetition rate for each of the two bandwidths of interest, 9 kHz and 120 kHz. Curves are shown for various instrument conditions as indicated in the legend. Prof. Krile wrote a MATLAB program to numerically simulate the response of the average detector in the R&S ESVP receiver if it were ideal, and his theoretical curve is shown in the figures along with those measured. It is essentially a straight line with a slope of minus 20 dB per decade. (See Appendix D for details of the MATLAB program.)

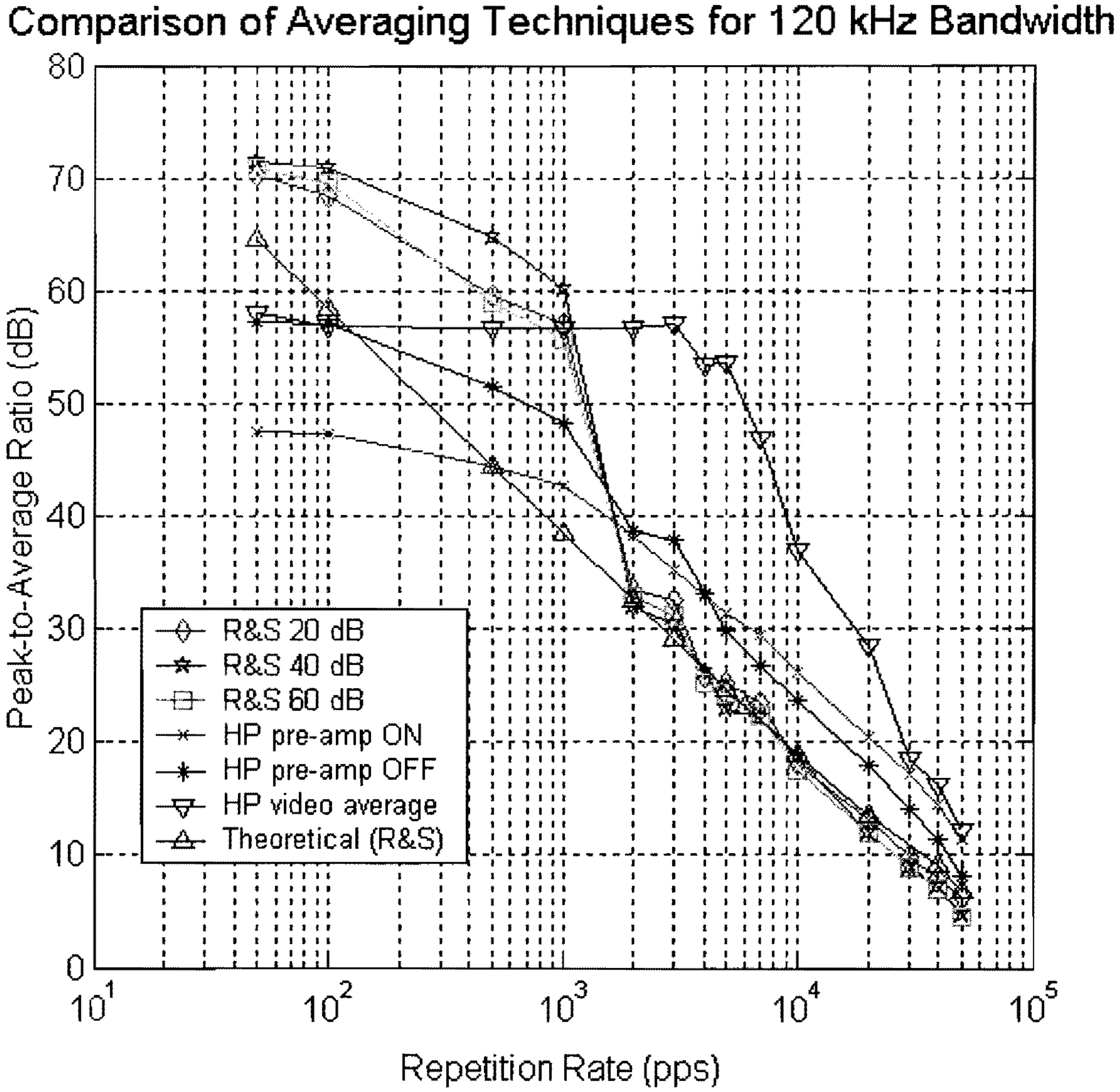
In Figure 4 the ESVP receiver bandwidth is given as 9 kHz. In fact the specification sheet for the receiver lists the bandwidth as 10 kHz. We carried out careful measurements of the shape of the passband and compared the results to the official CISPR 9 kHz spectral mask [12], and we found that the passband does indeed qualify as 9 kHz. Thus, in the present report we use the values 9 kHz and 10 kHz interchangeably.

Besides using peak and average detection, we also experimented with the use of quasi-peak detection, but could find no benefit from it in the TxDOT situation.



Pulses applied: length = 10 ns
amplitude = 39 dBμV at 47.18 MHz
HP = Hewlett-Packard E7401A EMC analyzer
R&S = Rohde&Schwarz ESVP receiver with 20, 40, or 60 dB display range
Frequency = 47.18 MHz
Theoretical = MATLAB simulation by T.F. Krile

Figure 4. Averaging with 9 kHz bandwidth



Pulses applied: length = 10 ns
amplitude = 60 dBµV at 47.18 MHz
HP = Hewlett-Packard E7401A EMC analyzer
R&S = Rohde&Schwarz ESVP receiver with 20, 40, or 60 dB display range
Frequency = 47.18 MHz
Theoretical = MATLAB simulation by T.F. Krile

Figure 5. Averaging with 120 kHz bandwidth

The main conclusions to be drawn from Figures 4 and 5 are that the average detectors in the two instruments behave somewhat differently and that there can be significant deviations from ideal (theoretical) performance especially at large values of peak-to-average ratio. Some details are given by P. Bahukudumbi [Appendix D].

3. Video averaging

Our HP EMC analyzer has a "video averaging" function, which is not exactly an average detector but which was used for one of the curves in Figures 4 and 5. Many spectrum analyzers have this feature, in which the values displayed on the screen, either dB values or amplitudes, are averaged together at each frequency. Using the dB values amounts to adding together the logarithms of the amplitudes, which corresponds to multiplying the amplitudes themselves; and the result is the calculation of their geometric mean. It is well known to mathematicians that the geometric mean of a collection of positive numbers is always less than or equal to the arithmetic mean. A proof is contained, for example, in the book by W. Rudin [13].

This result is one reason why using video averaging can yield a different result than using an average detector. And there is another possible reason for a difference. Video averaging uses samples of the signal which are separated by the analyzer sweep time, not a continuous record of the signal. So short-duration features in the signal, impulses for example, could be missed.

III. WHOLE-VEHICLE TESTS

A. Vehicles, Instrumentation, and Site

Our main vehicle-testing activity involved conducting Tex-899-B and J551/4 tests on five pickup trucks: we searched for DC-motor noise and electronic-module noise; we compared the pass-fail results of the two tests; and we tried out the use of average detection in J551/4. Other activities included carrying out a comparison of three different antennas on one of the trucks and assessing the noise emissions from our measurement equipment.

A list of the trucks that were tested in Phase II is given in Table 5. The TxDOT trucks had been converted to run on propane as well as gasoline, the Texas Tech University trucks had not. Testing was conducted from April 2000 through August 2000.

Table 5. List of trucks tested at TTU during 2000

Make	Model	Year	VIN	Fuel	Equipment	Owner
Dodge	RAM1500 V8	1999	1B7HC16Y6XS309435 (TxDOT 2-5643-G)	Gas/ Prop	ABS, airbag	TxDOT
Dodge	RAM1500 V8	1999	1B7HC16Y5XS309443 (TxDOT 2-5649-G)	Gas/ Prop	ABS, airbag	TxDOT
Dodge	RAM2500 V8	1999	3B6KC26Z5XM591021 (Tx768429)	Gas	ABS, airbag	TTU
Ford	F250 V8	1998	1FTPF27L4WKB76975 (Tx742655)	Gas	ABS, airbag	TTU
Chevrolet	S10 V6	1999	1GCCS14X8X8195815 (Tx763730)	Gas	ABS, airbag	TTU

Figure 6 shows one of the vehicles at our rural test site with students preparing for a test. The cart and the instrumentation it carried are shown in Figure 7. All the instrumentation was powered by the two 12-V batteries. J551/4 measurements were done with the R&S ESVP receiver. Tex-899-B measurements were done with the TxDOT (*MaraTrac*) radio, using the R&S CMS54 Radiocommunication Service Monitor as both an FM signal generator and a SINAD meter. The notation MM antenna refers to our magnetic-mounted Larsen NMO-50 base-loaded whip antenna. The Fluke 99B oscilloscope was used to examine video waveforms from the ESVP receiver. The HP E7401A analyzer mentioned above in Chapter II was used only to get a quick display of the noise levels across a range of frequencies, and it is not shown in Figure 7.

Figure 6. Texas Tech graduate students setting up for the testing of a TxDOT truck

The lower limit of our measurement capability is always set by instrumentation and ambient noise. In Table 6 we show the internal noise level of the ESVP receiver and the ambient noise level at our test site. For the TxDOT *MaraTrac* radio, the 12 dB SINAD test gave a value of −12 dBμV for radio sensitivity and − 8 to − 10 dBμV for ambient.

Table 6. Typical baseline noise levels (47.18 MHz)

	Pk (dBμV)		Avg (dBμV)	
	9 kHz	120 kHz	9 kHz	120 kHz
ESVP Receiver	−12	1	−23	−13
Outdoor Ambient	−9	5	−20	−9

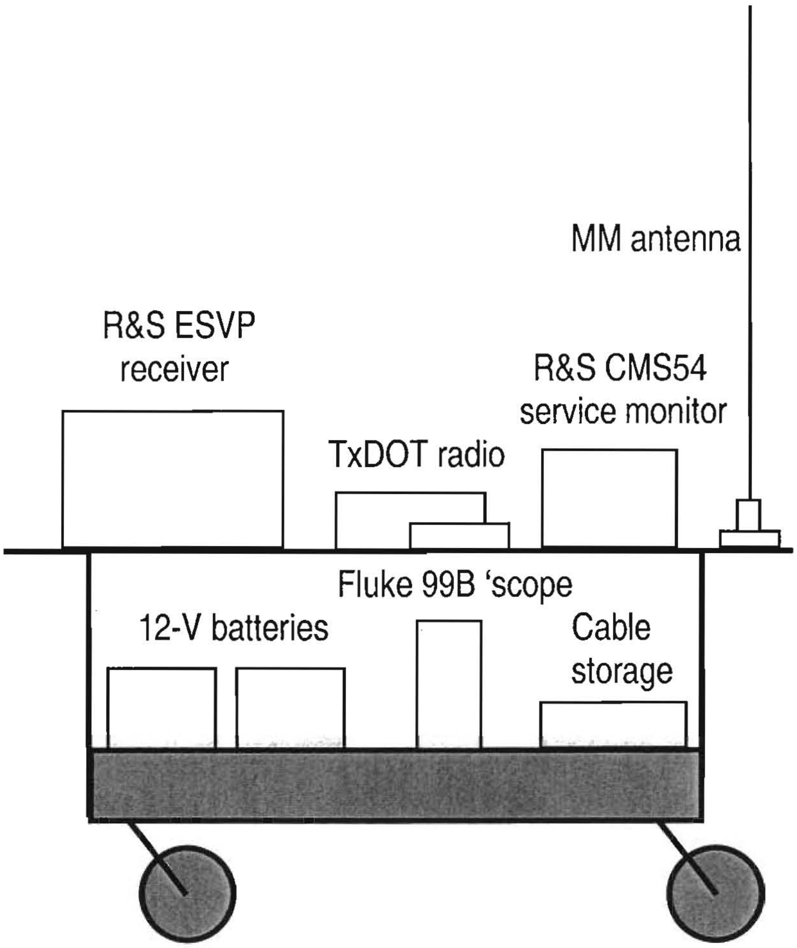


Figure 7. Rolling EMI Measurement System Used for SAE J551/4 and TxDOT Tex-899-B Testing

One problem encountered in conducting the J551/4 testing outdoors as we do, rather than in a shielded chamber, is noise emissions from the EMI receiver or spectrum analyzer. Over the years we have identified a few specific narrow-band emissions, using average detection to reduce the random, broad-band noise background. These are listed in Table 7. Such emissions are a real nuisance. The best way to identify them seems to be to use two different receivers listening to each other, switching each one on and off to identify its emissions.

Table 7. Spurious emissions from instrumentation

Receiver/Analyzer	Amplitude dBμV	Frequency MHz
R&S ESS receiver	– 17	47.56
R&S ESVP receiver	– 10	47.10
HP E7401A analyzer	– 7	46.97
	– 6	47.18
	– 6	47.39
	– 5	47.60

B. Noise from DC Motors

Of interest as potential noise sources were all of the DC motors on the trucks, that is, fuel pump, HVAC fan, windshield wiper, windshield washer, and light bar. J551/4 peak values were measured with the ESVP receiver for various combinations of these motors on all five trucks. The values were found to range from 10 dBμV to 60 dBμV. The measurement bandwidth was 120 kHz. Average values were also measured on three of the trucks, those from TTU. Values ranged from the noise level at – 9 dBμV to 3 dBμV.

For comparison with the J551/4 results, the Tex-899-B test was carried out on all five trucks. Values ranged from the noise level at about – 9 dBμV up to just under the 0 dBμV test limit.

After studying the test results on a case-by-case basis, our findings were as follows:

(i) The data for these particular vehicles did not support the 40 dBμV peak-detector limit that was determined from laboratory simulation (Chapter II, end of Section A). In the laboratory this limit was found to coincide with the Tex-899-B SINAD test limit. But on the vehicles, it appeared to be too stringent. Two cases must be distinguished— first, fuel pump, HVAC fan, and wipers running; and second, the previous three plus the windshield washer running. For the first case, the peak values were found to range up to 40 dBμV, while the SINAD values all remained below their limit. Thus the 40 dBμV limit looked as if it probably was too low for good correlation with the SINAD data. For the second case, the Dodge and Chevrolet (but not the Ford) showed large peak values, around 55 dBμV, but the SINAD values were still below their limit. Thus here the 40 dBμV limit definitely was too low. (But we had no way of knowing how much higher it should have been.)

This second case involved the operation of tiny windshield washer motors. Such motors were never tested in the laboratory because in normal vehicle operation they are used so briefly as to not merit inclusion in Tex-899-B testing. They were included in the vehicle tests for academic interest. As it turned out, they did indeed add some interest as they were the only motors which pushed the peak values above 40 dBμV.

(ii) Some support was found in the vehicle tests for the average-detector limit of 3 dBμV determined by laboratory simulation. The TTU Chevrolet gave the following results for all DC motors turned on, including the washer: Tex-899-B FM signal = – 0.8 dBμV; J551/4 peak noise = 65.8 dBμV; J551/4 average noise = 3.0 dBμV. Here we see a vehicle that just happens to fall on our J551/4 average limit of 3 dBμV, and it lies only a fraction of a dB under the Tex-899-B limit of 0 dBμV, thus almost agreeing with the laboratory result (advantage (i), Chapter II, Section C).

(iii) There is evidence from all of the TTU trucks that the average detector gives such a weak response to spark-ignition noise that DC-motor noise can be measured with the engine running (advantage (ii), Chapter II, Section C).

Detailed presentations of our measurements of DC-motor noise are given in by J. Yun [Appendix B] and P. Bahukudumbi [Appendix D].

A study of DC-motor noise which complements our own is described in a symposium paper by C. Suriano et al. [14]. They give information on the radio-frequency spectrum of the noise over the range 0.1 MHz to 1000 MHz.

C. Noise from Electronic Modules

Using the ESVP receiver, noise emissions from electronic modules were checked with the ignition key of the truck switched on, and everything else, engine and all accessories, switched off. The Dodge trucks proved to be by far the most interesting in this situation. As can be seen from the summary in Table 8, only the Dodges displayed a broad noise peak due to module emissions. We had not previously seen broad-band noise from modules, only narrow-band. Here we use the terms narrow-band (NB) or broad-band (BB) to mean narrow or broad compared to the TxDOT radio bandwidth of 15 kHz.

Table 8. Electronic-module emissions (46.9 MHz to 47.8 MHz)

Truck	Narrow-band Freq. (MHz)	Broad-band Freq. (MHz)
Dodges	47.38*	47.34 - 47.44
Ford	47.92	None observed
Chevrolet	None observed	None observed

* The NB emission was superimposed on the BB, like a carrier with sidebands.

The time-domain signature of the noise from the Dodges was examined at 47.38 MHz. AM and FM waveforms of this noise were obtained by connecting the AM and FM outputs of the ESVP receiver to channels A and B of a Fluke 99B oscilloscope (battery powered, digital recording with 8-bit 25 MSa/s and 25 pixels/div display). Several waveforms observed on the screen were stored in the oscilloscope memories. Figure 8 shows the waveforms from memories number 5 and 6. The sweep speed is 2 ms per division. The AM waveform shows two consecutive pulse trains, where the pulse period is 0.5 ms. The FM waveform does not reveal the pulses, but shows rapid noise fluctuations which seem to increase in amplitude during the time between the AM pulse trains. Arrows at the left show the zero-voltage level for each waveform.

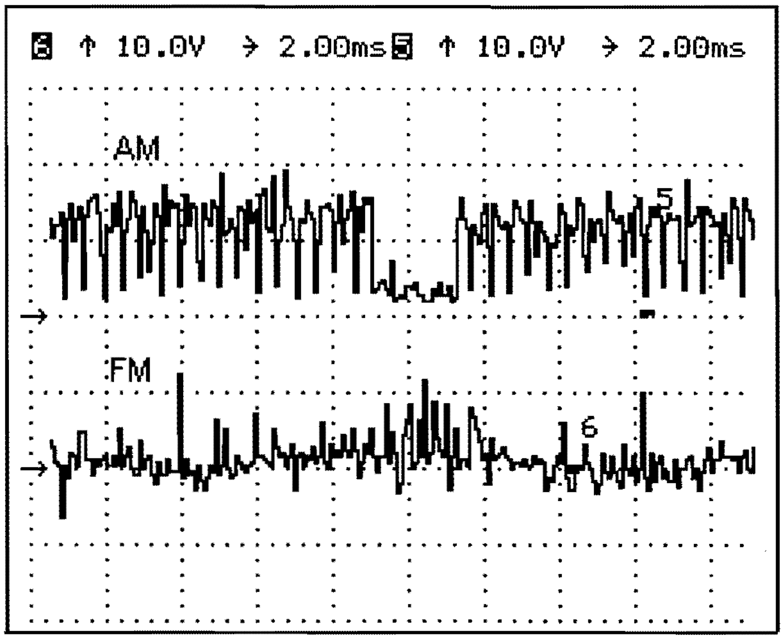


Figure 8. Oscillograph showing example of module noise from 1999 Dodge RAM2500 pickup truck

The frequency-domain signature of this noise was also examined. Figure 9 shows two frequency scans made with the ESVP receiver, one of the peak ambient noise level (ignition key OFF) and the other of the peak ambient-plus-module noise level (key ON). These scans were made one after the other with a measurement time of two seconds at each 5 kHz step. The three large spikes in the data are due to noise from vehicles driving past on the highway. The top of the module noise spectrum is quite flat and extends from about 47.34 MHz to about 47.44 MHz. The noise tapers off from this plateau rather unevenly on each side and persists weakly out to the edges of the graph, and perhaps well beyond.

What of the average level for this module noise? We re-measured across the top of the noise spectrum with the ESVP receiver, using both peak and average detectors, and the results are shown in Figure 10. Here we observe the interesting result that the peak-to-average ratio varies considerably; while the peak value forms a wide plateau, the average value contains a central peak with lowered sidebands.

An important question is how this noise-level data, which is J551/4 data, compares to SINAD or Tex-899-B data. To answer this question, we conducted the Tex-899-B test at three frequencies, 47.34 MHz, 47.38 MHz, and 47.42 MHz. The results are shown in Figure 11, where all three quantities are plotted— peak and average from Figure 10 and SINAD. Here the SINAD data is seen to be well correlated, from one frequency to the next, with the average data but not with the peak data. This result points to the benefit of using average measurements in a J551/4 test in order to achieve correlation with the Tex-899-B test. We return to this subject as part of our conclusions in Chapter V.

Switching the TxDOT radio's noise blanker on and off while the radio was tuned to the module noise had no effect on the SINAD value.

D. Vehicle Pass/Fail Results

The details of the noise aside, it is important to know whether these trucks pass the Tex-899-B test and thus should be accepted by TxDOT. In fact, four of the five trucks passed. The one which did not pass was the TTU Dodge. It failed at 47.34 MHz, which is the highest frequency in the TxDOT band. This truck was used for the data in Figures 10 and 11, and the failure is evident in Figure 11. As can be seen, the 12-dB-SINAD value at 47.34 MHz lies at 1 dBμV, just a slim 1 dB above the limit. It turned out that switching on DC motors— fuel pump, HVAC fan, and windshield wipers— contributed one additional dB. On the other hand, running the motors without the modules resulted in a pass. The culprit was the modules, not the motors. The failure occurred because the bottom end of the module-noise band was catching the top end of the TxDOT band. For the other two Dodges the module noise was shifted slightly higher in frequency, and they passed Tex-899-B.

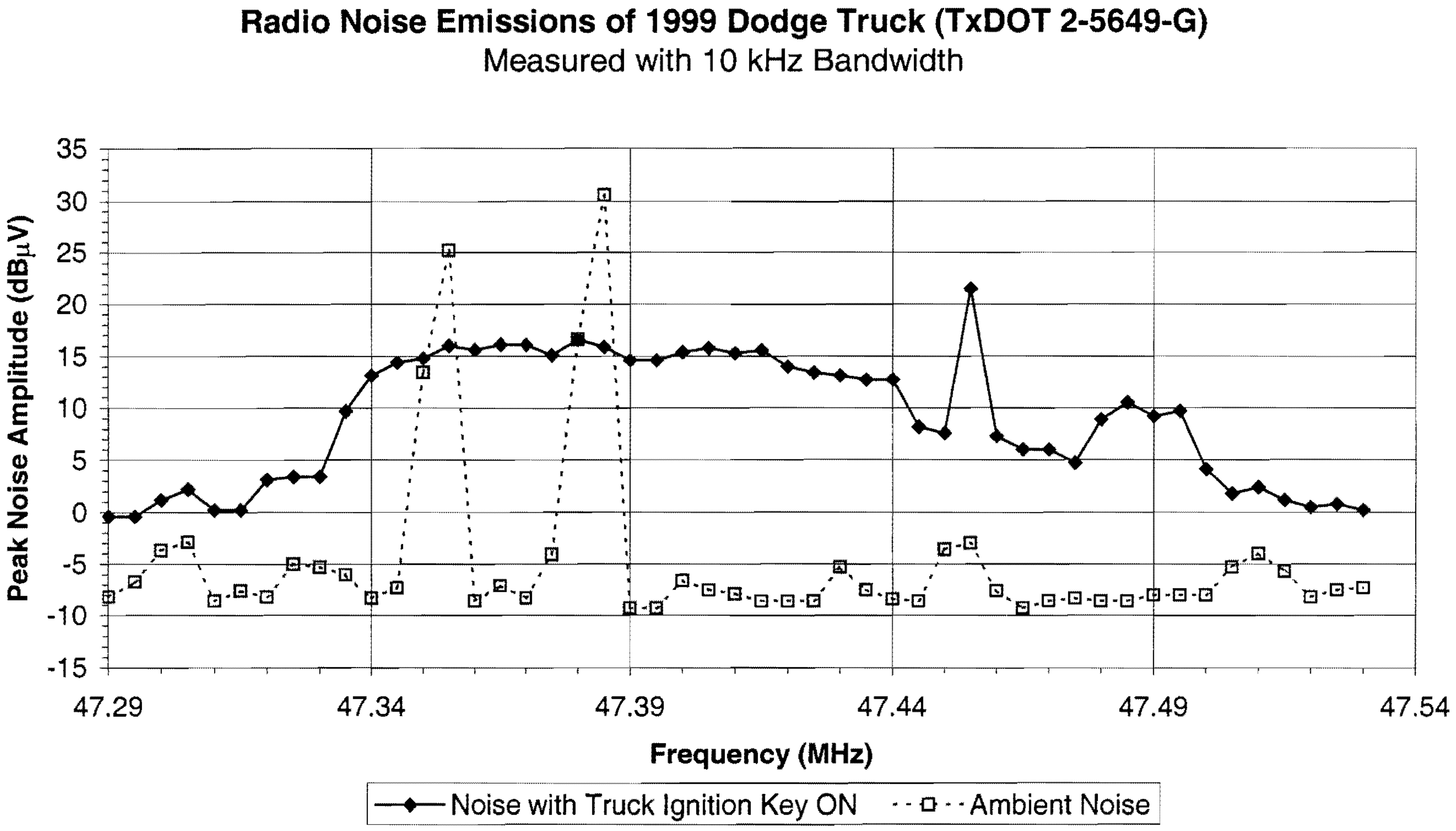


Figure 9. Spectrum of peak module noise from Dodge truck

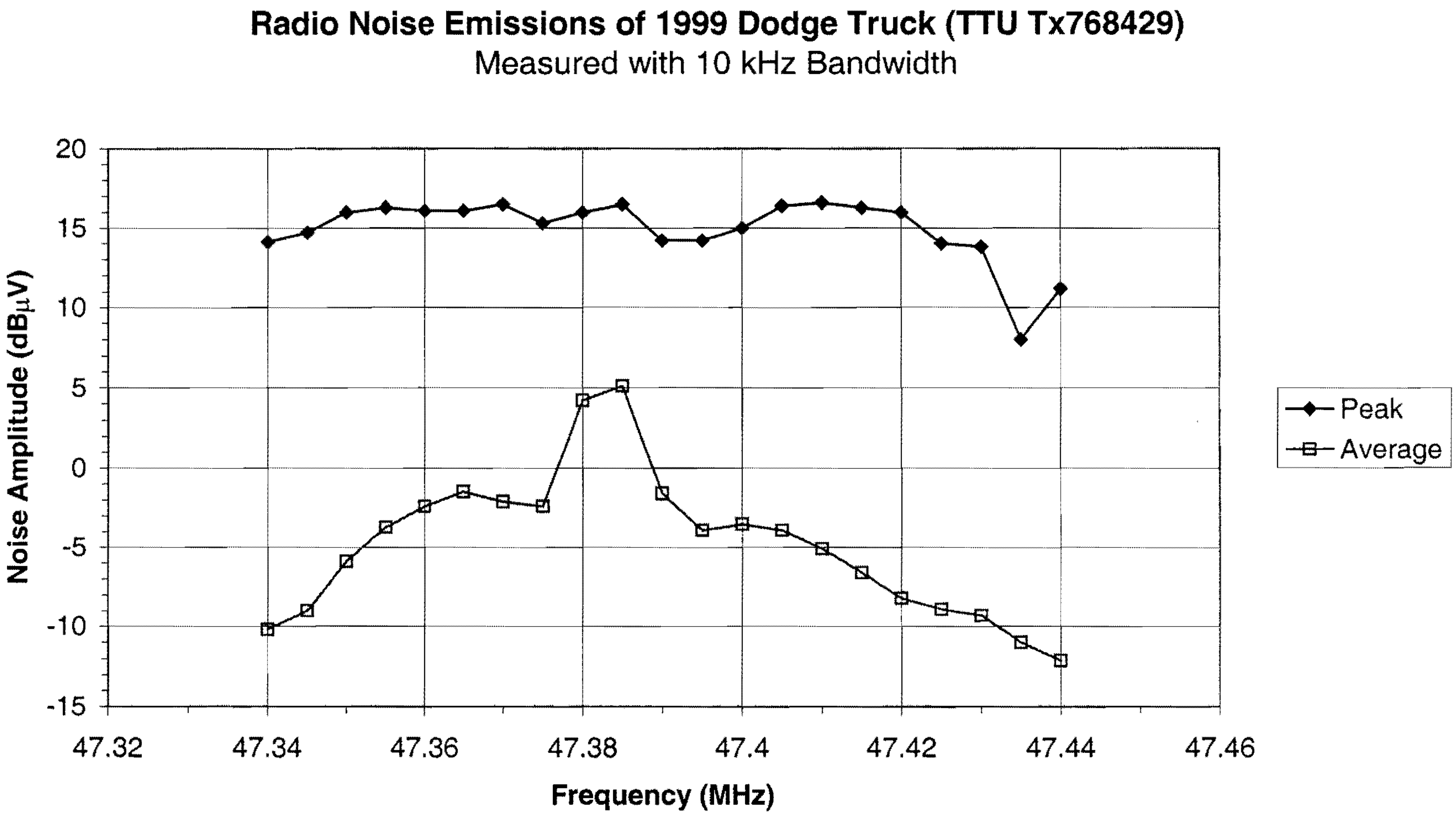


Figure 10. Peak and average module noise from Dodge truck

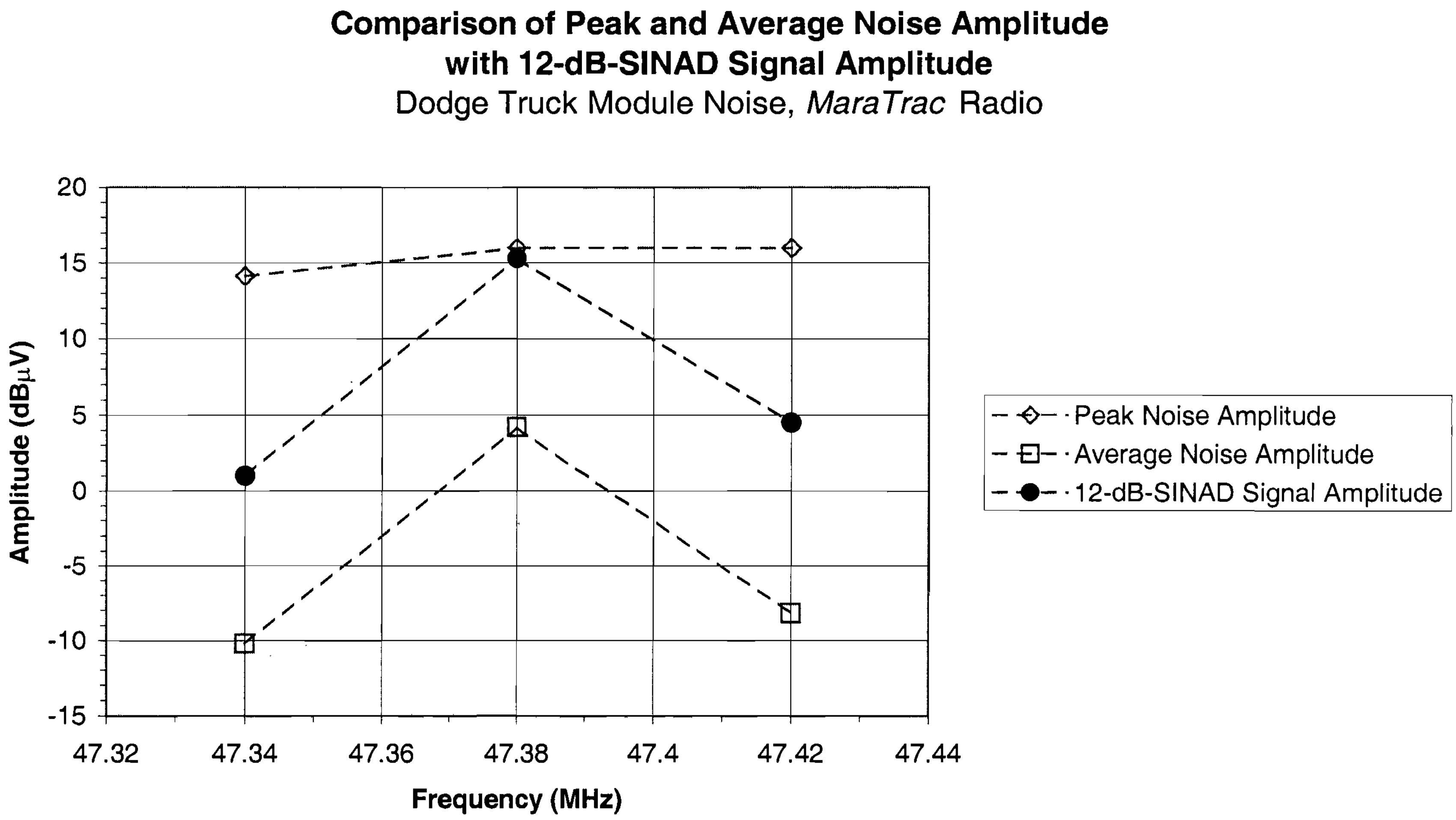


Figure 11. Peak and average module noise compared to SINAD measurement

E. Antenna Comparison

In order to judge the importance of a change in antenna as far as the results of the Tex-899-B test are concerned, three different antennas were used to measure module noise on the same Dodge truck with the same antenna mount and FM radio. The specifications of the truck, radio, mount, and antennas were as follows:

(i) Truck

Make: 1999 Dodge RAM2500 V8 gasoline pickup truck owned by TTU
Overall length: 5.61 m (26.7 MHz, 53.4 MHz, 80.2 MHz estimated resonances)
Configuration: Key switched on
Type of Noise: Electronic module

(ii) Radio

Make: Motorola *MaraTrac*
Frequencies: 47.34 MHz and 47.38 MHz

(iii) Antenna Base

Make: MAXRAD
Type: Magnetic mount, with 12 ft RG-58 A/U coaxial cable
Location: Center of roof of cab

(iv) Antenna 1

Make: Spectrum
Type: Base-loaded whip
Comments: Currently supplied with *MaraTrac* radios

(v) Antenna 2

Make: Larsen NMO 50 (length = 1.33 m including base)
Type: Base-loaded whip
Comments: Many in TxDOT fleet; used for all testing by us at TTU

(vi) Antenna 3

Make: Custom-made at TTU
Type: Quarter-wavelength whip
Comments: Suggested by B. Rehm [14]

To check for proper antenna impedance matching before carrying out the Tex-899-B test, the return loss of each antenna was measured with an HP 8753C network analyzer. The results are shown in Table 9.

Table 9. Return-loss data for three antennas

Antenna	Max. Return Loss in dB	Center Freq. in MHz	Bandwidth* in MHz
Spectrum	25	47.6	5.7
Larsen	18	47.6	7.6
Quarter-wavelength	11	47.6	8.4

* Bandwidth is defined as VSWR ≤ 2.0 or return loss ≥ 9.5 dB.

The results of the Tex-899-B test are shown in Table 10. Two frequencies were used. As evident from the table, all three antennas give about the same response. The output of the quarter-wavelength antenna is slightly lower than the rest probably because of its poor impedance-matching characteristics, as seen in the return-loss data. The close agreement between the base-loaded and non-base-loaded antennas observed here is apparently not consistent with results reported by B. Rehm [15].

Table 10. Tex-899-B results for three antennas

Antenna	Tex-899-B Sig. Gen. Amplitude for 12-dB SINAD, in dBμV 47.38 MHz	 47.34 MHz
Spectrum	14	– 1
Larsen	14	– 1
Quarter-wavelength	13	– 2

F. Questions

1. Current on outside of antenna cable

Unanswered questions always arise in research. Here are three, resulting from the vehicle test procedures.

There seems to be no standard procedure for choking off the undesirable current that can flow on the outside of the antenna cable in the J551/4 and Tex-899-B tests. It may be larger and thus more of a problem when the test instrumentation is grounded. In our vehicle tests we used battery-powered equipment, which was not connected to AC power and thus not grounded.

Various experimenters have developed their own procedures. For example, Gus Morgan, author of Tex-899-B, describes using a large loop of cable covered by a sheet of hardware cloth [6].

2. Surface below the vehicle

In the past, the vehicle-emissions part of the Tex-899-B test normally has been conducted outdoors with the vehicle-under-test parked in any convenient spot. On the other hand the J551/4 test often has been conducted with the vehicle located inside an all-metal chamber (with RF absorber lining the walls and ceiling). Thus in one case the vehicle is tested over a surface of unknown electrical conductivity and in the other over one of very high conductivity. Whether this is an important difference is an open question. A related matter is vehicle resonance, which is described below.

3. Vehicle electromagnetic resonances

In analyzing the electromagnetic fields existing on, say, a pickup truck due to various onboard noise sources, one can imagine different types of behavior which fall into three regions [16]: the quasi-static region where the frequency of the sources is very low so that the length of the truck is short compared to a wavelength, the resonance region where the truck is on the order of a wavelength in size, and the quasi-optical region where the frequency is so high that the truck is much longer than a wavelength. The trucks we have tested vary in length from about 17 feet to about 19 feet. For a wavelength equal to 18 feet, the frequency is 55 MHz. Thus, since our frequency of interest is the TxDOT communication band at 47 MHz, we see that in our case the trucks lie in the resonance region.

To a first approximation, the lowest resonance would occur when the truck is one-half wavelength long, at 27.5 MHz. The second resonance would be at one wavelength, 55 MHz, the third at 82.5 MHz, and so on.

We do not know how strong the resonance effects typically are for our trucks. The ground is lossy at these frequencies, which would cause some damping and lowering of Q. The general fatness of the truck bodies would broaden the resonances also. But the resonances would change somewhat, increasing in Q, if the truck were located on a conducting surface, a metal bridge for example. Computer modeling, like that described by F. Tesche et al. [17], would probably be a good way to investigate this effect.

In the event of a strong resonance, the position of the communications antenna on the truck would be critical. Located near a node in the resonant electric-field pattern, the antenna would pick up little noise, while near an antinode, the noise would be much stronger. For the one-wavelength resonance, which is the one closest to the TxDOT band, the antinodes are located at the front and back ends and the center of the truck. These would be undesirable locations for permanent mounting of the antenna. As a way of determining the actual strength of the resonance, it might be worthwhile to experiment with several different antenna locations.

G. Diesel Truck

As part of our measurement campaign, we tested one diesel-powered truck. It was a brief test, carried out at the TxDOT radio shop in Lubbock in response to a call from Leonard Bryan. The truck was a 1999 Chevrolet 3500 HD, TxDOT 5-5336-G (VIN 1GBKC34F3XF097674). The measurements consisted of spectrum scans with the HP EMC analyzer connected to the truck's antenna. They revealed a strong, narrow-band emission with the truck in the key-on condition and in the engine-running condition— obviously a module-noise problem. Amplitude was about 27 dBμV and frequency about 47.02 MHz. Unfortunately the emission lay on the lowest TxDOT frequency, the one mainly used in Lubbock. The truck clearly would not have passed the Tex-899-B test, being 30 dB above the limit for module noise.

Mr. Bryan, working with the local Chevrolet dealer, traced the problem to the module that monitors and controls the level of fuel in the truck's two tanks. A solution to the problem is still being sought as of this writing.

H. Limit on Electric Field Strength

For completeness we mention some EMC industry standards in addition to SAE J551/4. FCC Title 47 Part 15, CISPR 22, SAE J551/2, and MIL-STD-461D specify limits on the electric field strength of emissions. These standards are of some relevance for us because the TxDOT whip antennas are sensitive to the electric field, rather than the magnetic. However they are not useful in our situation for a number of reasons, some or which are given by Kimmel and Gerke [18]. If we were to specify a limit on electric field, it would be on the order of 1 μV/m for CW emissions since we can use $E \approx V/l$ and our J551/4 limit on voltage is on the order of 1μV and our antenna is about 1 m long. A book of general interest in the area of EMC testing and limits is that by K. Javor [19].

IV. SURVEY OF STATE DEPARTMENTS OF TRANSPORTATION

As part of Phase II, Prof. Mehrl conducted a survey of departments of transportation around the country. The objectives were to find out how many vehicles equipped with low-band mobile radios were in service and to learn what vehicle-generated interference problems have been experienced, that is, to see to what extent problems like TxDOT's existed beyond the borders of Texas. Compilation of the numbers supplied by the survey respondents gave a total of about twenty-eight thousand radios in use, of which about five thousand were in Texas. Many responses revealed vehicle RFI problems, and solutions or the lack thereof, similar to the experiences of TxDOT. The survey responses are included in Appendix E.

During the last briefing by Prof. Trost and Mr. Lewis to the SAE EMR Committee, i.e. the TEAM, in January 2001, copies of the survey responses were handed out. The intent was to make the committee members aware of the true extent of the low-band situation, and to provide added impetus to the vehicle manufacturers for eliminating the problems in the future.

To inform the state DOTs about our work on this project, each state DOT that participated in the survey was mailed a copy of Tex-899-B [Appendix B (appendix)], Prof. Trost's symposium paper [Appendix C], and the survey results [Appendix E].

V. CONCLUSIONS

A. A Pattern for Peak and Average Limits

We gathered together all the various results from laboratory and vehicle tests, including peak and average amplitude data from the EMI receiver and SINAD data from the FM radio; and we looked for evidence of an underlying pattern. We had in mind that a key ingredient in this complicated mix of data is how the radio behaves when teased by the various vehicle noise sources. The behavior depends in large part on the characteristics of the radio's FM detector and noise blanker.

We imagined characterizing all of the noise sources, electronic-module, DC-motor, and spark-ignition, according to their peak-to-average ratios (or crest factors). When we plotted out our proposed peak and average limits versus noise source peak-to-average ratio, a pattern indeed emerged. The resulting graph is shown in Figure 12. Lines have been drawn in to connect the data points and thus reveal the pattern formed by the splitting and curving apart of the two limits from their common value at the left. Notice that, according to the legend, the abscissa is divided into electronic-module noise at the left followed by DC-motor noise and then spark-ignition noise. The module noise occupies the range of 0 dB to 14 dB peak-to-average ratio; the motor noise from 14 dB to 36 dB; and the ignition from 36 dB to 44 dB. The peak-to-average ratio of 0 dB represents CW noise, such as a harmonic from a microcontroller clock, which has the same peak and average values. The splitting of the limit lines at the left is due to the response of the radio's FM detector to the pulsed AM noise of the modules; the upward curving of the lines at the right is due to the radio noise blanker which removes some of the noise pulses thus allowing the radio to tolerate a greater noise amplitude for a 12 dB SINAD.

The four data points near the center of the plot, those at peak-to-average values of 12 dB and 24 dB, were extracted from Figure 11.

The two coincident data points at the left edge come from our laboratory studies, where we simulated vehicle CW noise (the easiest kind to simulate).

The two data points on the right at the value of 32 dB peak-to-average were taken from a laboratory simulation by P. Bahukudumbi [Appendix D]. Note that the 40 dBμV value quoted often above in this report as the peak limit for DC-motor noise applies to a measurement bandwidth of 120 kHz, and in Figure 11 the bandwidth is 9 kHz, so the peak limit is lower, as is the average limit.

There is also some laboratory data obtained by Y. Jin [20] which fits the pattern of these diverging curves. It comes from one of our Phase I experiments that was motivated by an observation of module noise kindly supplied to us by the EMC laboratory at General Motors. The noise was pulsed AM but with a simpler frequency spectrum than the module noise from the Dodges described above. Jin's values are –2 dBμV (pk) and –8 dBμV (avg) at 6 dB peak-to-average and –1 dBμV (pk) and –14 dBμV (avg) at 14 dB peak-to-average.

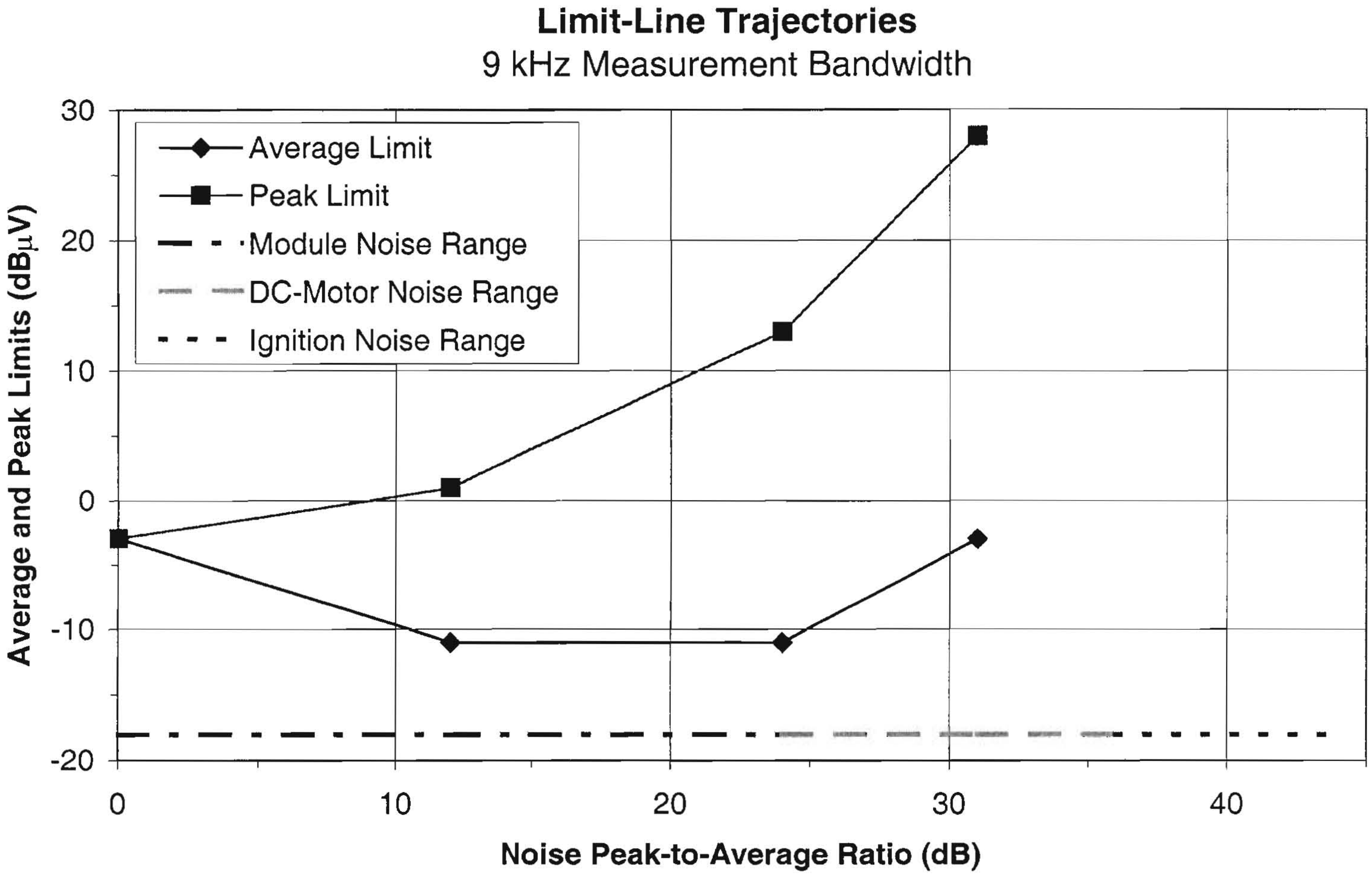


Figure 12. Trajectories of peak and average limits

B. Options for Testing New Vehicles for TxDOT Service

We have identified three vehicle noise sources, as shown in Figure 12: module, DC-motor, and ignition. However the TxDOT radios are immune to ignition noise, so that only module and DC-motor noise need be discussed. Between the two, it is likely that the module noise is the more important; it is the only type of noise that caused a vehicle to fail the Tex-899-B test in our testing campaign this past year, and in the future one can expect to find more modules, that is to say more electronic devices, on the vehicles, increasing the likelihood of interference to TxDOT radios. On the other hand, motor noise would seem to be the easier to suppress because it occurs on DC lines not signal lines, and it is currently being subjected to increasing attack from RF-suppression filters, such as the new chip filters made by Syfer Technology Limited in England.

As far as the module noise is concerned, one can see from the upper curve in Figure 12 that the J551/4-type limit on the peak value rises as one considers noise with higher peak-to-average ratios. In order to apply such a variable limit to a vehicle-under-test, one would need to measure both peak and average values, compute their ratio, and determine the appropriate limit by reference to the curve. (And one would of course prefer a better-defined curve, one with more points on it.) This procedure looks fine in principal, but in practice it would be somewhat time-consuming and perhaps confusing to the test operator, requiring two measurements and a computation. It might be just as well to carry out the SINAD test instead. An alternative, of the J551/4 type, which would be fast and simple, would be to just measure the peak value and apply the −3 dBμV limit, regardless of what peak-to-average the noise in question might have. This would amount to applying an accurate limit if the noise were CW but applying too stringent a limit if the noise were pulsed. But it would be just like the J551/4 tests currently run in the automotive industry in the sense that it would consist of a quick peak scan and superimposed limit line.

As far as DC-motor noise is concerned, we spent a good deal of time in a laboratory investigation, operating an HVAC fan and two fuel pumps with Stoddard solvent in a fume chamber. But it was rather frustrating work. Peak noise values were quite variable; in addition to motor-aging and battery-voltage variations, there was always a statistical variation with 2 dB standard deviation. On the test vehicles the noise was difficult to study because it was never strong enough, by itself, to cause a failure in the Tex-899-B test. The new limits we found for the J551/4 test, 40 dBμV peak and 3 dBμV average, are based largely on the laboratory measurements. These limits apply, by the way, when using a measurement bandwidth of 120 kHz, which is appropriate for very broad-band emissions like DC-motor noise.

Our options then appear to be threefold: a SINAD test, a modified J551/4 test with peak limits only, and a modified J551/4 test with peak and average limits. But, as we now explain, we must hold off on the average-detection option. Two published standards for average detectors are known to us; they are contained in CISPR 16-1 [12] and VDE 0876 Part 3 [21]. These standards require that average detection be reasonably accurate for noise with pulse rates (or frequencies) down to 5000 pps. This value is probably not low enough for our purposes since we have observed vehicle emissions with pulse rates in the range 50 pps to 2000 pps. Information on the specific average detector in the ESVP receiver is contained in the Operating Manual [22]. It indicates that the detector is accurate for pulse rates down to about 1000 pps when using the 120 kHz bandwidth. Our data in Figure 5 do not agree with this. By comparing the various R&S curves with the theoretical, one can see a lower-frequency limit of perhaps 2000 pps. The HP curve with pre-amplifier switched off actually looks more consistent at lower frequencies than the R&S. In any case, in order to make average detection a routine part of TxDOT testing, a more thorough study of average detector standards and performance will be required.

Thus we suggest to the automakers, as a test for new vehicles destined for TxDOT service, either of the two remaining options, SINAD or J551/4 with peak only. We have incorporated these options into a single detailed test procedure, which is included as Appendix A. This procedure is in fact an expanded version of the original Tex-899-B test, in which the new J551/4 peak-only test is included. Other important improvements over the original version of Tex-899-B have also been made. A summary of our changes to Tex-899-B is given in the following section.

C. Expanded Tex-899-B Test

Our various draft changes to Tex-899-B are listed below. For the reader who wishes to examine the original Tex-899-B and SAE J551/4 documents, copies as included as appendices in the thesis by J. Yun [Appendix B].

(i) Optional J551/4 testing

A modified version of J551/4 was included as an alternative to the SINAD test. The modifications to J551/4 include changing the narrow-band limit from 0 dBμV to – 3 dBμV and applying it to module noise, and changing the broad-band limit from 28 dBμV to 40 dBμV and applying it to DC-motor noise. The modified test thus looks like that shown in Table 1 in Chapter II, with the word "NB" deleted from the phrase "NB electronic-module emissions" in the Comment column.

(ii) SINAD testing

a. The combination of a 6 dB degradation limit and a 1 μV maximum-signal limit was replaced with just the 1 μV limit.

b. An option was included whereby the FM signal generator does not have to be adjusted for a 12-dB SINAD reading for each test condition but can be left at the setting corresponding to the 1 μV limit. This procedure results in a faster test. If the observed SINAD value is greater than 12 dB, the vehicle passes; if less than 12 dB, it fails. The signal amplitude required to bring the SINAD reading to 12 dB is not determined. This amplitude can be roughly estimated, but the variation in amplitude with SINAD value is a nonlinear one and depends somewhat on the type of vehicle noise being measured and on the ambient noise level. The nonlinearity is the result of the threshold effect [23] of the FM detector and is such that the SINAD value changes with signal amplitude more strongly in the vicinity of the 12 dB point than away from it.

The time-intensive nature of the original procedure was cited as a major drawback of the SINAD test from the point of view of the automakers. The new, faster procedure addresses this complaint.

c. The requirement was added that the TxDOT radio noise blanker must always be turned on during testing. This requirement was recognized early on in our vehicle tests [24].

(iii) Frequency range

The required range of testing frequencies was extended to include not only the TxDOT radio channels but also a number of frequencies between, above, and below. This change was made because it had been found [15] that narrow-band vehicle emissions lying near a TxDOT channel can, over the course of time, drift squarely onto it.

(iv) Miscellaneous changes

a. A Table of Contents was added.
b. Many additional details were included in the Equipment List.
c. Numerous minor changes in wording were made throughout.

D. Future Directions

One obvious avenue of research to pursue in the future is a comprehensive investigation of average detectors, their performance for various noise waveforms and their limitations. The inclusion of average detection in motor-vehicle emissions testing, as in our third option mentioned above in Section B, may prove to be an excellent technique, or it may force existing EMI receivers to work at or beyond their measurement limits, thus negating the potential benefit. And perhaps more rigorous standards are needed for average detection, as suggested by Poul Andersen at the January 2001 meeting of the SAE EMR Committee meeting.

It would also be worthwhile to answer the questions posed in Chapter III, Section F.

It is hoped that the vehicle manufacturers will put to use the expanded Tex-899-B test developed during this project. Time will tell to what extent EMC problems will decrease for TxDOT. But some kind of follow-up consultation with the manufacturers seems advisable, in order to discover their experience in testing their new models vis-à-vis the TxDOT requirements.

Along with the sharing of specific technical knowledge between TxDOT and the manufacturers, new paths of communication and personal relationships have grown out of the present project. These will serve to work to everyone's mutual interest.

Twelve states participated in our survey of low-band-VHF users; and, having established this database of other states with concerns similar to TxDOT's, it may be advantageous for TxDOT to set up some sort of ongoing cooperative activity. We have not made full use of all the information that is available from these other states. Perhaps some form of electronic clearinghouse for RFI information, problems and fixes, would be worthwhile.

The future of motor vehicle design undoubtedly holds new EMC challenges. But it may be that some help is on the way for TxDOT as a result of the myriad of new RF accessories that will be appearing on the future vehicles— e.g. telephones, navigation systems, traffic avoidance systems. These accessories will demand very low vehicle emissions over a very broad frequency range, including the TxDOT band. Thus a more comprehensive effort will be devoted to EM noise reduction by the vehicle manufacturers.

There is also the inverse issue, the vehicle susceptibility to the accessories. In the case of TxDOT, the problem of vehicle susceptibility to the radio transmitter has diminished in recent years, but it could undergo a resurgence in the future. It is a two-way street; as one author put it, ". . . VHF radios and microprocessors are mutual antagonists" [18].

The SAE standard J551/4 has been harmonized with the international standard CISPR 25 [25]. So the modifications we made to J551/4 in order to include it in Tex-899-B could find their way in some form into CISPR standards also.

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Appendix A: Expanded Tex-899-B Test

Test Method Tex-899-B (Trost Draft)

RADIO-FREQUENCY INTEFERENCE (RFI) TESTING

February 2001

This test method assures the compatibility of Texas Department of Transportation (TxDOT) fleet vehicles and VHF FM radio equipment operating in the frequency ranges of 30 to 50 MHz and 150 to 174 MHz. It is intended to identify 90 % or more of RFI ingress and egress problems.

Contents

I. DEFINITIONS

Ingress (vehicle electromagnetic susceptibility): Any action, reaction, indication, or failure to perform or comply by vehicle equipment and/or accessory items caused by the activation of the VHF FM radio transmitter in any mode of operation

Egress (vehicle electromagnetic emission): Any mode of operation, action, reaction or indication by the vehicle equipment and/or accessory equipment which degrades the VHF FM radio receiver effective sensitivity

II. EQUIPMENT

The following instrumentation is required if sections V and VI are to be carried out. However if section VII is substituted for section VI, then items 3, 4, 5, and 6 are omitted and an EMI receiver or spectrum analyzer, as specified in SAE J551/4 and CISPR 16-1, is required instead. (SAE J551/4: "Test Limits and Methods of Measurement of Radio Disturbance Characteristics of Vehicles and Devices, Broadband and Narrowband, 150 kHz to 1000 MHz," Society of Automotive Engineers, Warrendale PA, USA, May 2000. CISPR 16-1: "Specification for radio disturbance and immunity measuring apparatus and methods, Part 1: Radio disturbance and immunity measuring apparatus," International Special Committee on Radio Interference, International Electrotechnical Commission (IEC), Geneva, Switzerland, 1999 [available from American National Standards Institute (ANSI), New York NY, USA].)

1. 100-W VHF FM communications radio (transceiver) capable of operating on all frequencies of interest, such as Motorola *MaraTrac*, with noise blanker switched on. TxDOT low-band VHF channels lie at 47.02, 47.04, 47.06, 47.08, 47.10, 47.12, 47.14, 47.16, 47.18, 47.20, 47.22, 47.24, 47.26, 47.34 MHz.
2. 12-V DC power supply or 12-V battery for radio
3. FM signal generator
4. Signal-to-noise-and-distortion (SINAD) meter, as specified in "Land Mobile FM or PM Communications Equipment Measurement and Performance Standards," ANSI TIA/EIA-603-1992, Telecommunications Industry Association, Washington DC, USA, February 1993, Section 1.5.1
5. Audio load for radio
6. RF matched three-port coupler with one low-attenuation path, such as a directional coupler with less than 1.2 VSWR, less than 0.5 dB attenuation, about 20 dB or higher coupling, and greater than 20 dB directivity and all parameters essentially constant over the range of test frequencies

7. RF low-power coaxial load

8. Whip antenna with magnetic mount for frequencies of interest

9. Coaxial cable (RG-58 or similar) of sufficient length to reach from the vehicle under test to the test instrumentation. See Figure 1. If the test results are found to be sensitive to the position of the cable or the instrumentation, a suitable external RF choke should be employed. Such a choke could consist of several ferrite beads on the cable or of a 6 ft by 6 ft (1.8 m by 1.8 m) sheet of hardware cloth, laid flat on the test area floor with the coaxial cable making one complete loop approximately four feet in diameter under it

10. RF directional watt meter for radio

III. FACILITIES

1. Free of high ambient RF noise (for egress test)

2. Providing for rotation of vehicle wheels, such as, for example, by raising the vehicle off the floor (for ingress test)

3. Free of large nearby metal objects, except possibly the floor, unless they are covered with RF-absorbing material (for both tests)

IV. SAFETY NOTES

Safety must never be compromised during tests. Hazards exist due to moving vehicle parts, exposed electrical wires, and electromagnetic radiation. Strict compliance with accepted work practices must be observed at all times. Sudden actions may result when the radio transmitter is activated. Stay clear of vehicle and antenna. One person should operate the vehicle, and another the radio.

V. INGRESS COMPATIBILITY

A. Antenna Qualification

Step	Action
1	Locate vehicle at a suitable test site. (See FACILITIES.)
2	Assemble test setup as shown in Figure 1. Solid arrows in figure show signal path.
3	Verify engine is switched off.
4	Provide for rotation of vehicle wheels.
5	Place magnetic-mount antenna in center of vehicle roof. *
6	Key microphone on radio.
7	Record forward RF power to the antenna.
8	Record reflected RF power from the antenna.
9	Adjust length of antenna, if needed, and repeat steps 6 through 8 until forward power is 100 W ± 10 W and reflected power is less than 10 % of forward power on all TxDOT channels of interest.

* On some vehicles the roof may be obstructed so that an alternate antenna location, consistent with good radio communications, is required.

The antenna is qualified when the reflected power is less than 10 % of the forward power on all TxDOT channels of interest.

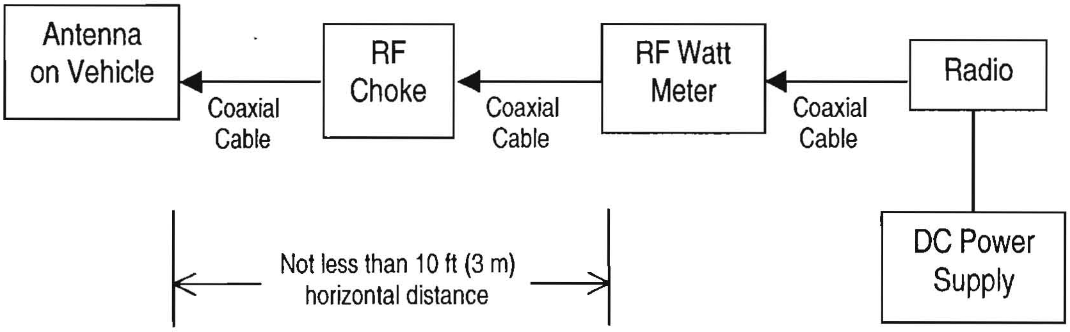

Figure 1. Setup for Antenna Qualification and Ingress Compliance Test

B. Ingress Compliance Test for Vehicle

Step	Action
1	Setup same as in Figure 1. Start vehicle engine.
2	Put vehicle in gear and rotate tires at a moderate speed.
3	Activate one vehicle system or accessory. Be certain to check the braking operation.
4	Activate the radio transmitter for approximately five seconds.
5	Record results as one of the following: 1. No adverse reaction. 2. Reaction resulting in safety hazard. 3. Reaction resulting in a nuisance operation.
6	Repeat steps 3 through 5 until all vehicle systems and accessories are activated.
7	Repeat vehicle qualification for all radio channels to be used.
8	Stop wheels of vehicle and turn off engine.

C. Vehicle Ingress Qualification

The vehicle under test passes the ingress compliance test when no reactions occur which result in a safety hazard or a nuisance operation.

VI. EGRESS COMPATIBILITY

A. Antenna Qualification

The antenna qualification procedure described above in INGRESS COMPATIBILITY serves also to qualify the antenna for egress compatibility testing.

An alternative to this procedure is to use an RF network analyzer instead of the radio and power meter to measure the reflected power and insure that it is less than 10 % of the incident power at the frequencies of interest.

B. Radio Receiver Qualification

Step	Action
1	Assemble test setup as shown in Figure 2.
2	Generate a standard signal (on-channel FM with 1.0 kHz sinewave tone at ± 3.3 kHz deviation) on first test frequency.
3	Vary signal amplitude to establish 12 dB SINAD.
4	Record signal amplitude, that is, receiver basic sensitivity, in dBμV.
5	Increase signal 6 dB above that in step 4.
6	Increase peak deviation until SINAD is degraded to 12 dB.
7	Record receiver modulation acceptance (bandwidth).
8	Repeat steps 2 through 7 at all remaining test frequencies. (See NOTE 1 below.)

NOTE 1: Test frequencies should include TxDOT channel frequencies plus additional nearby frequencies, in order to detect possible vehicle emissions that, over the course of time, could drift onto TxDOT channels. For the TxDOT frequency band from 47.020 MHz to 47.340 MHz, 61 test frequencies, spaced 10 kHz apart, are required as follows: 46.880, 46.890, 46.900, 46.910, 46.920, 46.930, . . . , 47.430, 47.440, 47.450, 47.460, 47.470, 47.480 MHz.

The receiver is qualified for vehicle acceptance testing if the following conditions hold at all test frequencies:

1. The receiver basic sensitivity value is less than – 8 dBμV (0.4 μV) for 12 dB SINAD.
2. The receiver bandwidth is a minimum of ± 6.5 kHz and a maximum of ± 8.0 kHz.

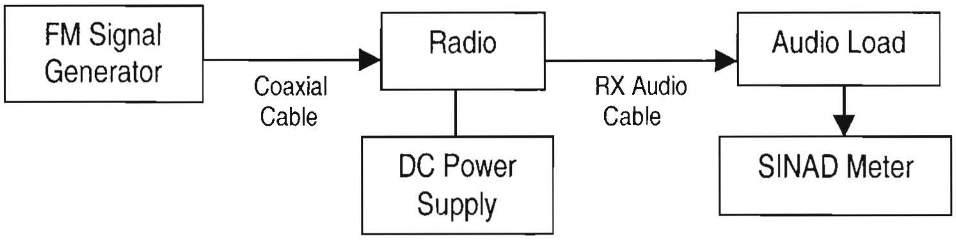

Figure 2. Setup for Receiver Qualification

C. SINAD Test Options

To complete sections D and E below, a large number of SINAD measurements is required because of a multiplicity of frequencies and vehicle conditions. According to the steps shown, in each measurement one adjusts the FM signal generator to give a 12-dB SINAD reading and then records the signal generator amplitude. From this amplitude one calculates the receiver effective sensitivity. After completing the measurements for Site Qualification, one checks to see if all of the receiver effective sensitivity values lie below the – 6 dBμV limit; and after completing the measurements for Egress Compliance, one similarly checks to see if all of the receiver effective sensitivity values lie below the 0 dBμV limit.

The process of adjusting the signal generator for 12 dB SINAD on each measurement is time consuming, but it gives one the effective sensitivity and thus allows one to know the dB difference between the effective sensitivity and the limit. If one does not care about the value of this difference but only whether the limit is exceeded and if furthermore the performance of the RF coupler does not vary over the test frequencies, one can save time by employing an alternate measurement procedure that does not require the adjustment for 12 dB. This faster measurement procedure is given in sections F and G as an alternative to the procedure in sections D and E.

D. Site Qualification

1. Measurements

Step	Action
1	Locate vehicle at a suitable test site. (See FACILITIES.)
2	Assemble test setup as shown in Figure 3. Low-attenuation path of coupler is between radio and antenna or load.
3	Verify that magnetic-mount antenna is located in center of vehicle roof.
4	Disconnect the vehicle battery cable.
5	Terminate the RF line into the RF load.
6	Generate a standard signal (on-channel FM with a 1 kHz sinewave tone at ± 3.3 kHz deviation) on first test frequency.
7	Increase the signal generator RF output level until a 12 dB SINAD indication is achieved.
8	Record signal amplitude, that is, sensitivity into RF load, in dBμV.
9	Disconnect load and connect antenna.
10	Increase signal generator RF output level until a 12 dB SINAD indication is achieved.
11	Record sensitivity into antenna in dBμV.
12	Compute and record the effective sensitivity, using steps in Table (Effective Sensitivity Calculation) below.
13	Repeat steps 5 through 12 at all remaining test frequencies. (See NOTE 1 under Radio Receiver Qualification above.)

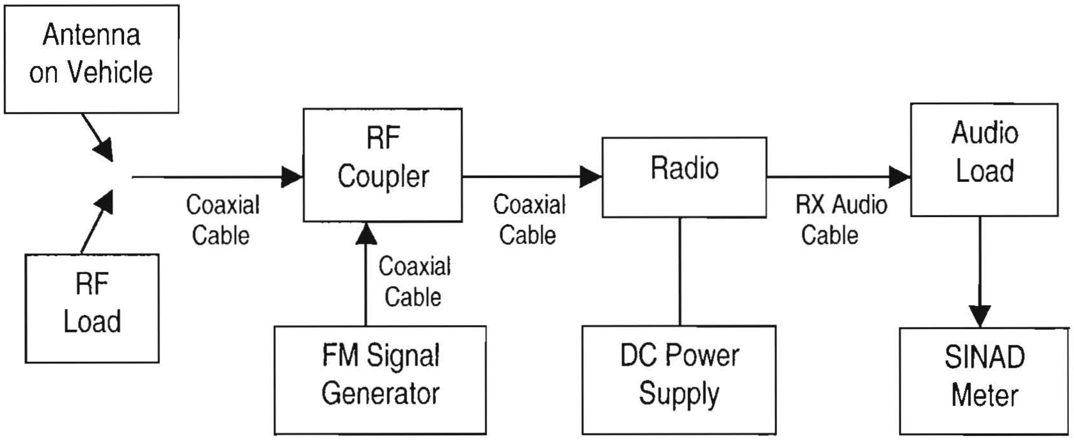

Figure 3. Setup for Site Qualification and Egress Compliance Test

2. Effective Sensitivity Calculation

Step	Action
1	Subtract sensitivity into load from sensitivity into antenna.
2	Record this difference.
3	Add this difference to the receiver basic sensitivity in dBμV.
4	Record the receiver effective sensitivity in dBμV.

The site is qualified if the receiver effective sensitivity value is less than – 6 dBμV (0.5 μV) at all test frequencies.

E. Egress Compliance Test for Vehicle

Step	Action
1	Setup same as Figure 3, with antenna connected. Reconnect the vehicle battery cable.
2	No vehicle systems are activated. Increase the signal generator RF output level until a 12 dB SINAD indication is achieved.
3	Record the signal generator RF output level.
4	Activate one vehicle system or accessory.
5	Increase the signal generator output level until a 12 dB SINAD indication is achieved.
6	Record the signal generator RF output level.
7	Repeat Steps 4 through 6 until all vehicle systems and accessories are activated.
8	Compute and record the effective sensitivity as in Table (Effective Sensitivity Calculation) above.
9	Repeat steps 2 through 8 at all remaining test frequencies. (See NOTE 1 under Radio Receiver Qualification above.)
10	Turn off engine.

F. Site Qualification— Faster Method

Step	Action
1	Locate vehicle at a suitable test site. (See FACILITIES.)
2	Assemble test setup as shown in Figure 3. Low-attenuation path of coupler is between radio and antenna or load.
3	Verify that magnetic-mount antenna is located in center of vehicle roof.
4	Disconnect the vehicle battery cable.
5	Terminate the RF line into the RF load.
6	Generate a standard signal (on-channel FM with a 1 kHz sinewave tone at ± 3.3 kHz deviation) on first test frequency.
7	Increase the signal generator RF output level until a 12 dB SINAD indication is achieved.
8	Record signal amplitude in dBμV.
9	Subtract from this value the value in step 4 of Radio Receiver Qualification and then add – 6 dBμV.
10	Set signal generator RF output level to this value.
11	Disconnect load and connect antenna.
12	If SINAD meter reading is less than 12 dB, the site exceeds the limit; if greater than 12 dB, the site does not exceed the limit. Record result.
13	Repeat step 12 at all remaining test frequencies. (See NOTE 1 under Radio Receiver Qualification above.)

The site is qualified if the SINAD meter reading is greater than 12 dB at all test frequencies.

G. Egress Compliance Test for Vehicle— Faster Method

Step	Action
1	Setup same as Figure 3, with antenna connected. Reconnect the vehicle battery cable.
2	Increase the signal generator RF output level by 6 dB from the value set in step 10 in Site Qualification— Faster Method above.
3	No vehicle systems are activated. If SINAD meter reading is less than 12 dB, the vehicle exceeds the limit; if greater than 12 dB, the vehicle does not exceed the limit. Record result.
4	Activate one vehicle system or accessory.
5	If SINAD meter reading is less than 12 dB, the vehicle exceeds the limit; if greater than 12 dB, the vehicle does not exceed the limit. Record result.
6	Repeat Steps 4 and 5 until all vehicle systems and accessories are activated.
7	Repeat steps 3 through 6 at all remaining test frequencies. (See NOTE 1 under Radio Receiver Qualification above.)
8	Turn off engine.

H. Vehicle Egress Qualification

The vehicle under test passes the egress compliance test when the effective sensitivity value does not exceed 0 dBμV (1.0 μV)— or in the faster method when the SINAD meter reading is greater than 12 dB— for all modes of operation, which includes engine off, engine on, (from idle to partial throttle), and all vehicle systems or any combination thereof.

VII. EGRESS COMPATIBILITY- *ALTERNATE METHOD*

A. Antenna Qualification

The antenna qualification procedure described above in INGRESS COMPATIBILITY serves also to qualify the antenna for egress compatibility testing.

An alternative to this procedure is to use an RF network analyzer instead of the radio and power meter to measure the reflected power and insure that it is less than 10 % of the incident power at the frequencies of interest.

B. Egress Compliance Test for Vehicle, Using Modified SAE Test

An alternative to the SINAD test specified above in section VI is a modified version of the test described in SAE Standard J551/4. See EQUIPMENT. This is not a SINAD test but rather an RF noise emissions test. The FM signal generator, RF coupler, SINAD meter, and audio load are not required. Instead an EMI receiver or spectrum analyzer, as specified in J551/4 and CISPR 16-1, is used. The J551/4 procedure should be followed with the following modifications:

1. The flow chart in FIGURE 1 and the limits in TABLE 1 of J551/4 are not used.
2. The limit of noise emissions from vehicle electronic modules = -3 dBμV measured with an EMI receiver or spectrum analyzer with 9 kHz bandwidth connected to the antenna on the vehicle. Module emissions can be measured with the ignition key switched on but engine and all DC motors off. DC motors include those used in fuel pump, HVAC fan, windshield wipers, radiator fan, and electric windows.
3. The limit of noise emissions from vehicle DC motors = 40 dBμV measured with an EMI receiver or spectrum analyzer with 120 kHz bandwidth connected to the antenna on the vehicle. DC-motor emissions should be measured with all DC motors running (only driver's electric window).
4. Since according to J551/4 the ambient noise emission levels must be at least 6 dB below the vehicle limits and in view of the modified vehicle limits specified in 2 and 3 above, the ambient limits are -9 dBμV and 34 dBμV, respectively.

Emissions should be measured at each TxDOT channel frequency of interest plus additional nearby frequencies as mentioned in NOTE 1 in Radio Receiver Qualification. For the TxDOT frequency band from 47.020 MHz to 47.340 MHz, the range 46.980 MHz to 47.380 MHz must be scanned. Peak detection is to be used, with a measurement time of two seconds at each frequency.

C. Vehicle Egress Qualification

The vehicle under test passes the egress compliance test when it meets these limits at all test frequencies.

VIII. VEHICLE QUALIFICATION FOR ACCEPTANCE

The vehicle passes the Tex-899-B test and is qualified for acceptance if it passes the ingress compliance test and one of the egress compliance tests.

Appendix B: MSEE Thesis by Jongsin Yun

LABORATORY SIMULATION OF MULTIPLE SOURCES OF MOTOR VEHICLE RADIO INTERFERENCE

by

JONG-SIN YUN, B.E.

A THESIS

IN

ELECTRICAL ENGINEERING

Submitted to the Graduate Faculty
of Texas Tech University in
Partial Fulfillment of
the Requirements for
the Degree of

MASTER OF SCIENCE

IN

ELECTRICAL ENGINEERING

Approved

Thomas F. Trost
Co-Chairperson of the Committee

David Mehrl
Co-Chairperson of the Committee

Thomas F. Krile

Accepted

D. J. Schmidly
Dean of the Graduate School

August, 2000

ACKNOWLEGMENTS

I would like to express my appreciation to Dr. Thomas Trost for his kindness and patient guidance on my thesis work. I also say thank you to Dr. David Mehrl and Dr. Thomas Krile for helping me during the research as my graduate committee members.

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CHAPTER I

INTRODUCTION – THE TxDOT RFI PROJECT

Back in the 1930s some engineers recognized that RFI (radio frequency interference) could be a nuisance. After years, with advancing technology, it turned into an even greater problem especially with the advent of high-tech communications systems and microprocessor-based control systems. Recognition of the problem led many engineers to become involved in EMC (electromagnetic compatibility) and as a result several test standards, including some for automotive EMC testing, have been made.

In 1957, the SAE (Society of Automotive Engineers) already decided to set up EMI (electromagnetic interference) standards for measuring as well as controlling RFI [1]. The current standard for EMI was adopted in 1961 and is known as J551. This version of test includes not just the test method and limits for broadband radiation, which was included in the first version, but also new test methods for measuring immunity of the vehicle to strong RF fields [2].

In the early 1980s, microprocessors and their associated circuitry became small and inexpensive enough so many vehicle manufacturers could use them to control many functions and add more complicated functions, which provided more convenience for drivers. Nowadays, these ECMs (electronic control modules) are standard in most cars. However, the clock oscillators in microprocessors, and the digital square wave signals used in the circuitry for processing and control in modern vehicles are rich in harmonics, and they are the main sources of narrow-band noise.

During the 1980s, the FCC (Federal Communication Commission) specified the amount of interference that can be generated by a motor vehicle [3]. Thus, auto manufacturer EMC experts worked to deal with testing and design issues, assuring compliance with the federal regulations. These regulations are adequate to protect other broadcasting radio services, such as TV, AM and FM radio reception in nearby homes, but they are not intended to protect against interference to radio transceivers installed in the vehicles. Thus the industry has had to devise an additional standard, which is part 4 of the SAE J551 [4] (see Appendix B). The SAE J551/4 has been harmonized with CISPR 25 [5].

SAE J551 has undergone modifications, and nine of the fifteen parts of SAE J551 are now in use by the major vehicle manufacturers in the US, including GM, DaimlerChrysler and Ford. (The other six parts are reserved for future use)

SAE is not the only US group involved in the automotive EMI problem. The Texas Department of Transportation (TxDOT) developed its own test standard called Tex-899-B to assure that the 800 or so new vehicles purchased every year work correctly with their installed two-way radios. TxDOT two-way communication systems are an essential part of the TxDOT vehicle fleet for conducting daily business. The Tex-899-B test has recently been revised and renamed as Tex-1160-T (see Appendix A).

There are two types of EMC problems in vehicles: one is the emissions (radiation) problem, in which the vehicle disturbs some communications equipment, and the other one is the immunity problem, in which some communications equipment disturbs the vehicle. Our project is related to the emissions problem.

In the first type of EMC problem a certain amount of radiation from the vehicle gets into the communication equipment as noise. This has occurred in TxDOT vehicles that have two-way radios installed. In the worst case, the noise radiated from a vehicle has been large enough that communication with other vehicles was almost impossible. The TxDOT test, Tex-899-B, can identify such vehicles, but this test is not used by the automakers. The purpose of the TxDOT RFI project is to modify the SAE J551/4 test, so as to make it correlate with Tex-899-B, in the hope that the automakers will then use this modified SAE J551/4 test to qualify their vehicles for TxDOT service and thus reduce TxDOT's RFI problem.

Two graduate students worked on this project previously [6,7]. They concentrated on the effect of single-noise-source emissions. The objectives of the current thesis were selected to complement the two former graduate students' work. They are as follows.

First, to measure the TxDOT radio response to multiple noise sources. To add to the two former students' work, we studied the effect of two or three combined noise sources. Chapter III of this thesis contains the results.

Second, to perform a statistical characterization of DC motor noise. The random properties of DC motor noise make it hard to measure exact values. Chapter III includes the statistical analysis of this random noise from an HVAC fan and fuel pumps.

Third, to carry out a simplified spectral analysis calculation of spark ignition noise. This noise is somewhat less random than DC motor noise, so we could calculate the frequency domain pattern and compare this with what we read from a spectrum analyzer. Chapter III contains the mathematical solution of the spectrum of the spark ignition noise.

Fourth, to determine TxDOT radio noise blanker parameters. There is a noise blanker installed in all TxDOT radios. Since the Tex-899-B test is performed while the noise blanker is switched on, we needed to specify the noise blanker parameters. This is described in Chapter III.

Fifth, to introduce new SAE J551/4 test limits for use with TxDOT vehicles. By means of our data we could evaluate and compare the two main EMC tests, Tex-899-B and J551/4, and decide on the new limits, which could improve the correlation of these two tests.

Sixth, to validate the new SAE J551/4 test limits through whole vehicle tests. We tested two pickup trucks used by TxDOT.

CHAPTER II

LABORATORY TEST SYSTEM

Noise sources in vehicles

Electromagnetic noise is produced by many parts of a motor vehicle such as the ignition system, battery charging circuitry, accessory motors, fuel pump, airbag system, microprocessors, starter motor, etc. Most of the above are impulsive sources, with the ignition system being the most intense. Besides the spark ignition noise, there are two other major noise contributors in modern vehicles. One is DC motors (also impulsive) such as the HVAC (heater ventilation air conditioner) fan, radiator fan, wiper and fuel pump. These are significant enough to generate some noise in on-board communication systems. The other major noise source is microprocessors and their associated digital circuitry. Since digital systems use relatively high frequencies and the switching action results in even higher frequencies, the noise from digital systems may cover a broad frequency range, including the TxDOT two-way radio band. Such noise is called narrow-band noise, since it appears at discrete frequencies (or very narrow frequency ranges). If the frequency components of the noise are truly discrete, they are referred to as CW (continuous wave). Narrow-band noise can be distinguished from broad-band noise, which has a wide, continuous frequency distribution like white noise. DC motor noise and ignition noise can be defined as broad-band noise.

Laboratory bench-top tests

The bench-top tests of the TxDOT project were conducted by simulating these three major noises in the Electrical Engineering Department at Texas Tech University. A main purpose of this simulation was to compare the two test methods, J551/4 and Tex-899-B, and find a modified new limit for the J551/4 test to make it as effective as Tex-899-B.

Spark ignition noise has a periodic waveform. When the breaker points open, there are two sparks and thus two noise pulses. One occurs at the distributor and the other at the spark plug. As the engine runs, the two pulses are repeated periodically. The simplified circuit is shown in Figure 1 [8]. In the upper diagram, the points are closed and the inductor, labeled TX, is charging. In the lower diagram, the points have opened, producing the high inductor voltage and the resulting sparks. (Nowadays, a transistor is used instead of breaker points.)

The spark ignition noise was simulated by an EH pulse generator. Since the antenna circuit works as a VHF band-pass filter, the pulse captured at the antenna has a ringing characteristic. Thus a band-pass filter was used at the output of the EH pulse generator to simulate the antenna ringing.

In order to simulate the HVAC fan noise, a Dodge fan was run alone with a 12 V battery. The battery and fan were put inside a metal chamber to isolate the fan noise from ambient noise in the laboratory. The metal chamber was also used for other DC-motor noise sources such as an AutoZone™ fuel pump and a Dodge fuel pump. These impulsive noises were captured by a current transformer (FCC F-33-1 current probe).

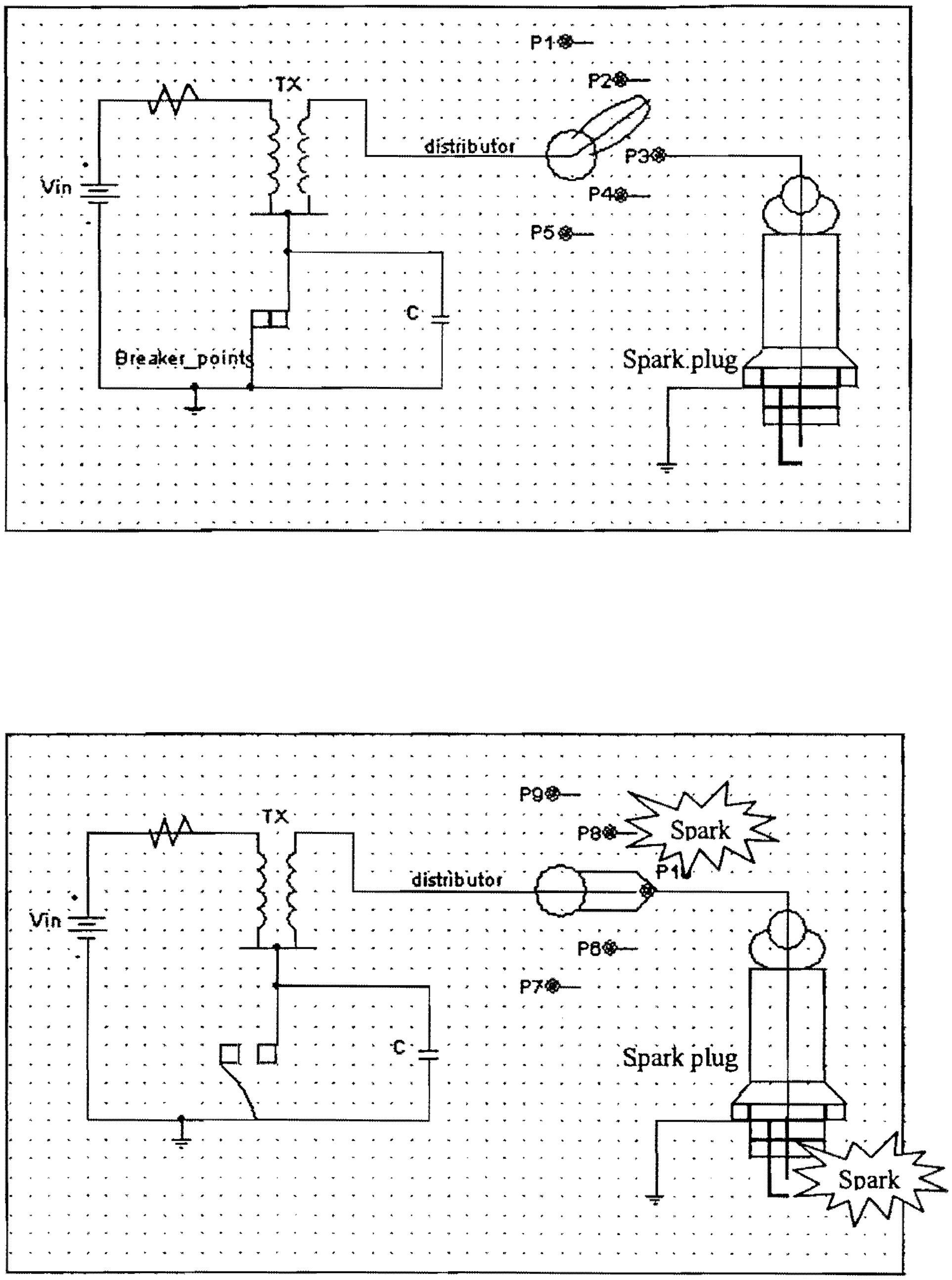


Figure 1. Simplified circuit of a spark ignition system in a gasoline engine vehicle

Noise from micro-controllers and their associated circuits is mainly divided into two types of signal. One is a CW signal and the other is an HMCW (heavily modulated continuous wave) signal. Simulation of the CW signal was done with our Rohde & Schwarz radio communication service monitor by setting it to a fixed frequency. Simulation of HMCW was conducted previously by Jin [6] but was not used for the present work. The detail block diagram of the test set up is shown in Figure 2.

A Fluke FM signal generator is used to simulate a received 1.0 μV FM communication signal at the antenna. A 1.0 kHz audio modulation frequency and 3.3 kHz frequency deviation were used for this signal. Two types of directional couplers allow this FM signal to combine with one, two or three noise sources. The combined noisy signal is delivered to the EMI receiver and TxDOT radio receiver through a coaxial cable. The reading from the CISPR-compliant EMI receiver (Rohde & Schwarz model ESS) represents the SAE J551/4 test [9].

The audio output of the TxDOT radio was connected to a SINAD meter through a load and transformer. The audio volume of the radio was adjusted for 1.0 W audio output power. HP 8903 A and B audio analyzers were used to measure SINAD (signal noise and distortion) values from the output of the radio. Measuring the SINAD value from the audio signal output of the radio is the procedure used for the Tex-899-B test. The SINAD value is defined as shown below [10].

$$SINAD(dB) = 20\log_{10}\left[\frac{\text{rms value of signal, noise and distortion (volts)}}{\text{rms value of noise and distortion (volts)}}\right]$$

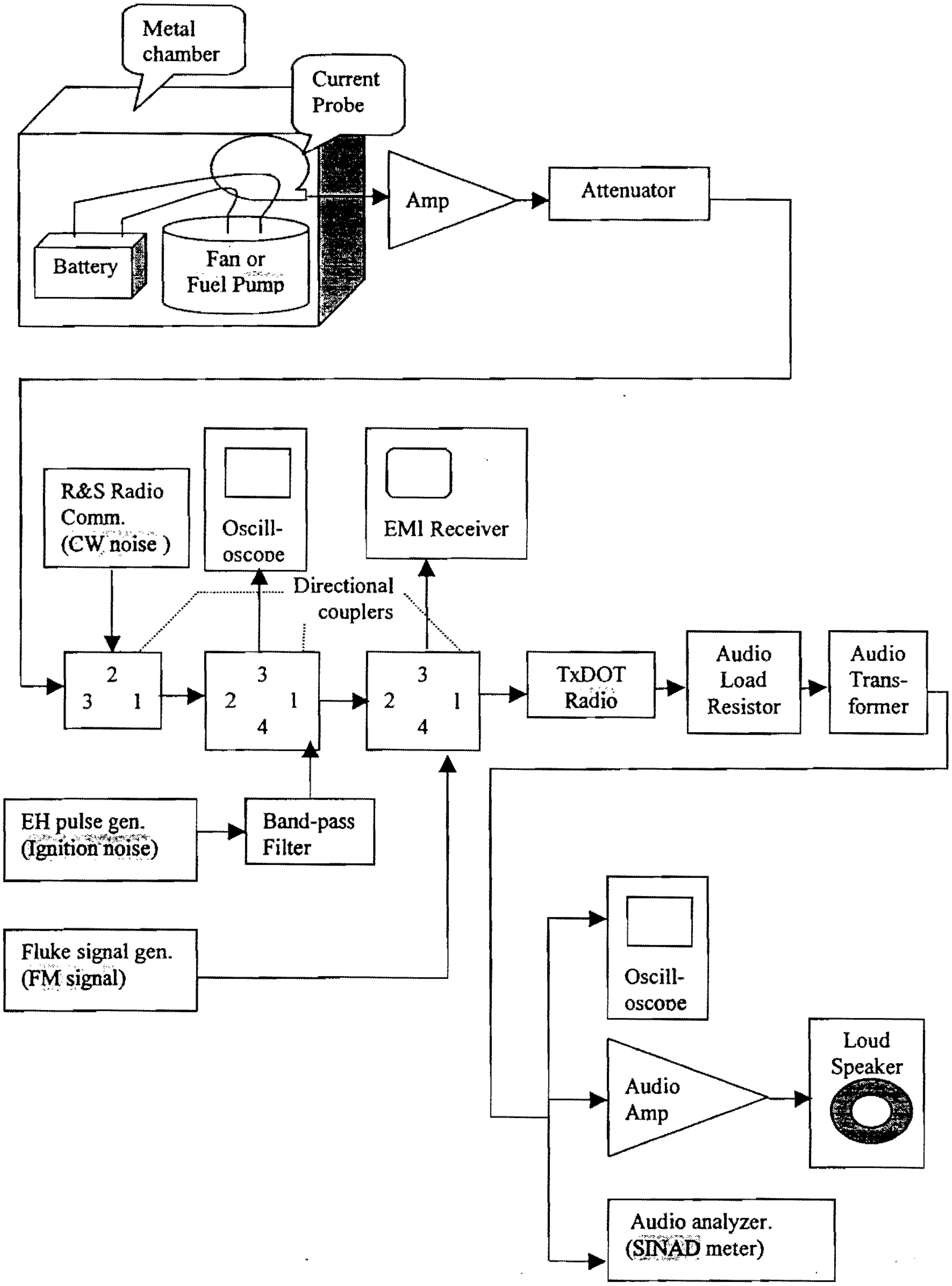


Figure 2. Block diagram of laboratory testing setup

Instead of measuring the amplitude of the signal and the noise from the audio output of the radio, the SAE J551/4 test measures the amplitude of the noise directly at the antenna. So, the SAE J551/4 test results appear with units other than dB. The most common units are dBμV and dBm. The dBμV is the unit defining the amplitude of a signal compared to 1 μV, that is

$$\text{dB}\mu\text{V} = 20\log_{10}\left[\frac{\text{amplitude in }\ \mu\text{V}}{1\,\mu\text{V}}\right].$$

The dBm is the unit relating the power of the signal to 1 mW, that is

$$\text{dBm} = \text{dBmW} = 10\ \log_{10}\left[\frac{\text{amplitude in mW}}{1\,\text{mW}}\right].$$

These two units are very popular in communication system engineering. If it is a 50 Ω system, the relation of these two units can be found as follows:

$$1\ \mu\text{V} = 20\ \log_{10}1\ \text{dB}\mu\text{V} = 0\ \text{dB}\mu\text{V}$$

$$= 10\ \log_{10}(1\times10^{-6}\times1\times10^{-6}\times10^{+3}/50)\ \text{dBm} = -106.98\ \text{dBm}.$$

Nine radios were supplied for the project by TxDOT radio shops in Austin and Lubbock. We used only four radios in the present study since these four are the ones mainly used by TxDOT. Four sensitive instruments have been used to measure the RF output level of the noise sources. The specifications of these instruments are mentioned in Table 1.

Table 1. EMI receiver and spectrum analyzer specifications
(Internal noise level and dynamic range)

ROHDE & SCHWARZ ESS EMI RECEIVER (dBμV)										
IF BW	120 kHz (pre-amp on, 2s measurement time)					10 kHz (pre-amp on, 2s measurement time)				
Detector	PK	QP	Pk/M	AV	RMS	PK	QP	Pk/M	AV	RMS
10 dB atten*	11.5~ 13.4	5.9~ 6.0	29.2~ 30.4	-0.4~ -0.6	0.3~ 0.4	-0.4~ 1.1	6.1	39.6~ 41.8	-11.4~ -11.5	-10.6
0 dB atten*	1.5~ 2.8	- 4.0~ -3.9	19.3~ 21.1	-10.4	-9.6	-8.3~ -10.5	-3.9~ -4.0	30.4~ 32.1	-21.5~ -21.4	-20.7
Dynamic range	Dynamic range : up to 137 dBμV (when RF attenuation ≥ 10 dB) Operating range : 60 dB Typical noise figure : 8 dB with preamplifier, 12 dB without preamplifier									

ROHDE & SCHWARZ ESVP EMI RECEIVER (dBμV)							
IF BW	120 kHz (pre amp on, 2s measurement time)				10 kHz (pre amp on, 2s measurement time)		
Detector	AV	Pk	CISPR	MIL	AV	Pk	MIL
10 dB atten*	-2.6	10.5 ~ 9.8	1.4	30.3 ~ 29.2	-6.0	-0.3 ~ -1.9	41.4 ~ 39.2
0 dB atten*	-12.6	1.1 ~ -0.2	-8.6	20.3 ~ 19.4	-16.0	-9.9 ~ -11.5	31.0 ~ 29.6
Dynamic range	Dynamic range : up to 137 dBμV (when RF attenuation ≥ 10 dB) Operating range : 60 dB Typical noise figure : 6~8 dB with preamplifier, 14 ~16 dB without preamplifier,						

SCHAFFNER SCR 3101 EMI RECEIVER (dBμV)					
IF BW	120 kHz (2s measurement time)			9 kHz (2s measurement time)	
Detector	PK	AVLD	QPcisp	PK	AVLD
10 dB atten*	16.4 ~ 17.5	5.5	-0.6 ~ -0.5	***	2.7
0 dB atten*	7.3 ~ 8.2	-4.5	-10.6 ~ -10.5	-6.2 ~ -7.8	-7.3
Dynamic range	Dynamic range : – 23 ~ + 130 dBμV. (In QP detection mode with no autoranging activated, it is 7 dB.) (Accuracy better than 1.5 dB in temperature range +15 ... +35 deg. Celsius.)				

HEWLETT PACKARD 8592L SPECTRUM ANALYZER				
Detector	PK (sweep time : 2 sec)		Video AV (100 sweeps : 2 sec for each)	
RF Attenuation	0 dB	10 dB	0 dB	10 dB
Level	21 dBμV	31 dBμV	9 dBμV	19 dBμV
Dynamic range	Optimum dynamic range (77 dB) Amplitude Range (-130 dBm to 30 dBm) Resolution Bandwidth (30 Hz to 3 MHz) Operating frequency range (9 kHz to 22 GHz)			

Atten* : RF attenuation

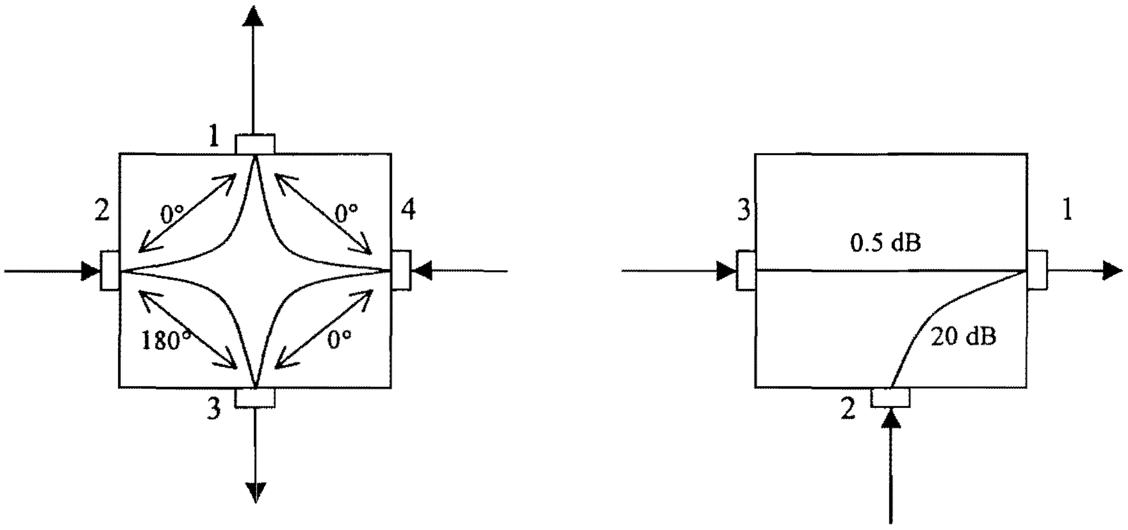
*** : not available

Each of the three receivers was available to us during a different period of time. The ESS receiver from Rohde & Schwarz is a newer model than the ESVP receiver. They have the same dynamic range but the ESS has additional automatic data-taking features. The Schaffner receiver has less sensitivity than the two receivers from Rohde & Schwarz, but it is very portable and good enough to measure broad-band noise. The HP 8592L spectrum analyzer is not good for measuring accurate noise values but is good enough to see the frequency domain characteristics of the noise.

Test equipment

A large array of equipment has been used for the bench-top tests. Three different pulse generators have been used to simulate spark ignition noise. Two RF receivers and two spectrum analyzers have been used to measure the amplitude of the noise. In addition multiple SINAD meters and oscilloscopes were used. Table 2 gives detailed specifications of the test equipment.

Two hybrid junctions and a 3-port directional coupler have been used to combine the signal with three noise sources. For the 4-port hybrid junctions, there is 3.6 dB loss from input to output and either 0° or 180° of phase shift. The 3-port directional coupler has two inputs and one output and each path has a different coupling loss. Port 3 to port 1 has 0.5 dB loss and port 2 to port 1 has 20 dB loss. Figure 3 shows the coupling paths of the couplers.



Hybrid Junction

3-port Directional Coupler

Figure 3. Directional couplers

Table 2. Brand, model and usage of principal equipment

Category	Brand and model	Usage
RF receiving equipment	Rohde & Schwarz ESS EMI receiver	Noise amplitude measurement in frequency domain
	Rohde & Schwarz ESVP EMI receiver	
	Schaffner SCR 3101 EMI receiver	
	HP 8592L spectrum analyzer	
	HP E7401A EMC analyzer	
SINAD meter	HP 8903 A and B audio analyzers	SINAD (dB) measurement
Oscilloscope	HP 54616B, 2 Gsa/s, 500 MHz	Visualize time domain waveform
	HP 54602B, 150 MHz	
	Fluke PM 3370A, 1 MSa/s, 60 MHz	Audio frequency waveform
Signal generator	EH Research Labs 139B pulse generator	Spark ignition noise simulation
	Tektronix 110 pulse generator	
	HP 222A pulse generator	
	Fluke 6060B RF signal generator	FM signal generation
	Rohde & Schwarz CMS 54 radio communication service monitor	CW noise simulation
Amplifier	Midland stereo amplifier	Audio signal amplification
	Mini circuits ZFL-500 HLN low noise pre-amp	RF signal amplification
Network analyzer	HP 8753C	Impedance check for the directional coupler
Current transformer	FCC F-33-1 current probe	Capture the current waveform
Attenuator	HP 8494B attenuator	Used to decrease the amplitude of DC motor noise and spark ignition noise
	Weinschel 3200T-1 programmable attenuator	
Directional coupler	Synergy Microwave DJK-702N 9650, DJK-702N 9723 and DJK-702S 9615	Couple multiple devices
Band-pass filter	Custom made	Simulate antenna ringing

CHAPTER III

BENCH-TOP TEST RESULTS

Broad-band noise in vehicles

Broad-band disturbance emissions are mostly caused by DC motors and spark ignition systems. We simulated three types of DC-motor noise sources: HVAC fan, fuel pump and radiator fan. We used actual DC motors taken from vehicles for these simulations. For the spark ignition noise simulation, we used an EH Research Labs 139B pulse generator. We measured the peak amplitude of this broad-band noise with the use of 120 kHz bandwidth. (The bandwidth for the measuring equipment is specified in the SAE J551/4 test. See Table 3 in Appendix B.)

HVAC fan noise

A Dodge HVAC fan and a Dodge radiator fan were used in this bench-top test. The fans were put inside the metal chamber while we measured the noise level. Only the HVAC fan was found to be noisy; the radiator fan was extremely quiet. The reason why the radiator fan has low noise, even though it has two DC motors, is that it has filters installed at the back of the motors. No further use was made of the radiator fan in our tests.

Because of the inherent random property of fan noise, we cannot give the exact waveform of the noise. Although it has a large quasi-periodic peak about every 1700 μs, the peak value and the period are not stable. Figure 4 is one sample of the HVAC fan DC motor noise waveform captured by the HP 54616B oscilloscope.

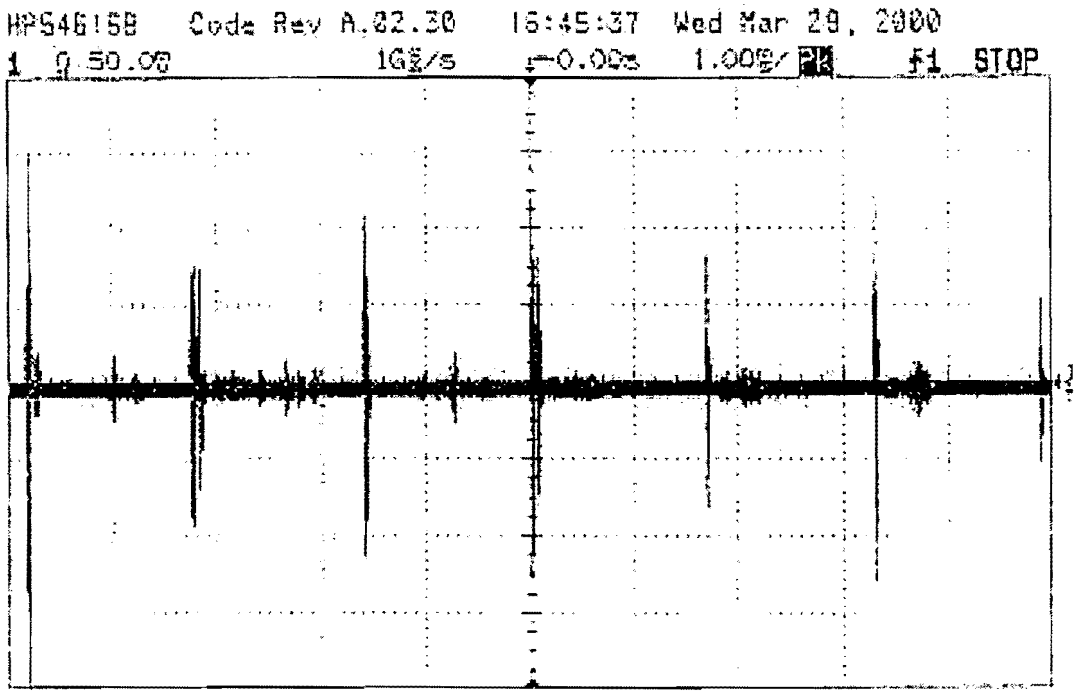


Figure 4. Sample waveform of noise from HVAC fan

The random property of the fan noise suggested that a statistical analysis was needed, and a test was performed using a computer program. The HVAC fan was run by battery inside the metal chamber. A current probe was connected to the R & S ESS EMI receiver to measure the peak amplitude of the fan noise. The ESS receiver was connected to a computer through IEEE cable, and 1000 data points of fan noise peak amplitude were captured by a LabView program. The captured 1000 data points are shown in Figure 5. It takes 2 seconds of measurement time to get each point. Horizontal and vertical axes of the figure indicate time in seconds and amplitude of the HVAC fan noise in dBμV, respectively. We used peak detection at a frequency of 47.02 MHz with 120 kHz bandwidth for this measurement. The speed of our fan is about 2700 rpm at 13 volts. A Stroboscope was used to measure the speed.

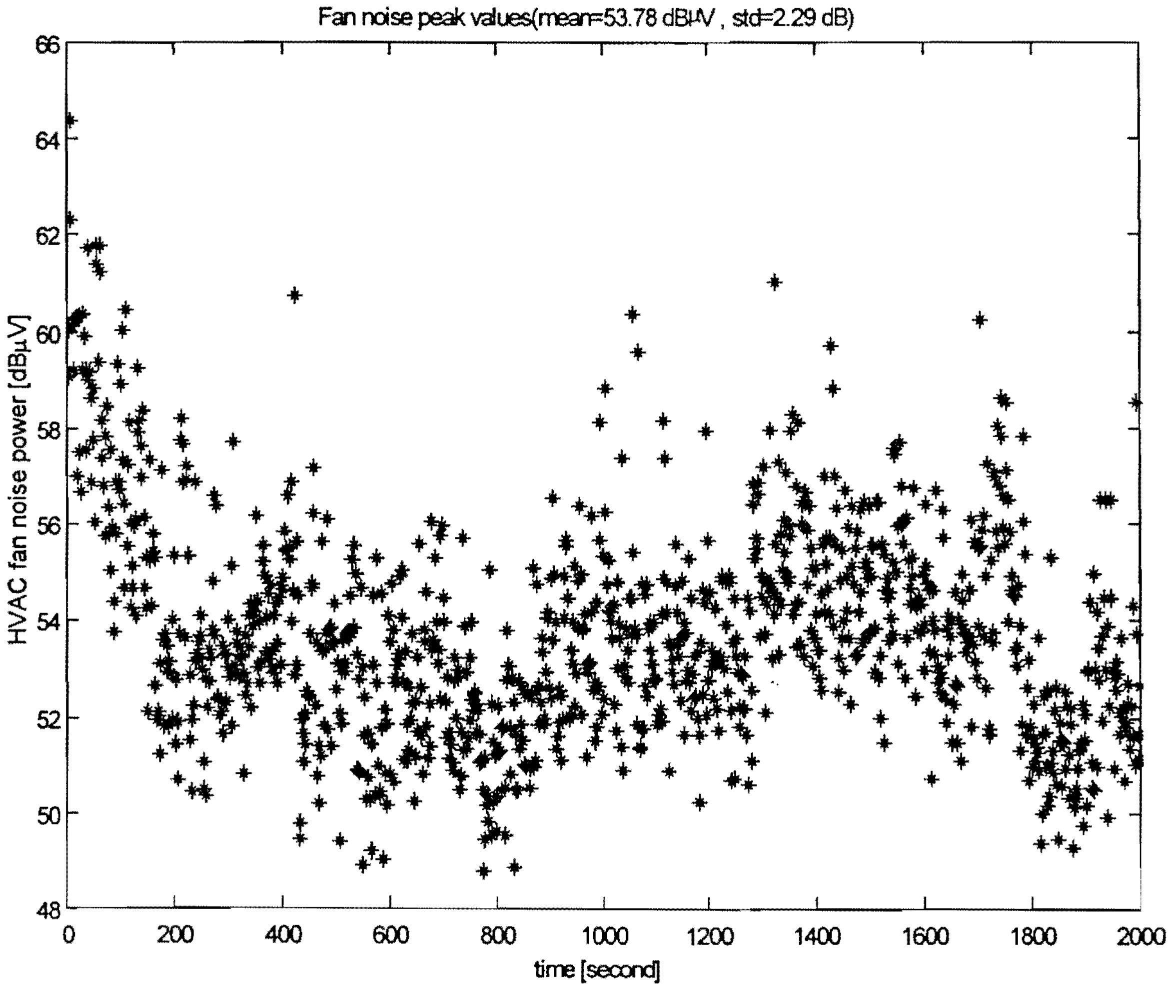


Figure 5. 1000 data points of fan noise peak amplitude
(2 s measurement time, 120 kHz BW)

The average of these 1000 data points of HVAC fan noise power was 53.78 dBμV, and the standard deviation was 2.29 dB. Perhaps the first hundred data points do not exactly represent fan noise because this portion of the data is decreasing while the later part is relatively stable. The decreasing may be just an initial transient effect, so we looked at the last four hundred values only. For these the mean value of the fan noise peak amplitude is 53.89 dBμV, and the standard deviation is 2.04 dB.

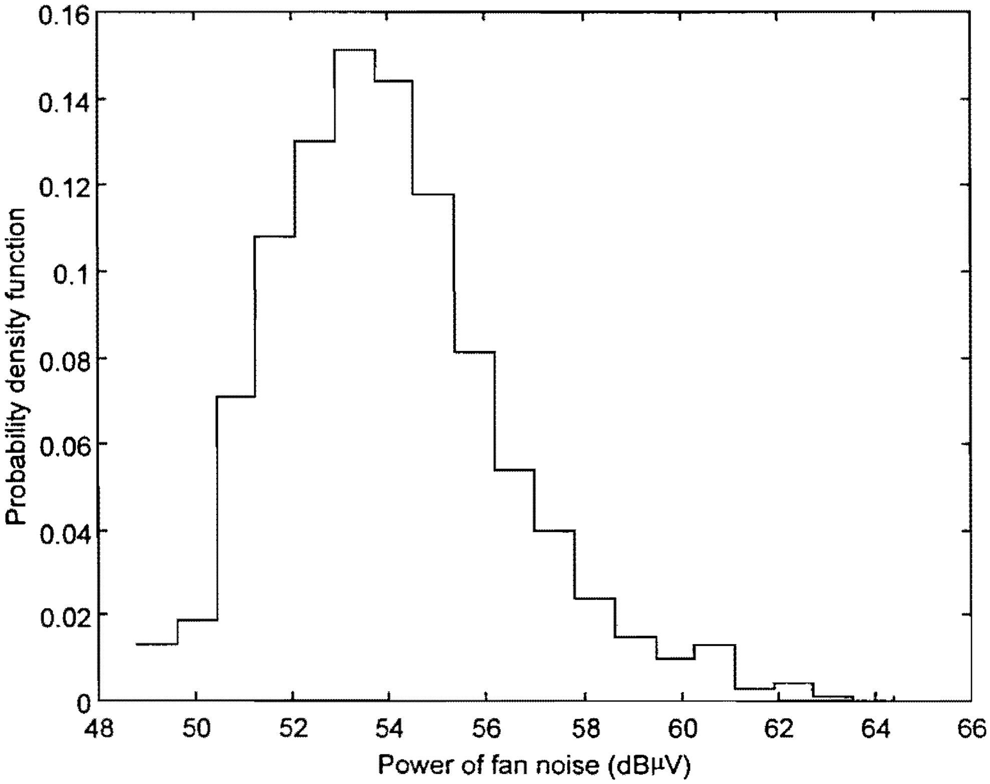


Figure 6. Probability density function of fan noise peak amplitude
(Mean : 53.78 dBμV, std dev : 2.29 dB)

Figure 6 shows the probability density function of these 1000 data points. From the figure you can see that most of the data are located between about 52 and 56 dBμV. Hence, we can say fan noise has random behavior, but it is fluctuating within a ± 2 dBμV range of its average value.

SINAD test for the HVAC fan noise

The bench-top setup shown in figure 2 allows us to measure the peak amplitude value of one or more noise sources while a signal with the noise produces a 12 dB SINAD reading. We adjusted the fan noise attenuation to make 12 dB SINAD, and we read the peak amplitude of the fan noise. Each EMI receiver read slightly differently, however they showed good agreement. Table 3 gives us a brief comparison of the fan noise peak value readings of the three different receivers. A Motorola *MaraTrac* radio was used for these tests.

Table 3. HVAC fan noise peak amplitude reading from three different receivers (for 12 dB SINAD)

Rohde & Schwarz ESS receiver	Rohde & Schwarz ESVP receiver	Schaffner SCR 3101 receiver
50 ~ 55 dBμV	48 ~ 53 dBμV	43 ~ 58 dBμV

Fuel pump noise

Fuel pumps can make as much broad-band noise as fans. We employed two fuel pumps for simulation purposes. One is used on Dodge trucks and the other is made by

AutoZone™ and used on GM trucks. The fuel pumps were mounted in metal containers filled with Stoddard solvent. The pressure of the pumping is measured during every test. The usual setting of pressure was 49.22 psi, which is the setting used on Dodge trucks. For the AutoZone™ fuel pump we set the pressure at 10.5 psi.

Like fan noise, fuel pump noise is random. Hence, We have done the same statistical analysis. Figures 7 and 8 show the probability density functions of fuel pump noise peak amplitude for the two pumps.

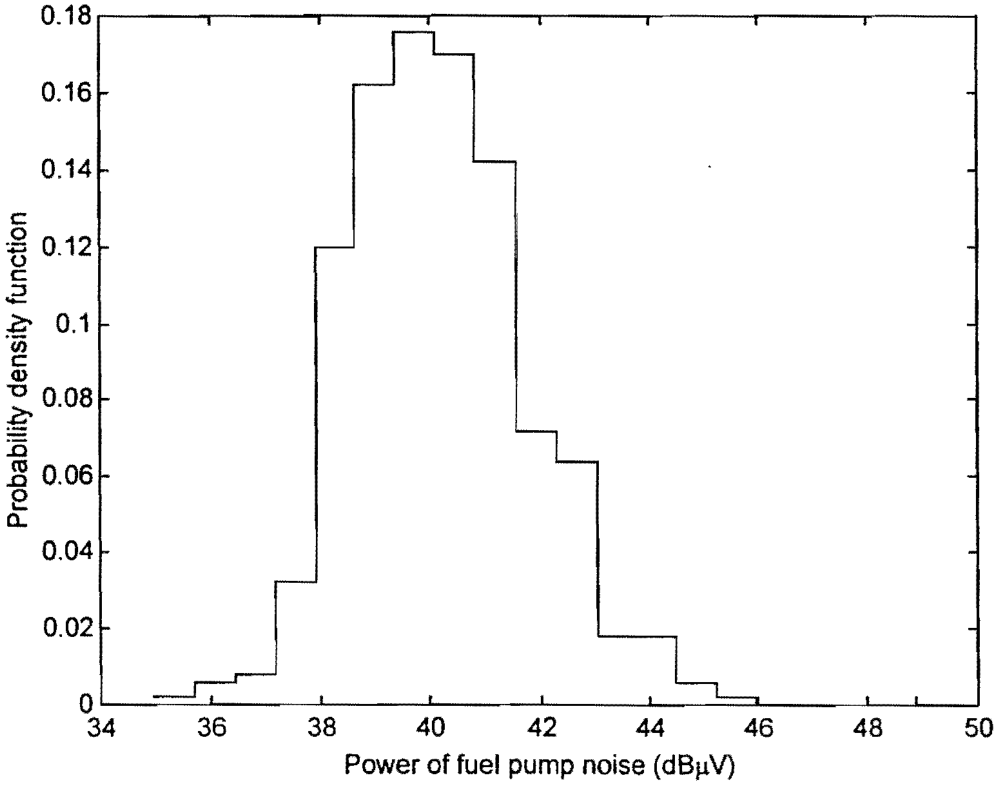


Figure 7. Probability density function of AutoZone™ fuel pump noise peak amplitude (Mean : 39.93 dBμV, std dev : 1.58 dB)

The AutoZone™ pump makes less noise than the Dodge pump by 15 dB, and the Dodge pump has a bigger standard deviation. From the figures, you can see that the fan noise has a wider distribution than the AutoZone™ fuel pump but narrower than the Dodge fuel pump, and the mean value of the fan noise is more like the Dodge fuel pump than the AutoZone™ fuel pump. A comparison of probability density functions of these three DC motor noise sources is plotted in Figure 9.

The Dodge fuel pump noise peak amplitude for 12 dB SINAD turned out to be around 44 dBμV. The Motorola *MaraTrac* radio was used for the measurement. The measurement time and bandwidth were 2 s and 120 kHz, respectively.

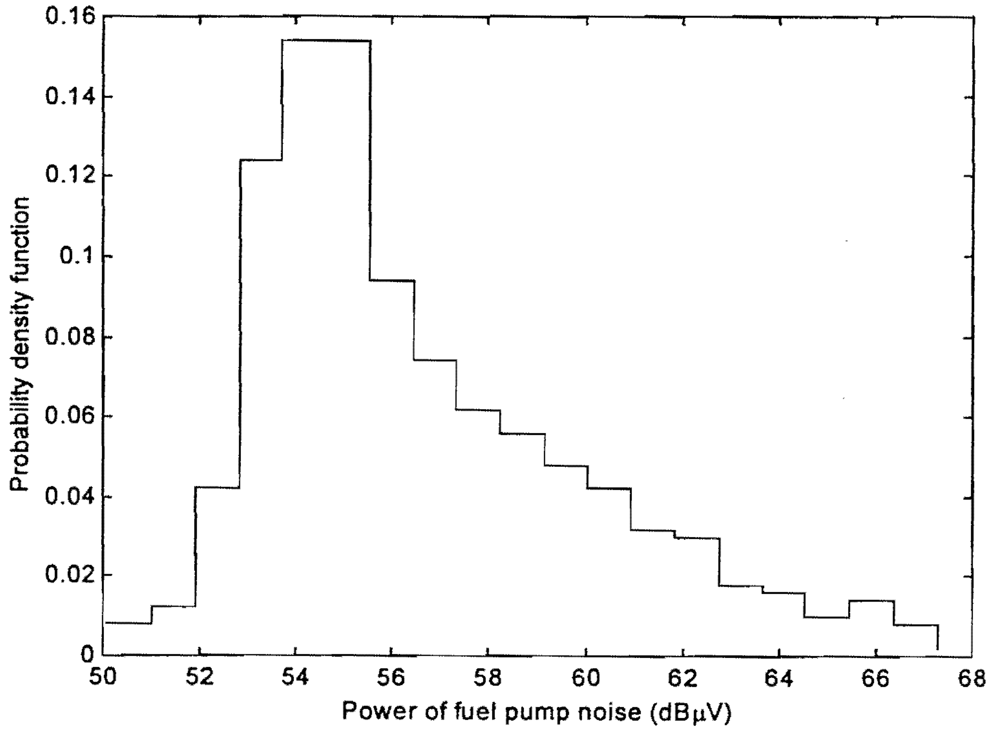


Figure 8. Probability density function of Dodge fuel pump noise peak amplitude (Mean : 56.31 dBμV, std dev : 3.27 dB)

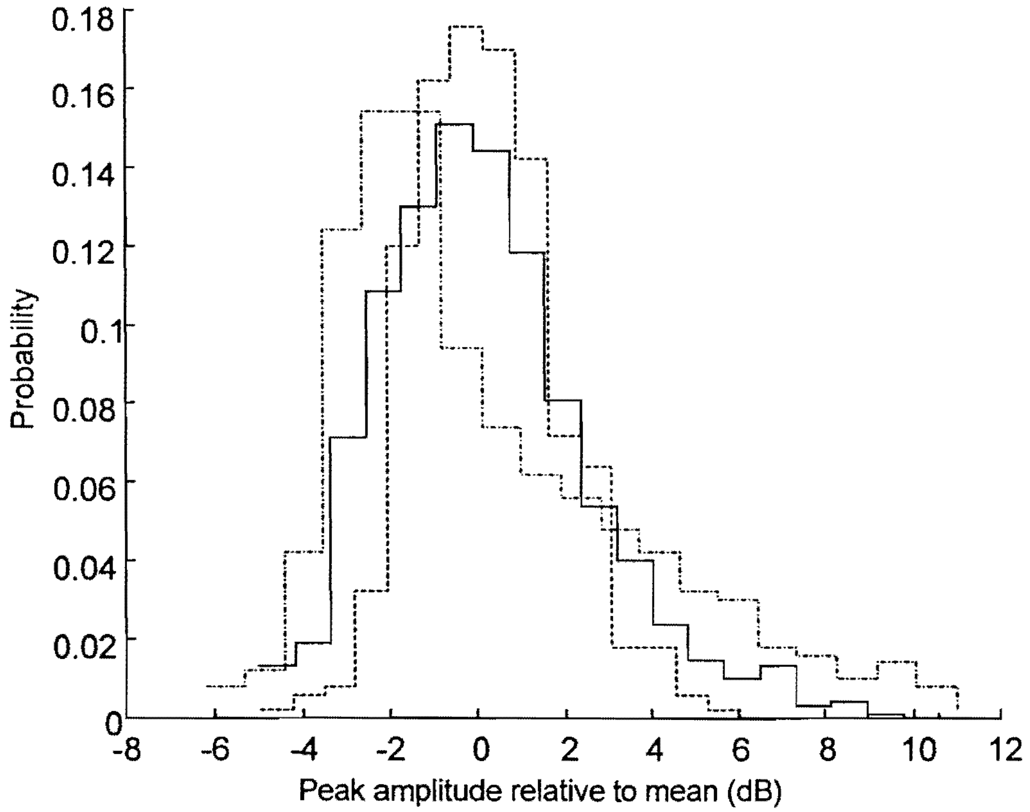


Figure 9. Probability density functions of three DC motors

(—— : HVAC fan, –·–·: Dodge fuel pump, ----- :AutoZone™ fuel pump)

Spark-ignition noise in gasoline engines

The next broad-band noise source is spark ignition. Figure 1 in chapter I shows the spark ignition system in a gasoline engine vehicle. The period of the spark ignition pulses can be derived from the engine speed. If a 6-cylinder engine is used and the speed at idle is 1000 rpm, there are six spark pulses in each turn of the crankshaft, that is, 6000 pulses in a minute, and thus 100 pulses in a second. Therefore, the period of the pulses is 10 ms. Assuming the ignition system has a distributor, sparks occur there in addition to at the spark plug. The interval between pulses from distributor and spark plug was measured from a vehicle as 10 μs. We set the pulse width as 10 ns, and the ringing pattern caused by the antenna circuit was simulated by use of a band-pass filter. The simulated pulse of spark ignition noise is captured by the HP 5416 B oscilloscope and shown in figure 10.

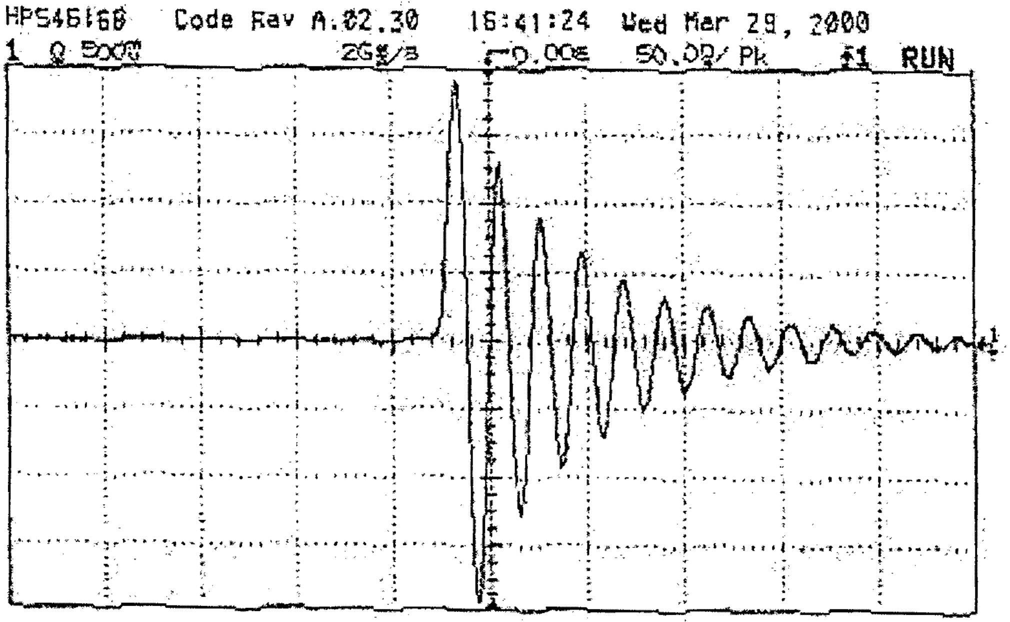


Figure 10. Simulated spark-ignition noise in gasoline engine vehicle
(one pulse)

We set the pulse width as 10 ns, second pulse delay as 10 μs and pulse period as 10 ms.

Figure 11. Rectangular pulse

Assuming for simplicity simple rectangular pulses, rather than the ringing pulses of Figure 10, we can easily calculate the Fourier transform. To begin let us consider one rectangular pulse itself (see Figure 11). The Fourier transform of a rectangular pulse is a sinc function as shown below.

$$X_1(\omega) = F(x_1(t)) = \int_{-\infty}^{\infty} x_1(t)e^{-j\omega t}dt = A\int_{-0.5}^{0.5} e^{-j\omega t}dt = j\frac{A}{w}[e^{-j\omega 0.5} - e^{j\omega 0.5}] = j\frac{A}{\omega}\left[-2j\sin(\omega 0.5)\right]$$

$$= A\frac{\sin(\pi f)}{\pi f} = A\mathrm{sinc(f)} \qquad \text{where } \omega = 2\pi f$$

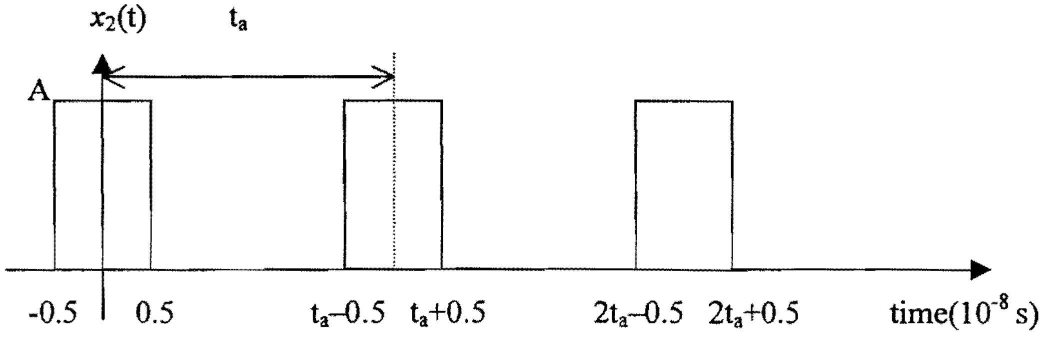


Figure 12. Periodic rectangular pulse

If the rectangular pulse is periodic, as shown in Figure 12, the Fourier transform needs to be modified as shown below.

$$X_2(\omega) = F(x_2(t)) = \int_{-\infty}^{\infty} x_2(t)e^{-j\omega t}dt = A[\int_{-0.5}^{0.5} e^{-j\omega t}dt + \int_{\pm(t_a-0.5)}^{\pm(t_a+0.5)} e^{-j\omega t}dt + \int_{\pm(2t_a-0.5)}^{\pm(2t_a+0.5)} e^{-j\omega t}dt + \cdots]$$

$$= j\frac{A}{\omega}\left[e^{-j\omega 0.5} - e^{j\omega 0.5}\right]\left\{1 + e^{\pm j\omega t_a} + e^{\pm j\omega 2t_a} + \cdots\right\} = X_1(\omega)\left\{\sum_{k=-\infty}^{\infty} e^{-j\omega k t_a}\right\}$$

(by using of the Poisson formula $\sum_{k=-\infty}^{\infty} \delta(\omega - \frac{2\pi k}{T}) = \frac{T}{2\pi}\sum_{n=-\infty}^{\infty} e^{jn\omega T}$) [11]

$$= X_1(\omega)\frac{2\pi}{t_a}\sum_{n=-\infty}^{\infty}\delta(\omega - \frac{2\pi n}{t_a}) = X_1(\omega)\frac{1}{t_a}\sum_{n=-\infty}^{\infty}\delta(f - n\frac{1}{t_a})$$

$$= A\,\mathrm{sinc}(f)\frac{1}{t_a}\sum_{n=-\infty}^{\infty}\delta(f - n\frac{1}{t_a})$$ where k,n is integer.

The resulting Fourier transform of the single periodic rectangular pulse is shown in Figure 13. This corresponds to a distributorless ignition system. As you can see in the figure, the spectrum is formed of consecutive delta functions, which follow the envelope of the sinc function. Each delta function is separated by 100 Hz, so figure 13 is exaggerated to show the delta function and sinc function together. [12]

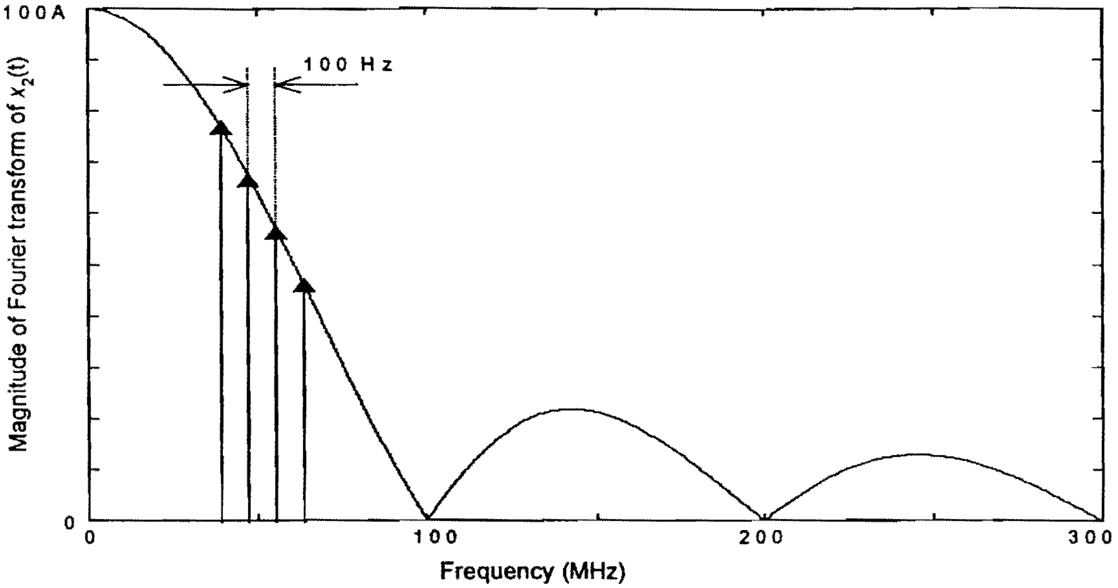


Figure 13. Fourier transform of periodic rectangular pulse (not to scale)

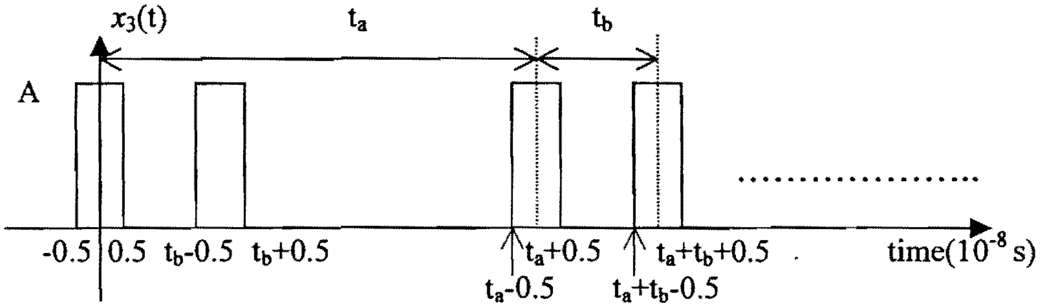


Figure 14. Periodic double rectangular pulse

Figure 14 shows the periodic rectangular pulse waveform, which corresponds to an ignition system with distributor. The Fourier transform is calculated below:

$$X_3(\omega) = F(x_3(t)) = \int_{-\infty}^{\infty} x_3(t)e^{-j\omega t}\,dt$$

$$= A\int_{-0.5}^{0.5} e^{-j\omega t}\,dt + A\int_{\pm(t_a-0.5)}^{\pm(t_a+0.5)} e^{-j\omega t}\,dt + A\int_{\pm(t_b-0.5)}^{\pm(t_b+0.5)} e^{-j\omega t}\,dt + A\int_{\pm(t_b+t_a-0.5)}^{\pm(t_b+t_a+0.5)} e^{-j\omega t}\,dt + \cdots$$

$$= X_2(\omega) + e^{-j\omega t_b}X_2(\omega) = X_2(\omega)(1+e^{-j\omega t_b}) = X_2(\omega)(1+\cos\omega t_b - j\sin\omega t_b)$$

$$= X_2(\omega)g(\omega t_b) = g(\omega t_b)X_1(\omega)\frac{1}{t_b}\sum_{n=-\infty}^{\infty}\delta(f - n\frac{1}{t_a})$$

$$= Ag(\omega t_b)\mathrm{sinc}(f)\frac{1}{t_b}\sum_{n=-\infty}^{\infty}\delta(f - n\frac{1}{t_a})$$

where, $g(\omega t_b) = (1+\cos\omega t_b - j\sin\omega t_b)$

The resulting graph is shown in Figure 15. The consecutive delta functions have an envelope given by the function g(ω t_b). Again, this graph is exaggerated to show every function in one picture. Actually, g(ω t_b) has 1000 peaks in each lobe of the sinc function, and each lobe of g(ω t_b) contains 1000 delta functions.

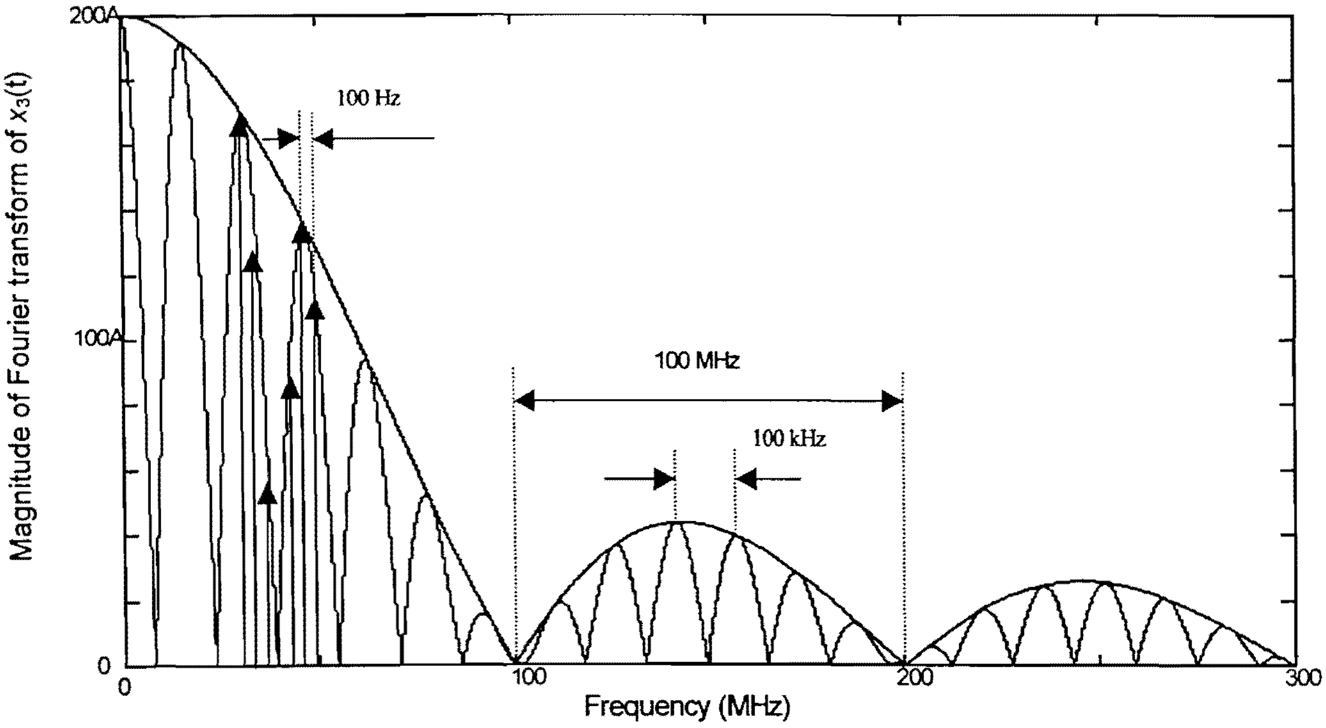


Figure 15. Spectrum of periodic double rectangular pulse (not to scale)

Somebody might ask whether we really need 120 kHz bandwidth for ignition noise amplitude measurement rather than 9 kHz bandwidth, which is used for narrow-band noise. The answer is definite. In a practical situation, there is always some jitter in the spectrum and in doing a peak amplitude measurement for an EMC test, you'd like to be able to make a single, accurate measurement. Using the 9 kHz bandwidth gives only a portion of a lobe of the 100 kHz periodic envelope, while using 120 kHz bandwidth gives an entire lobe. In view of the jitter, the 120 kHz bandwidth is preferred because the readings do not change from one measurement to the next. We verified this by experiments. We could get a stable peak value of the ignition noise with 120 kHz bandwidth, while we got an unstable peak value for 9 kHz bandwidth.

Light bar noise

Light bars do not come with new vehicles but are installed by TxDOT. The colored lights on the bars are used to provide warnings to motorists. The bars use tiny DC motors to rotate reflectors behind the lights. These motors are the noise sources in light bars.

We tested a light bar and two beacon lights at the lab. The beacon lights have a single flashing bulb and no motor. The light bar that we tested has four motors in it with filters installed on all motors. Three capacitors soldered at the back of each motor constitute the filter. We tested the light bar with and without the filters installed. The table shown below gives the data for the light bar and beacon lights (Table 4).

Table 4. Light bar and beacon light noise amplitudes

DBμV	Light bar With filter	Light bar Without filter	Beacon light I*	Beacon light II**
Peak amplitude	7.6 ~ 14.1	29 ~ 37	42 ~ 47	62 ~ 65

* : blinking light

** : blinking light with audible tone

From the table we found the light bar noise is not sufficiently high (not above the 40 dBμV limit) to fail the Tex-899-B test either with or without filters installed. We couldn't even reduce the SINAD value below 28 dB with this light bar. The two beacon lights have much higher peak amplitudes but just make 24 dB SINAD because their pulse rate is extremely low, on the order of a second. The measurement was made at 47.02 MHz with 120 kHz bandwidth, and the measurement time was 2 s. The ESVP receiver was used.

Narrow-band noise in vehicles

CW RF noise typically comes from harmonics of the oscillator used in digital circuitry. A sine wave without modulation at the same frequency that is used in the TxDOT radio under test was generated by the R & S CMS54 radio communication service monitor for the CW noise simulation. Since we were using a pure sine wave, it would measure the same with an average detector as with a peak detector. This type of noise is narrow-band and it can be measured at 9 kHz bandwidth rather than 120 kHz.

SINAD test for the spark-ignition noise

We were not able to reduce the SINAD value by increasing the peak amplitude of spark ignition noise. Since the noise blanker in the radios works very well for the ignition noise, even at the maximum output of the ignition noise generator, which is 88 dBμV in 120 kHz bandwidth, we couldn't make any change in the SINAD value.

FM signal

The FM signal is generated by a Fluke 6060B signal generator. Tex-899-B specifies the FM signal to be set on-channel and modulated with a 1 kHz sine wave tone at ± 3.3 kHz deviation. The maximum amplitude of the FM signal should be no more than 1 μV (-107 dBm) in order to obtain a 12 dB SINAD reading. These values were used for all the SINAD tests in our bench-top studies.

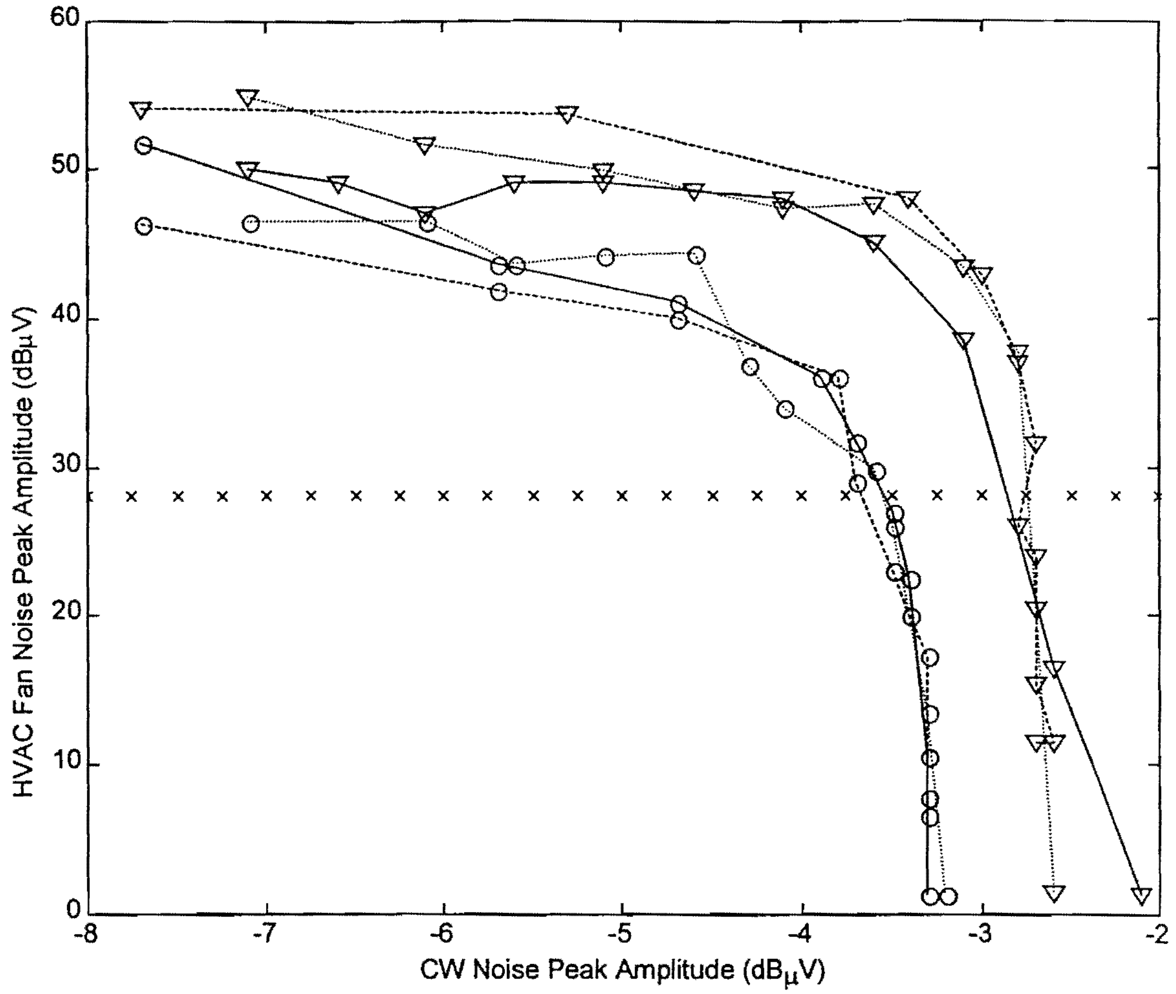
SAE J551/4 test and TxDOT Tex-899-B test

The Tex-899-B test specifies an RF emission limit of 12 dB SINAD at the audio output of the TxDOT radio while a 1 μV FM signal is present. This is different from the J551/4 test, which specifies the RF emission limit directly at the antenna without an FM signal present.

To see the correlation between the two tests, first we send the 1 μV FM signal and a selected noise to the TxDOT radio, and then adjust the noise to obtain a 12 dB SINAD. Once we get the 12 dB SINAD, the power of the noise is measured at the radio input, which gives the J551/4 test limit corresponding to the Tex-899-B test limit.

Multiple noise sources (HVAC fan and CW)

Instead of using only one noise source, we added two, fan and CW, to the FM signal and then performed the SINAD test. Two directional couplers were used to combine the noise and signal. An amplifier and attenuator were used to adjust the power of the fan noise. First we set the fan noise value very low (0 dBμV) and then adjusted the CW noise to get the total combined noisy signal to make a 12 dB SINAD. Then we measured the peak amplitude of each noise at the radio input. This indicated the SAE J551/4 test value corresponding to the TxDOT limit. Then we repeated the measurement for gradually increased HAVC fan noise, until the fan noise reached its maximum possible value (near 60 dBμV). Noise amplitudes were measured at 47.02 MHz by the Rohde & Schwarz EMI receiver with peak detection mode. The same 2 s measurement time was used, but different measurement bandwidths were used for the two noise sources. A 120 kHz bandwidth was used for the broad-band noise measurement, and 9 kHz bandwidth was used for the narrow-band noise measurement. The same test was repeated three times to check repeatability, and this resulted in three curves for each radio. There are nine radios of five different models in our laboratory, but we concentrated on just two radios, since these two radios are the most common ones in the TxDOT vehicle fleet. These are the GE RANGR™ and the Motorola *MaraTrac.* Figure 16 shows the SAE J551/4 test values for the two radios when the noise is at the limit of the Tex-899-B test. In other words, the curves in Figure 16 show the relationship of the peak noise amplitudes which results in a 12 dB SINAD with an FM signal. As the HVAC fan noise gets smaller, the CW noise becomes larger. The X-line indicates the current limit of the SAE J551/4 test for broad-band noise. The current limit for narrow-band noise of the SAE J551/4 test is 0 dBμV. Hence it's not shown in this graph.



∇ : Motorola *MaraTrac*.
O : GE RANGR^{TM}.
× : Current limit used for SAE J551/4 test.

Figure 16. SAE J551/4 test values for the two radios primarily used by TxDOT

As you can see, the two limits, the one corresponding to Tex-899-B and the current J551/4 one, don't agree with each other. The current J551/4 limit for broad-band should be increased from 28 dBμV up to 40 dBμV (or even to 50 dBμV if considering only the *MaraTrac*) to prevent the vehicle which makes noise between 28 dBμV and 40 dBμV from failing J551/4 while passing Tex-899-B. And for narrow-band, the limit should be decreased to about -3 dBμV to make J551/4 agree with Tex-899-B. This is reasonable, because Tex-899-B specifies that the maximum received FM signal should not be more than 1 μV (= 0 dBμV), and of course no radio can work with noise equal to signal power.

Multiple noise sources (HVAC fan and fuel pump)

We also performed a SINAD test for the HVAC fan and fuel pump together. We used the Dodge fuel pump for this test. Both of the DC motor noise sources were put inside of the metal screen box, and the current probe was connected to the Schaffner SCR 3101 EMI receiver and Motorola *MaraTrac* radio by a directional coupler. An amplifier and attenuator were connected before the directional coupler to adjust the power of the noise from the DC motors. A 120 kHz bandwidth and 2 s measurement time were used for this measurement. The results are shown in Table 5.

Table 5. Comparison of peak noise amplitudes for HVAC fan, fuel pump, and HVAC fan plus fuel pump

	HVAC fan	Fuel pump	HVAC fan + Fuel pump	HVAC fan	Fuel pump	HVAC fan + Fuel pump
Battery voltage	12.55	12.70	12.40	12.57	12.70	12.38
SINAD (dB)	8 ~ 15.5	11 ~ 13	10 ~ 14	10 ~ 14	11 ~ 13	9 ~ 15
Attenuation (dB)	6	6	11	4	8	10
EMI level (dBμV)	45 ~ 52 (48.5)*	41 ~ 48 (44.5)	42 ~ 48 (45)	49 ~ 53 (51)	40 ~ 48 (44)	40 ~ 46 (43)

Note*: average value of the peak amplitude readings

We conducted the test twice to check the repeatability of these values. We found that the HVAC fan noise peak amplitude for 12 dB SINAD went down by about 6 dB when we used both the fan and fuel pump simultaneously. In the previous section we discussed our new limit of the SAE test for broad-band noise. We saw that the fan noise peak amplitude for the 12 dB SINAD is around 48 to 55 dBμV, but if we add fuel pump noise, which is always present while an engine is running, this value will decrease about 6 dB. For this reason we choose the 40 dBμV as our new limit for broad-band noise.

Multiple noise sources (HVAC fan and spark ignition)

Instead of using fuel pump noise we added spark-ignition noise to the FM signal with HVAC fan noise. Our simulated spark-ignition noise, generated by the EH pulse generator, has the following specifications: double-pulse mode, 10 ns pulse width, 10 μs second pulse delay and 10 ms pulse period. In this particular test we connected the ignition pulses directly with the fan noise without using the band-pass filter in order to get more power for the ignition noise. The results are shown in Figure 17. The Motorola *MaraTrac* radio was used. Figure 17 will help you to see the distribution of fan noise peak amplitude for 12 dB SINAD at each ignition noise level. The solid line connects the mean value at each ignition noise level. A trend from lower left to upper right is seen in the data in Figure 17, although it is very slight, about 5 dB in fan noise. The reason for this trend is not known, and in fact it is not always repeatable, one test having produced an opposite trend.

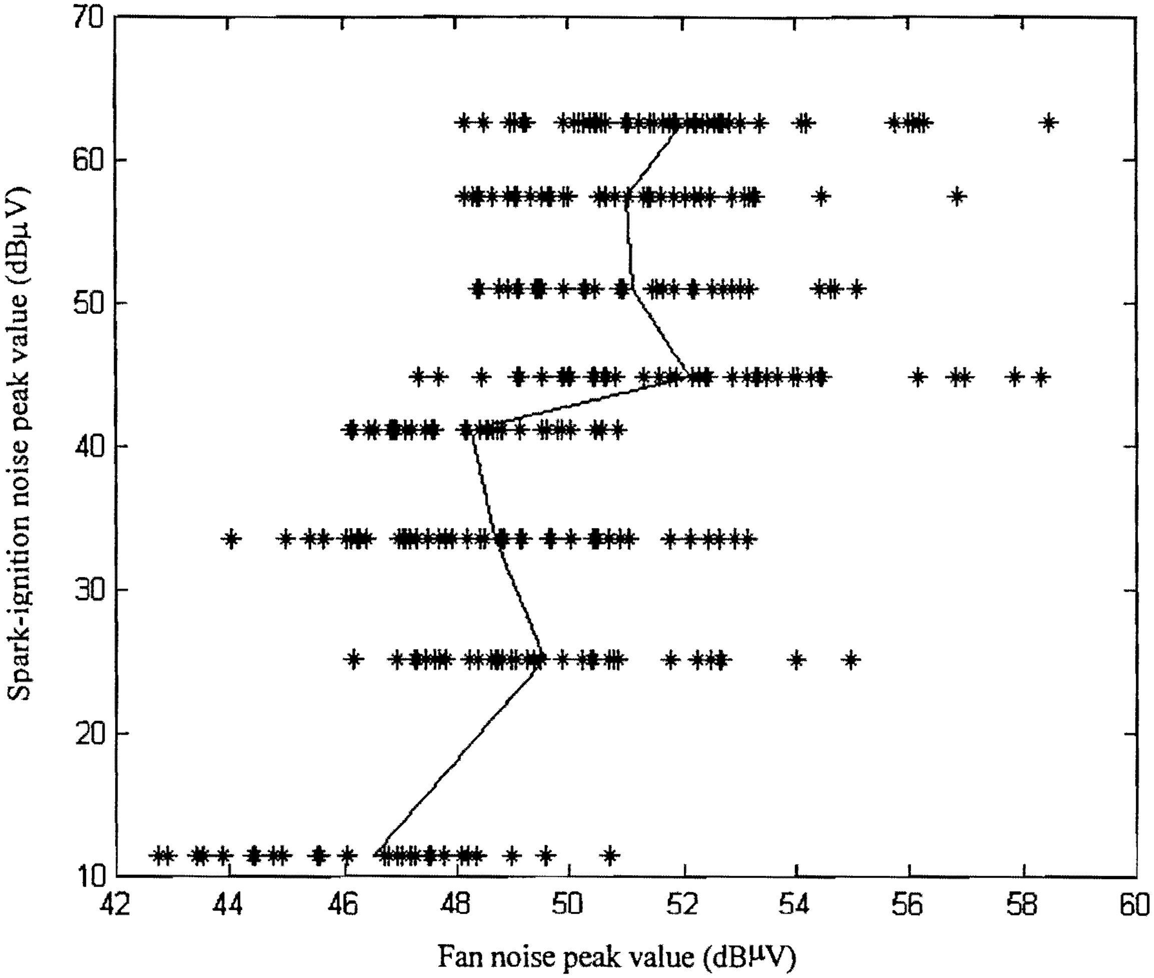


Figure 17. Fan and spark-ignition noise for 12 dB SINAD

Multiple noise sources (HVAC fan, spark ignition, and CW)

A question arising in regard to figure 16 is whether the presence of spark ignition noise, in addition to the fan noise and CW noise, would change the shape of the curves. This is a matter for practical concern since in a gasoline-powered vehicle with the engine running, the spark ignition noise would be present.

To investigate this situation we connected three noise sources: HVAC fan, spark ignition, and CW, in our test setup and performed the usual 12 dB SINAD test. We used the band-pass filter with the ignition noise, a Motorola *MaraTrac* as the TxDOT radio, and three directional couplers to combine noise and signal. The results are shown in figure 22.

Each curve in the figure corresponds to a particular value of ignition noise. If we look at the left end of the curves, there does seem to be a trend – as the ignition noise is increased, the fan noise must be lowered – but there is considerable random variation also. We find this data, like the data in Figure 17, to be somewhat inconclusive as far as the effect of ignition noise is concerned. And we do not feel justified in trying to use this data to adjust the 40 dBμV limit that we established on the basis of table 5.

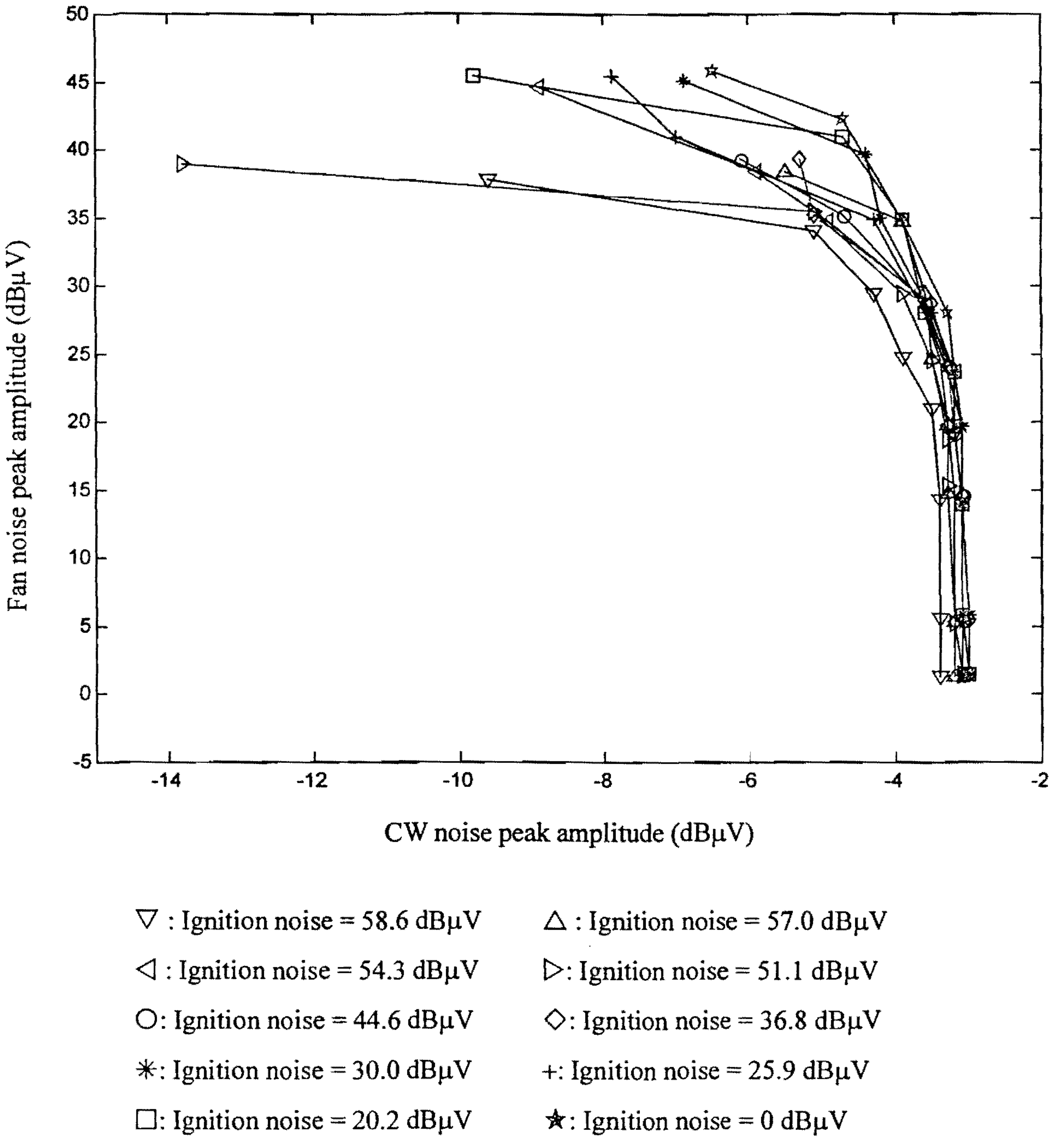


Figure 18. Fan and CW noise for 12 dB SINAD with specific ignition noise present.

Noise blankers in TxDOT radios

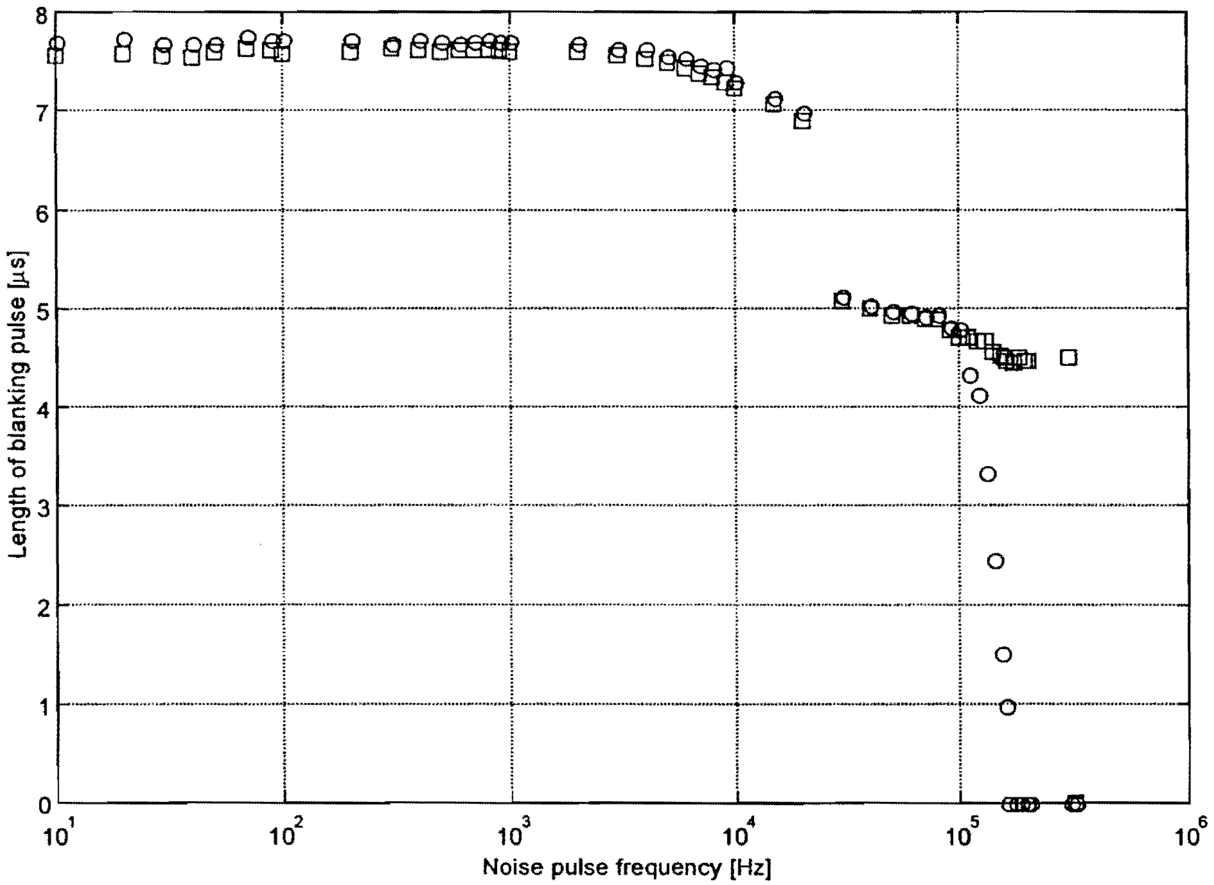
Noise blanker circuits are installed in the TxDOT radios. The GE RANGR™ circuit is turned on and off by connecting two jumper wires, while the Motorola *MaraTrac* can be turn on and off by a switch. The noise blanker circuits in these radios are very effective for spark ignition noise, somewhat effective against noise from DC motors such as fuel pumps and HVAC fans, and ineffective for CW noise and thermal noise [6].

The noise blanking circuits of the two radios work similarly but against DC-motor noise the Motorola *MaraTrac* is somewhat more effective. A brief summary of the characteristics of the noise blankers in both radios is shown in Table 6. The characteristics were found by using an EH pulse generator as the noise input to the radio.

Table 6. Laboratory test of noise blanker performance of TxDOT radios
(Pulse length of noise pulses = 10 ns)

Blanker Characteristic	Radio	
	MaraTrac	RANGER™
Type of circuit	IF detect and IF blank	IF detect and IF blank
Blanking disable / enable	Push button	Internal jumpers
Length of blanking pulses	8 μs	2 μs
Minimum amplitude of noise pulses for blanking	3 mV	2 mV
Maximum amplitude of noise pulses for blanking	> 7 V	> 7 V
Pulse-rate shut down	300 kpps	250 kpps

For the Motorola *MaraTrac* the length of blanking pulses depends on the amplitude and repetition rate of the noise pulses. Figure 19 illustrates the relationship of length of blanking pulse and noise pulse repetition rate (frequency).



o : Measured while decreasing the frequency.
□ : Measured while increasing the frequency.

Figure 19. Length of blanking pulse vs. frequency of noise pulse for *MaraTrac* radio

You can see that the noise blanker in this radio, Motorola *MaraTrac*, is totally turned off when the noise frequency reaches about 300 kHz. However the noise blanker in the GE RANGR radio works in a somewhat different way. As we increase the frequency of noise, the percentage of blanked noise is reduced, and it seems that the blanker is not totally turned off no matter what the noise frequency is. This noise blanker property is illustrated in Figure 20.

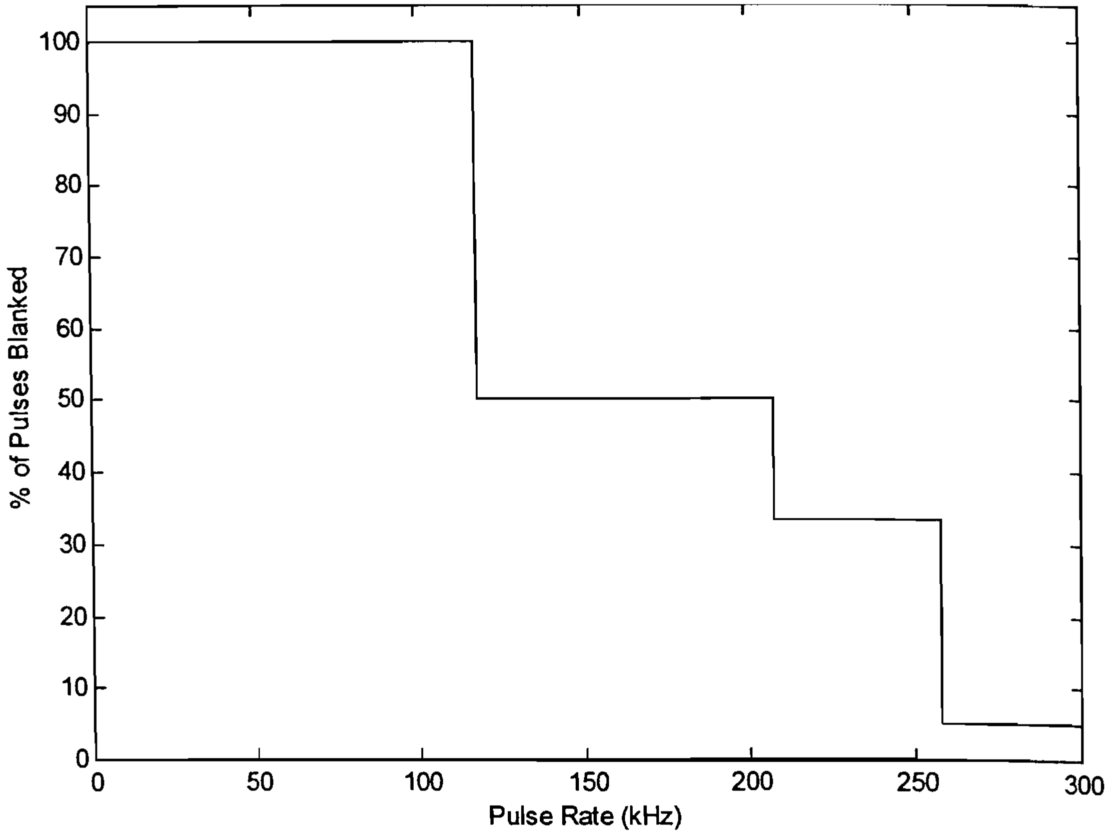


Figure 20. Noise blanker performance of RANGR^{TM} radio

We also applied very large pulses to see if they would get past the blanker and produce noise in the radio output. Our short, 10 ns pulses, produced no noise, even with amplitude up to 7 V. But when we tried larger pulse lengths, we were able to achieve a low SINAD value. The data in the following table was measured at a fixed noise repetition rate, 15.15 kHz (66 µs period). We adjusted the length of the noise pulse so that we could achieve a 12 dB SINAD. As we increased the pulse length of noise, we needed to reduce the amplitude so that we could maintain a 12 dB SINAD. We repeated the test to see the consistency of the values. The amplitude in dBμV was measured by peak detection on the Rohde & Schwarz ESVP receiver at 120 kHz BW with a 2 s measurement time. We used the Motorola *MaraTrac*. The data are shown in Table 7.

Table 7. Noise peak amplitude vs. noise pulse width (12 dB SINAD).

Amplitude (V)		0.8	1	1.5	2	2.5	3	3.5	3.6
Amplitude(dBμV)		48.7	50.0	54.4	56.6	59.2	60.9	60.9	61.8
Pulse length (μsec)	Trial #1	33	16	9	3.2	2.5	2.3	2.1	1.9
	Trial #2	33	19	10	3.2	2.8	2.5	2.1	2.1

66 μs pulse period (15.15 kHz)

The noise blanker makes a blanking pulse at the leading edge of the noise pulse with a 1 μs delay. If the length of the noise pulse is shorter than 8 μs (2 μs for GE RANGR$^{\text{TM}}$) the blanker makes as many blanking pulses as noise pulses. However it makes twice as many blanking pulses as noise pulses, if the noise has a longer pulse length than that of the blanking pulse. This is because the blanking circuit triggers not only at the rising edge but also at the falling edge of a noise pulse. That is not very good because at the falling edge the blanking pulse cuts out the signal instead of the noise if the noise pulse has a longer pulse length than that of the blanking pulse. Examples are shown in Figures 21 and 22.

The big pulses are blanking pulses and the small pulses mark the edges of a noise pulse. The blanking pulses were captured from the radio circuit board, but the noise pulse was captured from a hybrid junction ahead of the radio antenna port. Since the hybrid junction has limited frequency range, its output just shows the edges of the noise pulse, which had a pulse length of 20 μs in figure 20 and 4 μs in Figure 21.

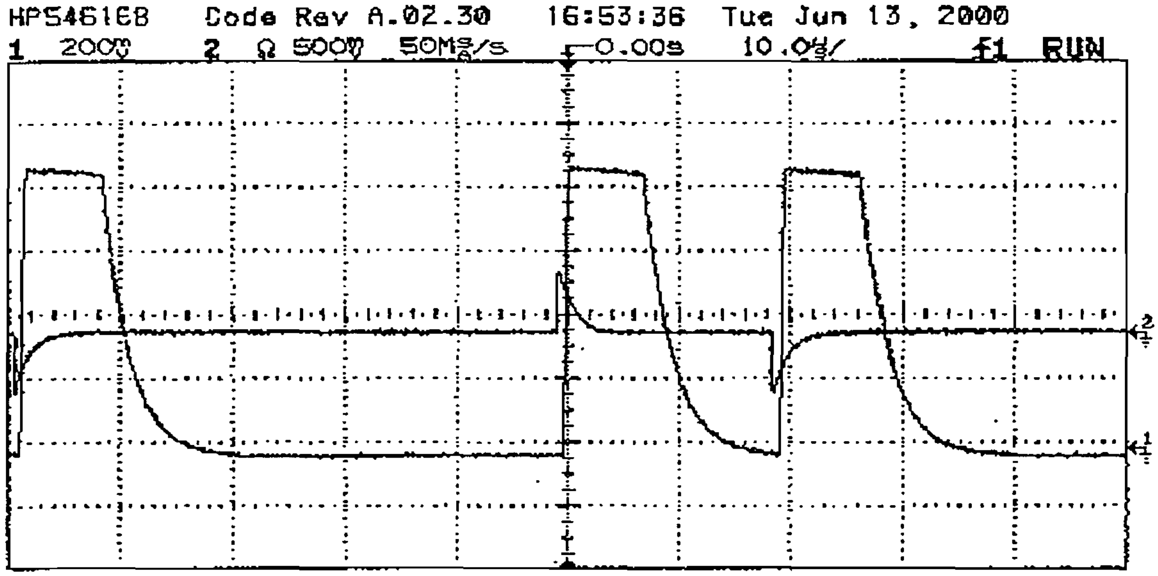


Figure 21. Noise pulses and blanking pulses of Motorola *MaraTrac*

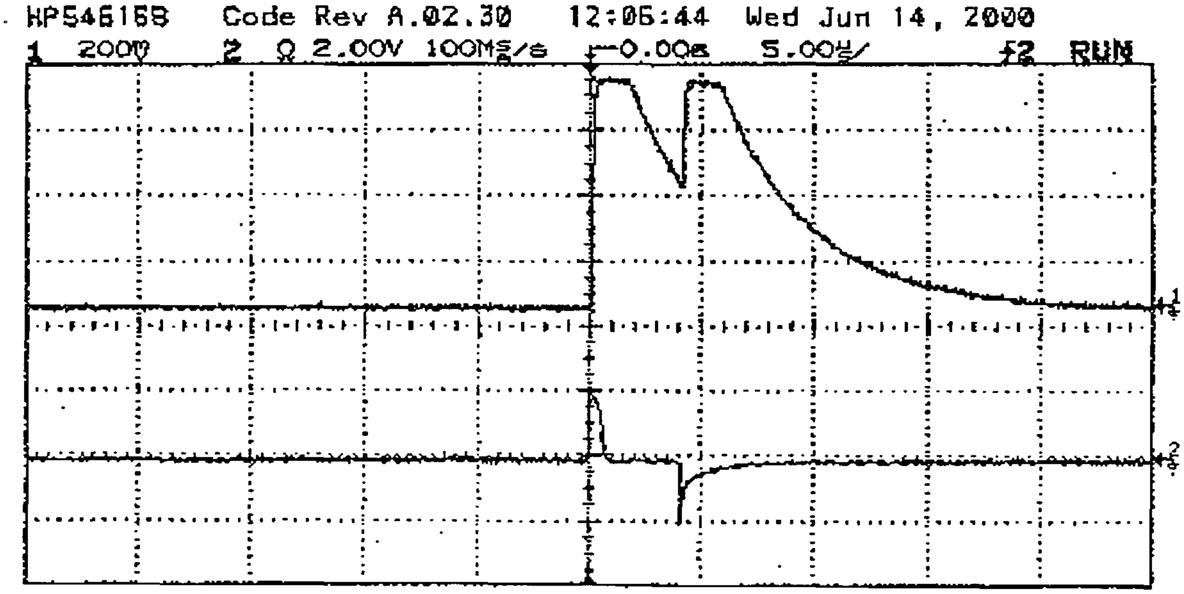


Figure 22. Noise pulses and blanking pulses of GE RANGR™

As part of our study of noise blankers, we also conducted the TxDOT acceptance test for noise blanker operation. Of course both the *MaraTrac* and RANGR^{TM} radio passed this test [13].

CHAPTER IV

TESTS ON TxDOT TRUCKS

TxDOT vehicles

Not all the TxDOT vehicles have the installed two-way radio system, however most of their trucks do. We tested two trucks; both were '99 Dodge Ram 1500s and could run on either gasoline or propane. A Motorola *MaraTrac* radio was installed behind the seat and the radio control box with microphone and speaker was installed under the cigarette lighter. The radio was connected to power on with the vehicle key turned on. There were two switches that were not installed by the manufacturer. These were the alternate fuel (propane) switch and the light bar switch. Manufacturers do not test these two after-market products, but they might produce noise, so we included them in our testing. We tested the vehicles for J551/4 as well as Tex-899-B compliance.

Table 8. Receiver sensitivity and ambient noise level (SAE test setup)

Receiver sensitivity	BW : 10 kHz		BW : 120 kHz	
	Peak	Avg	Peak	Avg
Pre-amp on, 0 dB atten	-11~ -10.5	-23.3	0.6 ~ 1.5	-12.5
Pre-amp off, 0 dB atten	-3.6 ~ -1.9	- 15.7	8.6 ~ 9.7	- 4.7
Ambient noise level	BW : 10 kHz		BW : 120 kHz	
	Peak	Avg	Peak	Avg
Pre-amp on, 0 dB atten	-6.4 ~ -5.8	-18	5.4 ~ 6.1	-7.2
Pre-amp off, 0 dB atten	-2.5 ~ -1.4	-14.5	9.7~ 10.1	-3.5

Table 8 gives the J551/4 ambient noise level of the site where we performed both tests. The ambient noise levels were read from the Rohde & Schwarz ESVP EMI receiver, which was directly connected to the magnetic-mount antenna on top of the vehicle roof. The receiver sensitivity is the internal noise level of the receiver, which we measured with a 50 Ω load at the input of the receiver. The scanning frequency was 47.18 MHz.

To get reliable data for the SAE J551/4 test, the measurement system noise floor should be 6 dB lower than the limit, which means we need –9 dBμV for narrow-band and 34 dBμV for broad-band noise (peak). Our receiver meets these conditions but our field site, on the day of testing, did not meet the narrow-band condition (-6.4 ~ -5.8 vs. –9 dBμV). However, the site was much quieter than the Texas Tech University campus, which has an ambient background noise level of 2 dBμV and 42 dBμV for narrow-band and broad-band noise, respectively.

The ambient noise level and receiver sensitivity were measured by means of the Tex-899-B test method also and are shown in Table 9.

Table 9. Receiver sensitivity and ambient noise level (TxDOT test setup)

	Mode 6 47.02 MHz	Mode 1 47.18 MHz	Mode 5 47.34 MHz
SG_R Receiver sensitivity	-12 dBμV		
SG_L 12 dB with load	8 dBμV		
SG_A 12 dB with antenna	12.3 dBμV	12.3 dBμV	12.3 dBμV
$SG_{AL}=SG_A-SG_L$	4.3 dB	4.3 dB	4.3 dB
$SG_E=SG_{AL}+SG_R$	- 7.7 dBμV	- 7.7 dBμV	- 7.7 dBμV

In this test, the Rohde & Schwarz radio communication service monitor works as signal generator and SINAD meter at the same time. The receiver sensitivity (SG_R) is just the amplitude of the signal generator while it is connected to the TxDOT radio and adjusted so that the SINAD meter is reading 12 dB. Receiver sensitivity with 50 Ω load (SG_L) is measured by the same method except for using the 3-port directional coupler between generator and radio. See Appendix A for a diagram of the connections. Since the directional coupler attenuates about 19.5 ± 0.5 dB from port 2 to port 1, it is reasonable that the SG_R and SG_L had 20 dB difference. The signal generator is connected to port 2 and port 1 goes to the TxDOT radio. The 50 Ω load is connected to port 3.

For checking the ambient noise level, the antenna on top of the vehicle is connected to port 3 while port 2 and port 1 are connected the same way as above. The ambient noise level at the field site was 12.3 dBμV. The difference (SG_{AL}) between SG_A and SG_L was 4.3 dB. The environmental noise level (SG_E) is calculated by $SG_E=SG_{AL}+SG_R$ and it should be lower than –6 dBμV. The environmental noise on the testing day was –7.7 dBμV at the frequency of 47.18 MHz

Perhaps because of their antenna differences, the ambient noise measurements on the two trucks were slightly different. Generally the 2-5649-G truck had about 1 dB less ambient noise, and it was true for the TxDOT and SAE tests too.

The two-way radios installed in the TxDOT trucks have 8 channels, or modes. The frequencies of the channels are listed in Table 10.

Table 10. Mode number and frequency of the TxDOT radios.

Mode #	Frequency (MHz)
1	47.18
2	47.06
3	47.24
4	47.26
5	47.34
6	47.02
7	47.04
8	47.08

Note: The whole list of the frequencies used by TxDOT is given in Appendix C.

Antennas

The TxDOT trucks that we tested were equipped with Spectrum antennas with Larsen magnetic mounts. The antennas were mounted near the center of the vehicle roof. To determine the frequency range of the antenna on the TxDOT vehicle, we looked at the SWR (standing wave ratio) and reflection coefficient log magnitude graphs. A network analyzer was directly connected to the antenna on the vehicle roof for this experiment. The scanning frequencies were from 30 MHz to 80 MHz. The SWR is defined as $\frac{1+|S_{11}|}{1-|S_{11}|}$, where S_{11} is the reflection coefficient. The SWR graphs of the antennas show us a notch-filter-like graph as we would expect. The following two graphs are the SWR graph and S_{11} log magnitude graph of the antenna on the 2-5643-G truck.

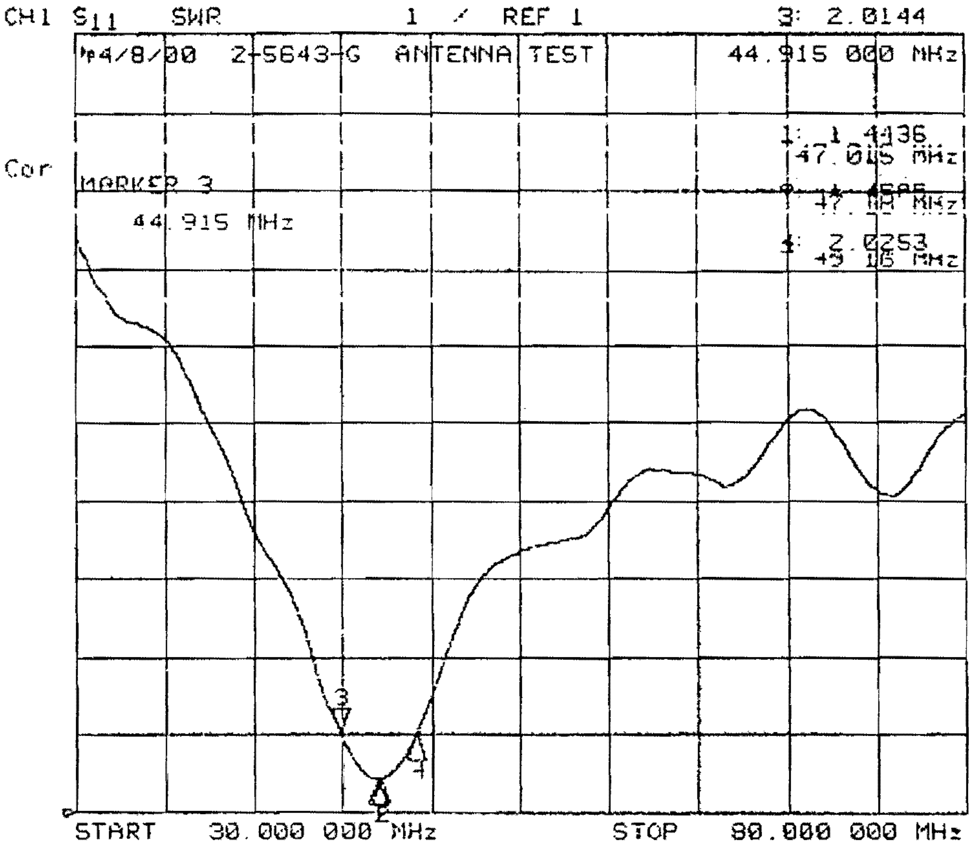


Figure 23. SWR of the antenna on TxDOT truck 2-5643-G

The deep valley of the SWR graph means that the antenna has the lowest reflection coefficient at that frequency. In other words the valley frequency is the matched frequency for the antenna. There was a slight difference in SWR graphs between the two trucks. The 2-5643-G truck has a minimum at the 46 MHz while the other one, 2-5649-G, has a minimum at 47.18 MHz, which is the center of the 8 frequencies of the radio. However, both truck antennas were judged satisfactory for use.

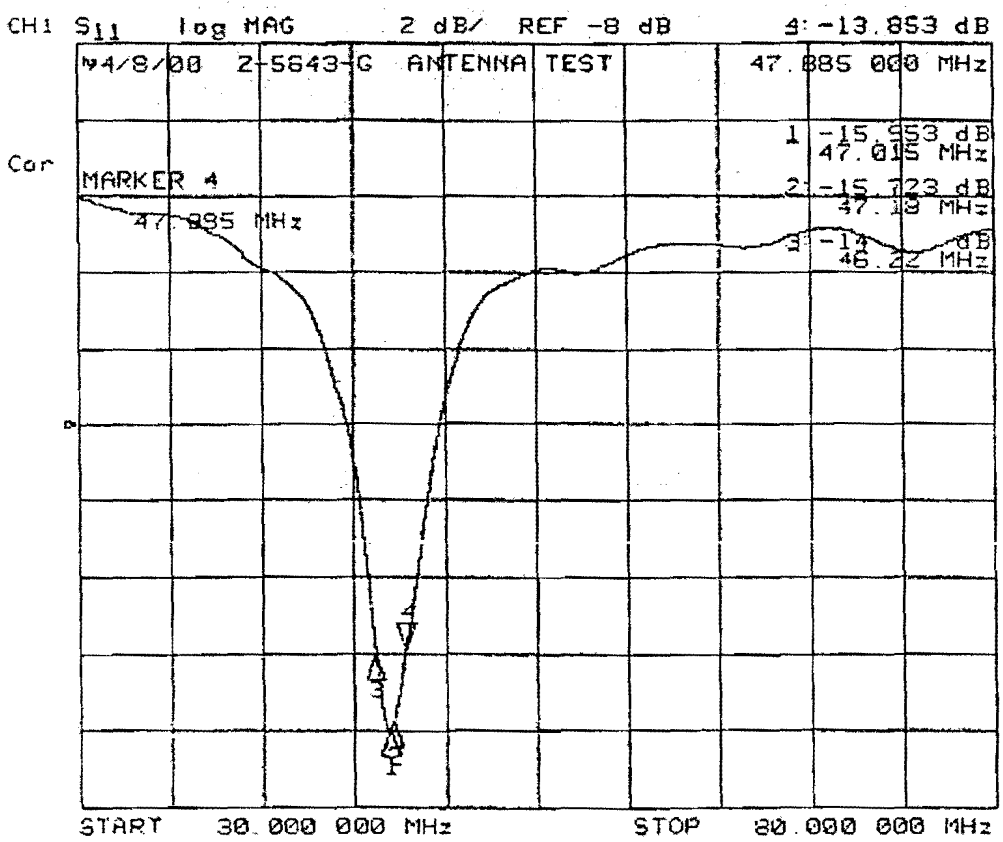


Figure 24. S_{11} log magnitude of the antenna on TxDOT truck 2-5643-G

SAE J551/4 test results

The Rohde & Schwarz ESVP receiver was used for the SAE test. The receiver was directly connected to the antenna on the vehicle and measured the noise value while each of the noise sources in the vehicle were turned on. Tables 11 and 12 show the data from the SAE J551/4 test on both trucks.

Table 11. SAE J551/4 test results for TxDOT truck 2-5643-G

Unit : dBμV	Mode 6 47.02 MHz	Mode 1 47.18 MHz	Mode 5 47.34 MHz
Light bar on	26.1 ~ 30.1	27.8 ~ 29.8	30 ~ 34.8
Ignition + HVAC fan on	55.3 ~ 57	54.5 ~ 56.7	54.3 ~ 56.2
HVAC fan on	9.6 ~ 16.3	10.9 ~ 16.0	19.5
Ignition +HVAC+Light bar on	55.6 ~ 59.4	54.3 ~ 57.2	56.1 ~ 59
Ignition + Light bar on	53.1 ~ 58.8	53.2 ~ 59.1	55.1 ~ 59.2
Fuel pump on	6.3	5.1 ~ 6.3	4 ~ 6
Wiper on	22.7 ~ 29.8	25.7 ~ 30.5	29.8 ~ 34.2
Wiper with water spray on	55.9 ~ 60.6	49.8 ~ 54.1	52.8 ~ 56.2
Ignition + wiper on	52.4 ~ 53.8	52.3 ~ 55	53.8 ~ 54.6
Ignition only (propane)	52.5 ~ 56.3	53.0 ~ 55.3	53.2 ~ 56.2
Key on (propane)*	10.9 ~ 11.8	10.9 ~ 11.8	20

* the key on noise was measured at 120 kHz bandwidth

For the SAE test, ignition noise is the dominant noise source. Because of this, all ignition-involved noise measurements are about the same as ignition noise itself, so the peak measurements of ignition noise with some other noise sources are not very important in this test. For that reason, some of the noise tests on the 2-5649-G truck are omitted.

Table 12. SAE J551/4 test results for TxDOT truck 2-5649-G

Unit : dBμV	Mode 6 47.02 MHz	Mode 1 47.18 MHz	Mode 5 47.34 MHz
Light bar on	43.3 ~ 47	39 ~ 43	44 ~ 46
Ignition + HVAC fan on	48 ~ 54.2	**	52.7 ~ 54.8
HVAC fan on	10.5 ~ 11.7	12.4 ~ 8.3	15.7 ~ 17
Ignition +HVAC+ Light bar on	51.3 ~ 53.9	**	52.2 ~ 53.4
Ignition + Light bar on	51.3 ~ 53.9	**	50.4 ~ 52.1
Fuel pump on	11 ~ 13.5	8.3 ~ 9.6	10.3 ~ 12.4
Wiper on	31.3 ~ 35.2	38 ~ 39	28.9 ~ 32.4
Wiper with water spray on	52 ~ 54.9	54 ~ 58	49.1 ~ 54.3
Ignition + wiper on	53.4 ~ 54.3	**	53.2 ~ 55.2
Ignition only (propane)	49.7 ~ 54.5	53.2 ~ 54.6(prop*) 54.5 ~ 55.0(gasol*)	52 ~ 53.9
Key on (propane)***	-2.6	-1.4	9.7

gasol* : gasoline is used for the engine idle

prop* : propane is used for the engine idle

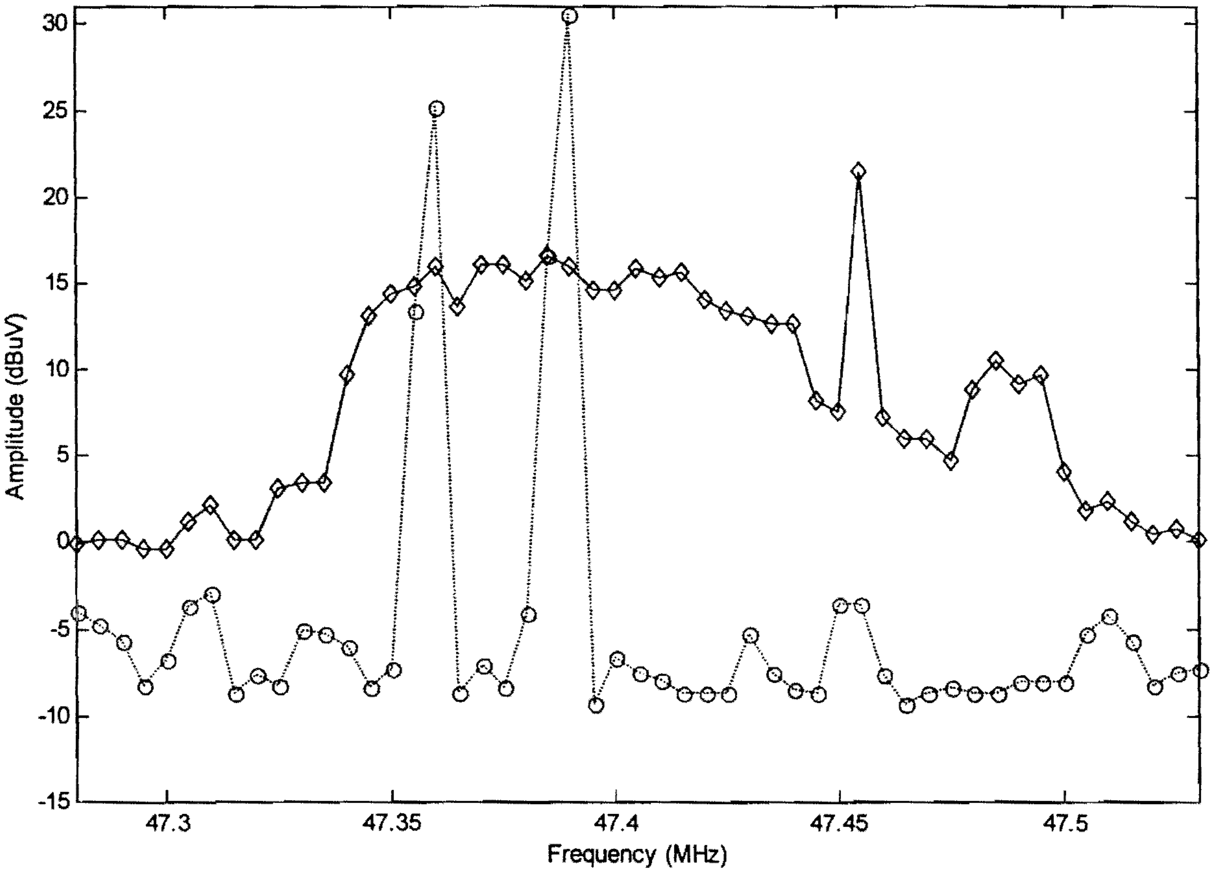
* * : not tested

*** : key on noise was measured at 10 kHz bandwidth

After spark ignition noise and wiper with water spray, the light bar is the highest noise contributor in the SAE test. The two trucks have light bars in different locations. One of them has the light bar installed on the roof about 2 inches away from the antenna, while the other one has the light bar on the top of the headache rack. For the 2-5649-G truck, which has the light bar near the antenna, the measured value of the noise from the light bar is higher than our new SAE J551/4 test limit, 40 dBμV, for broad-band noise. The light bars on both trucks have no visible filters installed, but the peak value of noise from the light bar was reduced about 6 dB when two ferrite chokes were placed on the light bar wire. However, we found that the noise from the fuel pump and HVAC fan is very quiet and far from our 40 dBμV limit, so they evidently have installed noise-reducing filters.

We had a chance to test in our laboratory a different light bar from TxDOT. It has two more motors in it and has filters installed on all of the motors (see Chapter III). The filter is composed of three capacitors soldered onto the back of the motor. We tested the light bar with the filters and without the filters as well. Although this light bar produces lower noise, it is enough to see the effect of the filter. With the filter installed the noise of the light bar was reduced by 20 dB and it had a peak amplitude at 33 MHz.

When we performed the vehicle tests with key on, a new type of noise was observed. It is probably generated from micro-controllers (so-called "modules"). The peak value of this noise stayed around -2 dBμV until the frequency reached 47.34 MHz, which is the highest TxDOT frequency. After 47.34 MHz the peak values went up by 17 dB until the frequency reached 47.53 MHz and then went back down to –2 dBμV. The graph in Figure 25 shows frequency scans obtained by the ESVP receiver. The bandwidth of this measurement was 10 kHz and the frequency step size was 5 kHz. The key on with propane and key on with gasoline produce almost the same noise. The key-on noise in this chapter is key on with propane. (The key-on noise values in table 9 were measured with 120 kHz bandwidth and the values in table 10 were measured with 10 kHz bandwidth.) The occasional large peak occurred when a car passed by the test site.



(··········· : ambient noise only, ——— : ambient + module noise)

Figure 25. Frequency scan of module noise and ambient noise

This noise from the modules spreads about 150 kHz wide, so it looks more like broad-band noise than narrow-band noise. We compared the peak and average value for this noise at 47.37 MHz using 10 kHz bandwidth. The values are shown in table 13. There is about 16 dB difference between peak and average. From the guideline of the

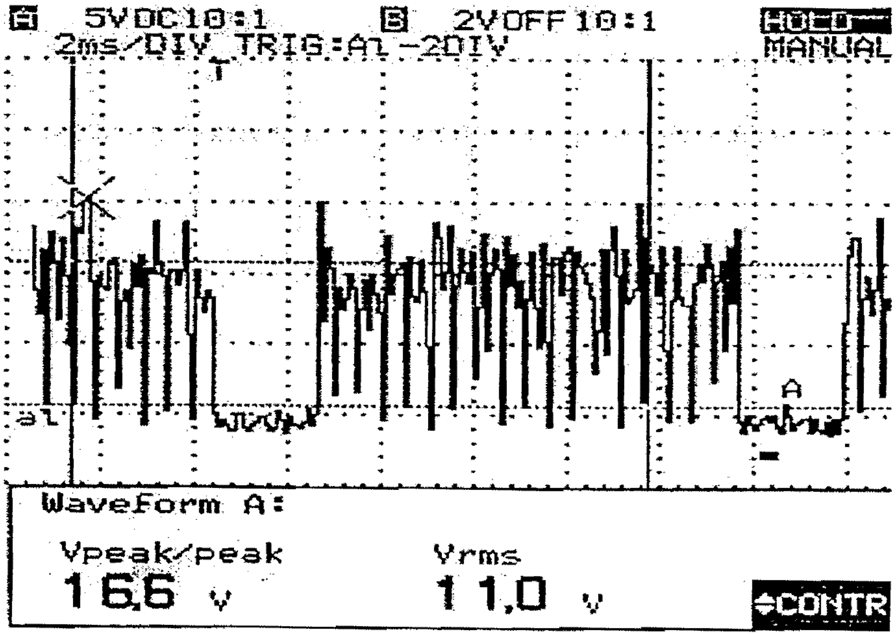
SAE test, if a 10 kHz bandwidth measurement for peak and average values of the noise shows more than a 6 dB difference, the noise should be treated as broad-band noise. Thus the noise from the modules is broad-band.

Table 13. Peak and average value comparison of key-on noise (2-5643-G)

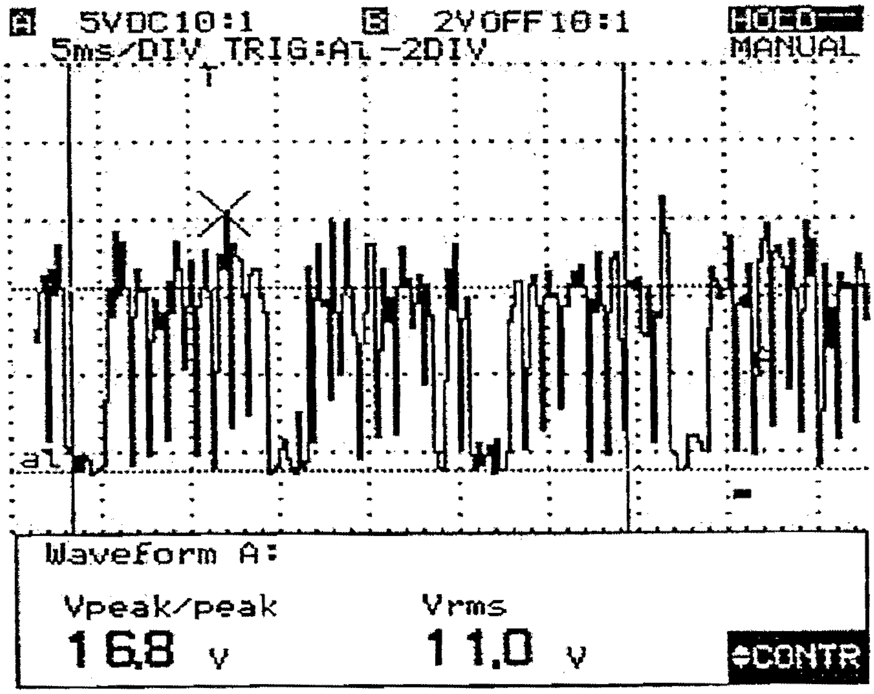
Unit : dBμV	Peak value	Average value
Key on (gasoline)	15.2	-0.4
Key on (propane)	15.6	-1.3

Notes: frequency = 47.37 MHz

When we hooked up the AM output of the ESVP receiver to a Fluke portable oscilloscope, we observed the waveforms of the module noise. The oscillograms in figure 26 show some examples. The frequency was 47.34 MHz.



(a)

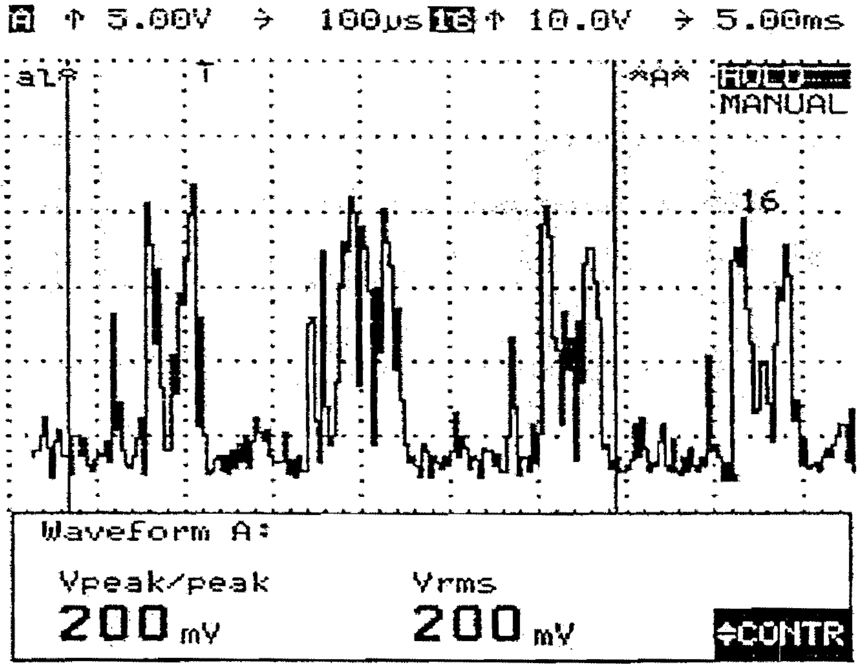


Waveform A:

Vpeak/peak 16.8 V

Vrms 11.0 V

(b)



Waveform A:

Vpeak/peak 200 mV

Vrms 200 mV

(c)

Figure 26. Noise from module (key-on noise)

From figure 26 (a) we found that the waveform has 2 kHz pulse rate and 90 kHz bunch rate. Switching the noise blanker in the *MaraTrac* radio on and off had no effect on these pulses. The ESVP receiver has an FM output also, and it would be interesting to see what FM content these pulses might have.

TxDOT Tex-899-B test results

The Rohde & Schwarz radio communication service monitor was used with the installed radios for the Tex-899-B test. The values in the next two tables indicate the amplitude of the signal needed to obtain a 12 dB SINAD reading with the corresponding noise source. The 3-port directional coupler was used to combine the FM signal and noise from the antenna as described previously.

Table 14. TxDOT Tex-899-B test results for TxDOT truck 2-5643-G

Unit : dBμV	Mode 6 47.02 MHz	Mode 1 47.18 MHz	Mode 5 47.34 MHz
Light bar	16	15.6	19.9
Wiper	16.2	15	18
HVAC fan	15	14.8	18.6
Fuel pump	13.9	13.6	15.1
Key on (propane)	15	14.7	18.4
Key on (gasoline)	14.7	14.3	18.3
ALL VEHICLE SYSTEMS ON (GASOLINE)			
SG_A 12 dB with antenna	17.4 dBμV	18.2 dBμV	19.6 dBμV
$SG_{AL}=SG_A- SG_L$	9.4 dB	10.2 dB	11.6 dB
$SG_E=SG_{AL}+ SG_R$	- 2.6 dBμV	- 1.8 dBμV	- 0.4 dBμV
ALL VEHICLE SYSTEMS ON (PROPANE)			
SG_A 12 dB with antenna	17.4 dBμV	17.6 dBμV	19.6 dBμV
$SG_{AL}=SG_A- SG_L$	9.4 dB	9.6 dB	11.6 dB
$SG_E=SG_{AL}+ SG_R$	- 2.6 dBμV	- 2.4 dBμV	- 0.4 dBμV

From the “all vehicle systems on” value, we can see that the 2-5649-G truck failed the Tex-899-B test by 0.1 dB when running on gasoline. In individual noise tests, key-on noise is the highest contributor at 47.34 MHz. The 0.5 dB difference between trucks for “all vehicle systems on” noise makes the 2-5643-G truck pass the Tex-899-B test. However, it also has strong key-on noise. From all the data, we can see there is no big difference in noise when the vehicles run on gasoline or propane.

Table 15. TxDOT Tex-899-B test results for TxDOT truck 2-5649-G

Unit : dBμV	Mode 6 47.02 MHz	Mode 1 47.18 MHz	Mode 5 47.34 MHz
Light bar	12.2	11.9	13.7
Wiper	13.0	15.3	16.7
HVAC fan	12.5	12.5	15.9
Fuel pump	13.2	12.9	12.5
HVAC fan + fuel pump	13.8	13.2	17.9
Turn signal	12.2	11.9	12.3
Key on (propane)	13.1	12.7	17.7
Key on (gasoline)	13.2	12.9	15.8
ALL VEHICLE SYSTEMS ON (GASOLINE)			
SG_A 12 dB with antenna	16 dBμV	16 dBμV	20.1 dBμV
$SG_{AL}=SG_A- SG_L$	8 dB	8 dB	12.1 dB
$SG_E=SG_{AL}+ SG_R$	- 4 dBμV	- 4 dBμV	0.1 dBμV
ALL VEHICLE SYSTEMS ON (PROPANE)			
SG_A 12 dB with antenna	16.2 dBμV	16 dBμV	19.5 dBμV
$SG_{AL}=SG_A- SG_L$	8.2 dB	8 dB	11.5 dB
$SG_E=SG_{AL}+ SG_R$	-3.8 dBμV	- 4 dBμV	- 0.5 dBμV

Truck test summary

In the J551/4 test the spark ignition noise was the strongest, as expected, with one small exception. When running the windshield wiper and activating the washer, peak noise levels comparable to ignition noise were observed. The culprit was the washer motor. However the very intermittent nature of this source makes it questionable as to whether it should be of concern.

The next strongest noise sources were the light bar on the 5649 truck, followed by the light bar on the 5643 truck and the windshield wipers and then the HVAC fans and fuel pumps

In the Tex-899-B test the various vehicle noise sources were all rather weak except for the key-on noise at 47.34 MHz. At this frequency, with all vehicle systems on, the key-on noise together with the other noise sources was sufficient to put the vehicles essentially at the TxDOT limit.

An objective of the truck testing was to validate the new limits for DC-motor noise: 50 dBμV for one motor, and 40 dBμV for two motors of comparable noise output. These limits were derived from our bench-top simulation where the two motors were an HVAC fan and a fuel pump.

Unfortunately we were unable to accomplish the validation, as far as HVAC fans and fuel pumps are concerned, because the noise from the fans and fuel pumps in the vehicles was low, much lower than expected. However the noise from two other DC-motor sources provided important new information. The light bar, with its two motors, generated noise above the 40 dBμV limit and the windshield washer, with one motor, generated noise above the 50 dBμV limit. Yet neither light bar nor washer motors exceeded the Tex-899-B limit. That is, the noise produced by the tiny motors in the light bar and washer has less effect on the TxDOT radio than expected (due possibly to the effect of the noise blanker in the TxDOT radio), and thus these motors must have a higher J551/4 limit placed on them than the limit for fan and fuel pump motors.

CHAPTER V

CONCLUSIONS

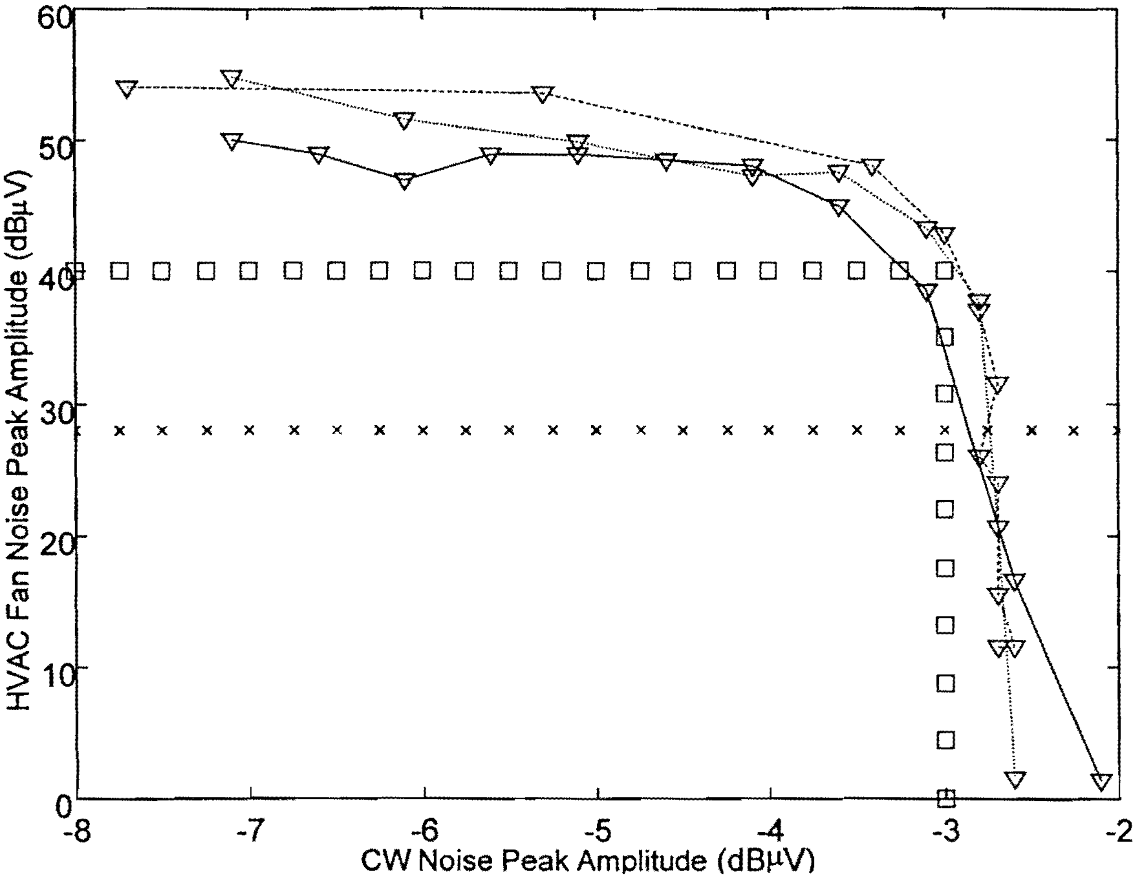
Limit for narrow-band noise

Narrow-band noise emission is due to microcontrollers and their associated circuitry. The current narrow-band noise limit for the SAE J551/4 test is 0 dBµV. This limit is too high to match the Tex-899-B test. The Tex-899-B test restricts its maximum input FM signal to 1 µV (= 0 dBµV). Since the noise level should be at least a few dB lower than the signal amplitude for good reception, with no doubt, the current limit for the narrow-band noise should be decreased.

The suggested new limit for narrow-band noise peak amplitude is –3 dBµV. This value is obtained from the data plotted in Figure 27. The experiments were performed three times to test the repeatability of the noise. Except for one curve, all curves are just slightly higher than –3 dBµV until the fan noise peak amplitude reaches 40 dBµV. We used a Motorola *MaraTrac* radio, since this radio is the newest in the TxDOT vehicle fleet.

Limit for broad-band noise

Broad-band noise emission is mostly caused by DC motors and spark ignition. DC motor noise is emitted from the fuel pump, HVAC fan and radiator fan. The noise emission from DC motors has inherent randomness, which causes a 2 dB standard deviation even with 2 second measure time.



∇ : TxDOT Tex-899-B test result for combined noise

□ : Suggested limit of SAE J551/4 test for narrow-band noise and DC motor noise

x : Current limit of SAE J551/4 test

Figure 27. Modified SAE J551/4 limits and TxDOT Tex-899-B limit for combination of CW and HVAC fan noise using Motorola *MaraTrac* Radio

Using a Motorola *MaraTrac* radio, we found the HVAC fan noise peak value for 12 dB SINAD is between 50 and 55 dBµV. This value decreased a bit when we added other DC-motor noise such as fuel pump, radiator fan and wiper noise. However, the current limit of the SAE J551/4 test for broad-band noise is 28 dBµV, which is too low.

The suggested new limit for emissions from multiple DC motors is 40 dBμV and this is plotted in Figure 27. This value is reasonable because the maximum DC-motor noise measured from nine TxDOT vehicles was 37 dBμV and they all passed the Tex-899-B test. [7]

During the SAE vehicle tests we found that the spark ignition system generates more noise than the noise from DC motors. However spark ignition noise had no effect on the SINAD test. This is because the noise blanker in the TxDOT radio is very effective for spark ignition noise while considerably less effective for DC-motor noise. In the bench-top test for the spark ignition noise itself we could not achieve 12 dB SINAD. Even at the maximum output of our spark ignition simulator, the SINAD value was 28 dB. The maximum output of this pulse generator was 11 volts which is 88 dBμV at 47 MHz. In the vehicle test, we found the maximum spark ignition noise peak is at 56 dBμV. That means we applied 30 dB above the highest peak value of the practical spark ignition noise, but the SINAD still stayed at 28 dB. Hence, the limit for spark ignition noise is a lot higher than the limit for DC-motor noise, and each broad-band noise emission needs to be measured separately with a different limit.

The broad-band noise limit for the light bar needs to be somewhat higher than that for the HVAC fan. For one truck we tested, the light bar produced 43 dBμV peak noise but it passed the Tex-899-B test, so the broad-band noise limit for the light bar should be higher than the 40 dBμV limit for the HVAC fan.

Modified SAE J551/4 test

As discussed in the two previous sections, the modified new limits for narrow-band noise and DC-motor noise are –3 dBμV and 40 dBμV, respectively. Table 16 shows the suggested SAE J551/4 test limits and corresponding bandwidth of measuring equipment for each noise source. The limits of the measurement system's noise floor need to be at least 6 dB lower than the noise limits for the test. Thus the narrow-band and broad-band noise floor limits for the system should be –9 dBμV and 34 dBμV, respectively. Table 16 also gives the test procedure (or steps) for the modified SAE J551/4 test.

Although methods and units of output data for both tests are different, the modified SAE J551/4 test shows a better correlation with the Tex-899-B test and can be substituted for it. Since the SAE J551/4 test measures the noise directly from the antenna by using an EMI receiver or spectrum analyzer, it's easy to set up and less time consuming. Also, with the use of computer control, this test allows for automatic measurement of data at many different frequencies. If the measurement is performed by a spectrum analyzer, the data can even be visualized as a frequency-domain plot. This is a very attractive aspect of the SAE test. Therefore the modified SAE J551/4 test provides not just an alternative to the Tex-899-B test but also provides better test efficiency.

Table 16. Modified SAE J551/4 test procedure

Vehicle status (Engine warm before testing)	Measuring instrument Bandwidth [kHz]	Limits of terminal Noise voltage at receiver antenna terminal [dBμV] Peak Detection	Noise type
1.All off	10	-9	Measurement system narrow-band noise floor (ambient noise)
2.All off	120	34	Measurement system broad-band noise floor (ambient noise)
3.Engine off, key on	10	-3	Narrow-band noise from microcontroller
4.Engine off, key on; fuel pump on, wiper on, radiator fan on (if electric)	120	40	Broad-band noise from DC motor
5.Engine on	120	>88	Spark ignition noise (broad-band noise)

Future work

A conclusion from figure 16 is that the noise blanker in the Motorola *MaraTrac* radio is more effective than the blanker in the GE RANGR™ at reducing fan noise. This may be due to the fact that the *MaraTrac* has a longer blanking pulse than the RANGR™, as seen in Figures 20 and 21. Perhaps even better noise-blanker performance could be obtained by modifying the radio to provide an even longer blanking pulse.

The results of our tests of TxDOT vehicles (chapter IV) show that we must apply different limits to the peak values of the emissions from different types of DC motors. This is a nuisance. One would like to have a single limit for all DC motors. A possible alternative is to use the average value of the emissions rather than the peak value. This might result in a single limit and is an area worth investigating.

The key-on noise we observed in the TxDOT vehicles (Figures 25 and 26) is of a type we had not previously seen: amplitude modulated and with a bandwidth of about 150 kHz. It is evidently produced by electronic modules in the vehicles. Such noise is likely to become more common in future vehicles. It requires laboratory study and assignment of a limit.

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APPENDIX A

TxDOT Tex-899-B TEST

RADIO FREQUENCY INTEFERENCE (RFI) TESTING

This test method assures the compatibility of Texas Department of Transportation (TxDOT) fleet vehicles and VHF FM radio equipment operating in the frequency ranges of 30 to 50 MHz and 150 to 174 MHz, but not inclusive. It is intended to identify 90% or more ingress and egress problems.

Definitions

Ingress – any action, reaction, indication, failure to perform or comply, by vehicle equipment and/or accessory items, caused by the activation of the VHF FM radio transmitter in any mode of operation.

Egress – any mode of operation, action, reaction or indication or by the vehicle equipment and/or accessory equipment which degrades the VHF-FM radio receiver effective sensitivity performance by more than six dB.

Equipment

- 100 watt VHF FM communications transmitter and receiver capable of operating on all TxDOT frequencies.
- 12 V regulated DC power supply
- RF signal generator with a calibrated attenuator
- Signal-to-noise audio distortion (SINAD) meter
- Receiver audio termination load
- RF directional coupler rated at 40 dB directional, minimum
- RF termination load
- Magnetic mount antenna for the testing frequencies
- RF isolation choke, a (6 ft. by 6 ft.) sheet of hardware cloth, laid flat on the test area floor with the coaxial cable making one complete loop approximately four feet in diameter under it
- RF wattmeter

Facilities

- Free of high ambient RF noise (receiver test)
- Equipped with lift capable of raising vehicle tires six inches above floor (transmission test)

Safety notes

Safety be must never be compromised during tests. Hazards due to vehicle parts moving and radio frequency/electrical burns exist. Strict compliance with accepted work practices must be observed at all times. Sudden actions may result when the radio transmitter is activated. Stay clear of vehicle and antenna. One person should operate the vehicle, and another the radio.

Egress compatibility

- Receiver qualification

Step	Action
1	Assemble a test set-up as shown figure 1
2	Generate a standard test signal and establish 12 dB SINAD
3	Record receiver basic sensitivity.
4	Increase signal 6 dB above step 3.
5	Increase peak deviation until SINAD is degraded to 12 dB SINAD
6	Record modulation acceptance (Bandwidth)

Compliance of the test setup qualifies the receiver for acceptance testing if:

- the receiver basic sensitivity is less than 0.4 µV(-114 dBm) for 12dB SINAD
- The receiver bandwidth shall be a minimum of ± 6.5 kHz and a maximum of ± 8.0 kHz.

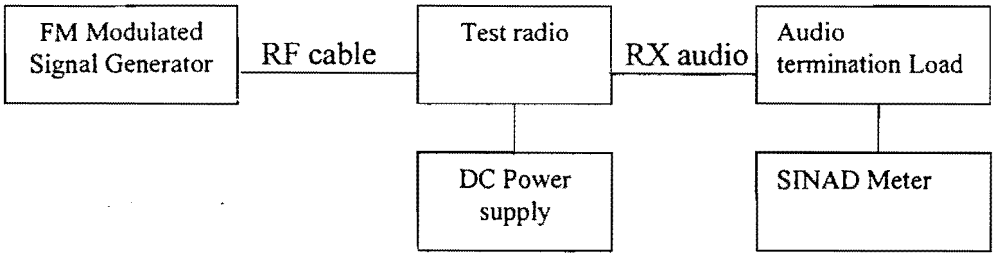

Figure 1

- Site Qualification

Step	Action
1	Assemble a test set-up as shown in figure 2.
2	Move test vehicle into radio frequency interference shield room or onto site.
3	Temporarily install the magnetic mount antenna on the center of the vehicle loop.
4	Disconnect the battery cable.
5	Terminate the RF line into the RF load terminal.
6	Generate a standard test signal of on-channel center frequency FM modulated with a 1 kHz sine wave tone at ±3.3 kHz deviation.
7	Increase the signal generator RF output level until a 12 dB SINAD indication is achieved.
8	Record sensitivity into RF road termination in dBm.
9	Remove the RF load termination and terminate the RF line into the temporary antenna.
10	Increase signal generator RF output level until a 12 dB SINAD indication is achieved.
11	Record sensitivity into antenna in dBm.
12	Compute the effective sensitivity and determine if the site is qualified.
13	Repeat site qualification at all test radio channels/frequencies to be used

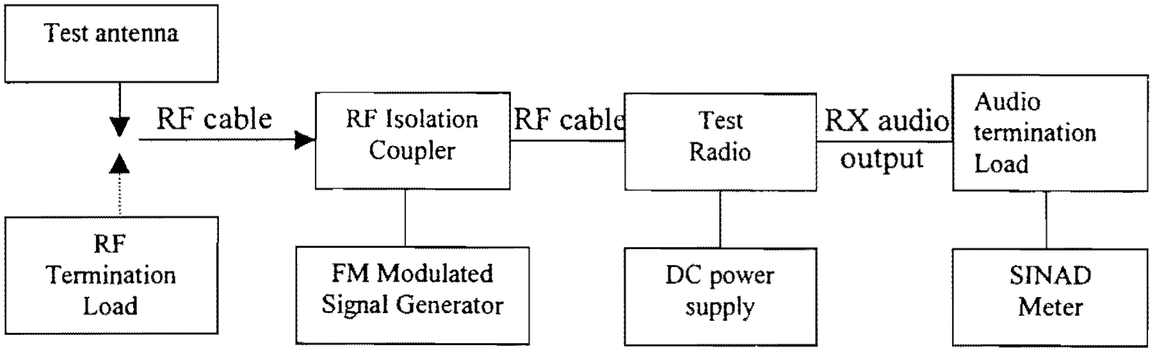

Figure – 2

- Effective Sensitivity Calculation

Step	Action
1	Subtract the sensitivity into antenna from sensitivity into RF load termination.
2	Record this difference.
3	Subtract this difference from the basic receiver sensitivity.
4	Record the effective receiver sensitivity in dBm.
5	Convert the effective receiver sensitivity to microvolts.

- Site Qualification Standards

  The site is qualified if the effective receiver sensitivity is less than 0.5 µV (-113 dBm)

Egress compatibility

- Egress compliance test for test for test vehicle

Step	Action
1	Reconnect vehicle battery.
2	Increase the signal generator RF output level until a 12 dB SINAD indication is achieved.
3	Record the signal generator RF output level.
4	Activate one vehicle system or accessory.
5	Increase the signal generator output level until a 12 dB SINAD indication is achieved.
6	Record the signal generator RF output level.
7	Repeat Steps 4 through 6 until all vehicle systems and accessories are activated.
8	Compute total degradation. See NOTE.
9	Repeat compliance test for all test radio channels/frequencies to be used.
10	Turn off engine.

NOTE: The electrical system should be designed so the effective sensitivity of the VHF FM receiver requires not more than 1 μV (-107 dBm) to produce 12 dB or greater SINAD. The effective sensitivity should not exceed 1 μV for all modes of operation, which should include engine off, engine on, (from idle to full throttle), and all vehicle systems or any combination thereof

- Test vehicle qualification

The test vehicle passes the egress compliance test when the total degradation does not exceed 6 dB

Ingress compatibility

- Antenna qualification

Step	Action
1	Assemble a test set-up as shown in Figure 3.
2	Verify engine is OFF.
3	Raise test vehicle (6 in.) off floor.
4	Verify that magnetic mount antenna is mounted in center of vehicle roof.
5	Key microphone on test radio.
6	Record nominal forward RF power to the antenna.
7	Record rectified RF power from the antenna.
8	Adjust length of antenna, if needed, and repeat steps5 through 7 until nominal forward power is 100 watts ± 10 watt and reflected power is less than 10 % of the forward power.

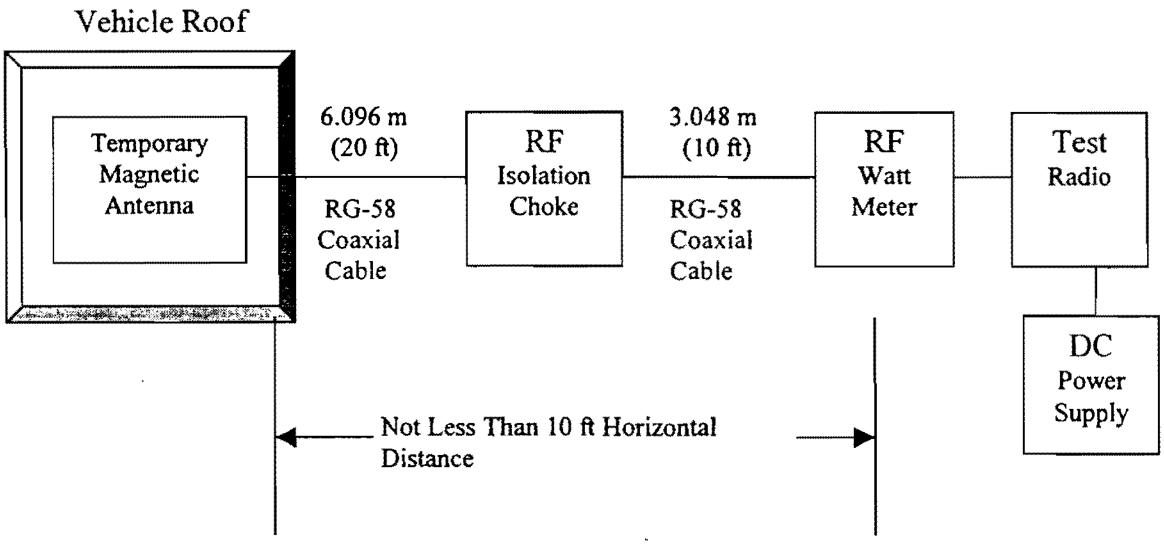

Figure 3.

Vehicle Qualification for Acceptance

Step	Action
1	Start vehicle.
2	Put vehicle in gear and rotate tires at a moderate speed.
3	Activate one vehicle system or accessory. Be certain to check the braking operation.
4	Activate the radio transmitter for approximately five seconds.
5	Record results as one of the following : 1. No adverse reaction 2. Reaction resulting in safety hazard 3. Reaction resulting in a nuisance operation.
6	Repeat steps 3 through 5 until all vehicle systems and accessories are activated.
7	Repeat vehicle qualification for all test radio channels/frequencies to be used.
8	Stop wheels of vehicle and turn off engine.

Vehicle Qualification Results

Safety Hazard – No vehicle system and/or accessory shall operate and/or fail to operate as a result of the activation of the VHF FM radio transmitter in a manner which constitutes a safety hazard.

Nuisance operation – correct nuisance operations of any vehicle system and/or accessory.

Failure to meet the criteria of this test method will result in rejection of the vehicle.

APPENDIX B

SAE J551/4 TEST

Test limit and methods of measurement of radio disturbance characteristics of vehicles and devices, broadband and narrowband, 150 kHz to 1000 MHz

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Forward – This SAE standard is based on CISPR 25 which has been developed by CISPR Subcommittee D and has been approved to be published. The SAE Electromagnetic Radiation Committee has been an active participant in Subcommittee D and in the development of CISPR 25.

This document provide test limits and procedures for the " protection of vehicle receiver from radio frequency (RF) emission caused by on-board vehicle components"

NOTE – Appendix II provides helpful methodology for resolution of interference problems.

Table of Contents

1. scope – this SAE Standard contains test limits[1] and procedures for the measurement of radio disturbances in the frequency range of 150 kHz to 1000MHz. The document applies to any electronic/electrical component intended for use in vehicles. Refer to International Telecommunication Union (ITU) Publications for details of frequency allocations. The tests are intended to provide protection for receivers installed in a vehicle from disturbances produced by components/modules in the same vehicle[2].

   The receiver types to be protected are: broadcast radio and TV[3], land-mobile radio, radio telephone, amateur and citizens' radio.

   The limits in this document are recommended and subject to modification as agreed between the vehicle manufacturer and the component supplier. This document shall also be applied by manufacturers and suppliers of components and equipment, which are to be added and connected to the vehicle harness or to an on-board power connector after delivery of the vehicle.

   This document does not include protection of electronic control systems from RF emissions, or from transient or pulse type voltage fluctuations. These subjects are covered in other sections of SAE J551 and in SAE J1113.

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[1] only a vehicle can be used to determine the component compatibility to a vehicle limit.
[2] adjacent vehicle can be expected to be protected in most situations.
[3] adequate TV protection will result from compliance with the levels at the mobile service frequencies

The Word Administrative Radiocommunications conference (WARC) lower frequency limit in region 1 was reduced to 148.5 kHz in 1979. For vehicular purposes, test at 150kHz are considered adequate. For the purpose of this document, test frequency ranges have been generalized to cover radio services in various parts of the world. Protection of radio reception at adjacent frequencies can be expected in most cases.

2. References

2.1 Applicable Documents – the following publications contain provisions which, through reference in this text, constitute provisions of this document. At the time of publication, the editions indicated were valid. All documents are subject to revision, and parties to agreements based on this document are encouraged to investigate the possibility of applying the most recent editions of the documents indicated. Members of IEC and ISO maintain registers of currently valid International standards.

2.2.1SAE Publication – Available from SAE, 400 Commonwealth Drive, Warrendale, PA 15096-0001.

SAE J551/1 MAR94 – Performance Level and Method of Measurement of Electromagnetic Compatibility of Vehicle and Devices (60 Hz to 18 GHz)

2.1.2 CISPR Publication – Available from ???

CISPR16-1:1993-08–Specification for Radio Disturbance and Immunity Measuring Apparatus and Methods. Part 1: Radio disturbance and immunity measuring apparatus

3. Definitions – See SAE J551/1.

4. Requirements common to vehicle and component/module emissions measurement

4.1 General Test Requirements and Test Plan

4.1.1 Test Plan Notes – A test plan should be established for each item to be tested. The test plan should specified the frequency range to be tested, the emission limits, the disturbance classification [Broad Band (long or short duration) Narrow Band], antenna types and locations, test report requirements, supply voltage, and other relevant parameters.

4.1.2 Determination of Conformation with Limits – If the type of disturbance is unknown, test should be made to determine whether measured emissions are narrow band and/or broad band to apply limits properly as specified in the test plan. Figure 1 outlines the procedure to be followed in determining conformance with limits.

4.1.3 Categories of Disturbance Sources (as applied in the test plan) – Electromagnetic disturbance sources can be divided into three types:[4]

a. Continuous/long duration broadband and automatically actuated short duration devices
b. Manually actuated short duration broadband
c. Narrowband

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[4] For example see 4.1.4 and 4.1.5 and Table 1.

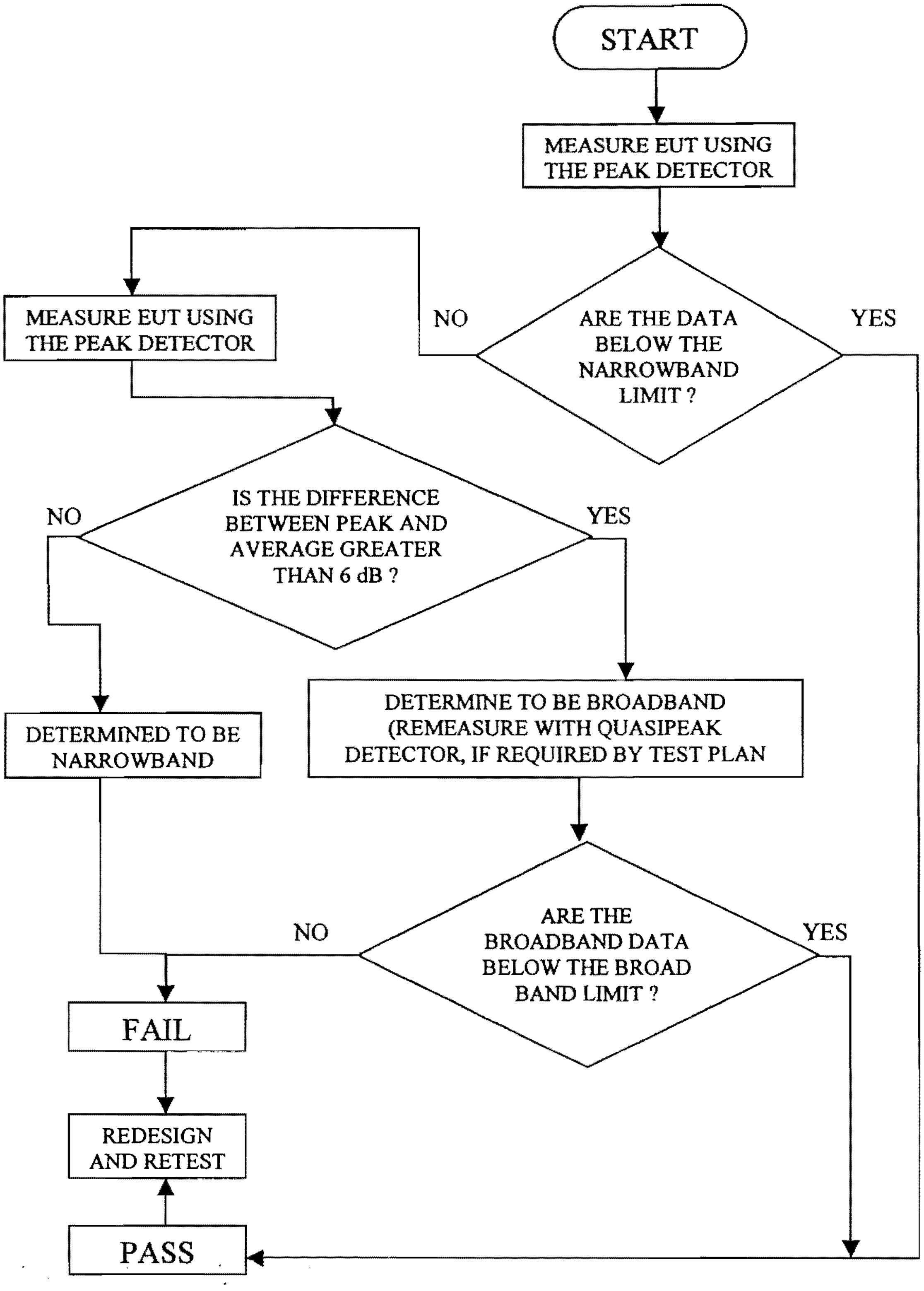

FIGURE 1 – METHOD OF DETERMINATION OF CONFORMANCE OF RADIATED/CONDUCTED DISTURBANCE

4.1.4 Example of Broadband Disturbance sources

Note – The Examples in table 1 are intended as a guide to assist in determining which test limits to use in the test plan.

Table 1- Example of Broadband Disturbance Sources by Duration.

Continuous	Long Duration[1]	Short Duration[1]
Ignition system	Wiper motor	Power antenna
Active ride control	Heater blower motor	Washer pump motor
Fuel injection	Rear wiper motor	Door mirror motor
Instrument regulator	Air conditioning compressor	Central door lock
Alternator	Engine cooling	Power seat

[1] As defined in the test plan

4.1.5 Narrowband Disturbance Sources – Disturbances from sources employing micro processors, digital logic, oscillators or clock generators, etc., cause narrowband emissions.

4.1.6 Operating Conditions – All continuous and long duration system shall be operated at their maximum RF noise creating conditions. All intermittently operating systems (i.e., thermostatically controlled) that can operate continuously, safely, shall be caused to operate continuously.

When performing the narrowband test , Broadband sources (i.e., ignition system, in particular) may create noise of higher amplitude. In this situation, it will be necessary to test for narrowband noise with ignition switch ON, but the engine not running

4.1.7. Test Report – The report shall contain the information agreed upon by the customer and the supplier

4.2. Shielded Enclosure – The ambient electromagnetic noise levels shall be at least 6 dB below the test limits specified in the test plan for each test to be performed. The shielding effectiveness of the shielded enclosure shall be sufficient to assure that the required ambient electromagnetic noise level requirement is met.

The shielded enclosure shall be of sufficient size to ensure that neither the vehicle/EUT nor the test antenna shall be closer than (a) 2 m from the walls or ceiling, and (b)1m to the nearest surface of the absorber material used.

4.4. Absorber-Lined Shielded Enclosure (ALSE) – For radiated emission measurements, however, the reflected energy can cause errors of such as 20 dB. Therefore, it is necessary to apply RF absorber material to the walls and ceiling of a shielded enclosure that is to be used for radiated emission measurements. No absorber material is required for the floor. The following ALSE requirement shall also be met for performing radiated RF emission measurements:

4.4.1 Reflection Characteristics – The reflection characteristic of the ALSE shall be such that the maximum error caused by reflected energy from the wall and ceiling is less than 6 dB in the frequency range of 70 to 1000 MHz.

4.4.2 Objects in ALSE – In particular, for radiated emission measurements the ALSE shall be cleared of all items not pertinent to the tests. This is required in order to reduce any effect they may have on the measurement. Included are unnecessary equipment, cable racks, storage cabinets, desks, etc. Personnel not actively involved in the test shall be excluded from the ALSE.

4.5 Receiver – Scanning receivers which meet the requirements of CISPER 16 are satisfactory for measurements. Manual or automatic frequency scanning may be used. Spectrum analyzer and scanning receivers are particularly useful for interference measurements. Special consideration shall be given overload linearity, selectivity, and the normal response for pulses. The peak detection made by spectrum analyzer and scanning receiver provides a display indication which is never less than the quasi-peak indication for the same bandwidth. It may be convenient to measure emissions using peak detection because of the faster scan possible than with quasi-peak detection. When quasi peak limits are being used, any peak measurements close to the limit shall be measured using the quasi-peak detector.

4.5.1 Minimum Scan Time – the scan rate of a spectrum analyzer or scanning receiver shall be adjusted for the CISPR frequency band and detection mode used. The minimum sweep time/frequency (i.e., most rapid scan rate) is listed in table2:

TABLE 2 – MINIMUM SCAN TIME

	Band	Peak Detection	Quasi-Peak Detection
A	9 to 150 kHz	Does not apply	Does not apply
B	0.15 to 30 MHz	100 ms / MHz	200 s / MHz
C,D	30 to 1000 MHz	1 ms /100 ms / MHz[1]	20 s / MHz

Band definition from CISPR 16 part 1

[1]When 9 kHz bandwidth is used, the 100 ms / MHz value shall be used

Certain signals(e.g., low repetition rate or intermittent signal) may require slow scan rates or multiple scans to insure that the maximum amplitude has been measured.

4.5.2 Measuring Instrument Bandwidth – The bandwidth of the measuring instrument shall be chosen such that the noise floor is at least 6 dB lower than the limit curve. The bandwidths in table 3 are recommended.

Note – When the bandwidth of the measuring instrument exceeds the bandwidth of a narrowband signal, the measured signal amplitude will not be affected. The indicated value of impulsive broadband noise will be lower when the measuring instrument bandwidth is reduced.

TABLE 3 – MEASURING INSTRUMENT BANDWIDTH (6 dB)

Frequency Band MHz		Broadband Peak	Broadband q-Peak	Narrowband Peak	Narrowband Average
0.15 – 30		9 kHz	9 kHz	9 kHz	9 kHz
30 – 1000	FM broadcast	120 kHz	120 kHz	120 kHz	120 kHz
	Mobile service	120 kHz	120 kHz	9 kHz	9 kHz

If a spectrum analyzer is used for peak measurements, the video bandwidth shall be at least three times the resolution bandwidth.

For the narrow band/broadband discrimination according to figure1, both bandwidths (with peak and average detectors) shall be identical.

5. Antenna and Impedance Matching Requirements – Vehicle Test

5.1 Type of Antenna – An antenna of the type to be supplied with the vehicle shall be used as the measurement antenna. Its location and attitude are determined according to the production specifications.

If no antenna is to be furnished with the vehicle (as is often the case with a mobile radio system), the antenna types in table 4 shall be used for the test. The antenna type and location shall be included in the test plan.

TABLE 4 – ANTENNA TYPES

Band		Antenna Type
Broadcast		
LW	AM	1m monopole
MW	AM	1m monopole
SW	AM	1m monopole
VHF	FM	1m monopole
Mobile Services		
30 – 54		load quarter wave monopole
70 – 87		quarter wave monopole
144 – 172		quarter wave monopole
420 – 512		quarter wave monopole
800 – 1000		quarter wave monopole

5.2 Measurement System Requirements

5.2.1 Broadcasting Bands – For each band, the measurement shall be made with instrumentation which has the specified characteristics.

5.2.1.1 AM Broadcast

a. Long Wave (150 to 300 kHz)
b. Medium Wave (0.53 to 2.0 MHz)
c. Short Wave (5.9 to 6.2 MHz)[5]

The measuring system shall have the following characteristics:

a. Output Impedance of Impedance Matching Device: 50 Ω resistive.
b. Gain: the gain (or attenuation) of the measuring equipment shall be known with an accuracy of ±0.5 dB. The gain of the equipment shall remain within a 6 dB envelop for each frequency band as shown in figure 2. Calibration shall be performed in accordance with Appendix I.
c. Compression Point: The 1 dB compression point shall occur at a sine wave voltage level greater than 60 dB(μV)
d. Measurement System Noise Floor: The noise floor of the combined equipment including measuring instrument, matching amplifier and preamplifier (if used) shall be at least 6 dB lower than the limit level.
e. Dynamic Range: From the noise floor to the 1 dB compression point.
f. Input Impedance: the impedance of the measuring system at the input of the matching network shall be at least 10 times the open circuit impedance of the artificial antenna network in Appendix I.

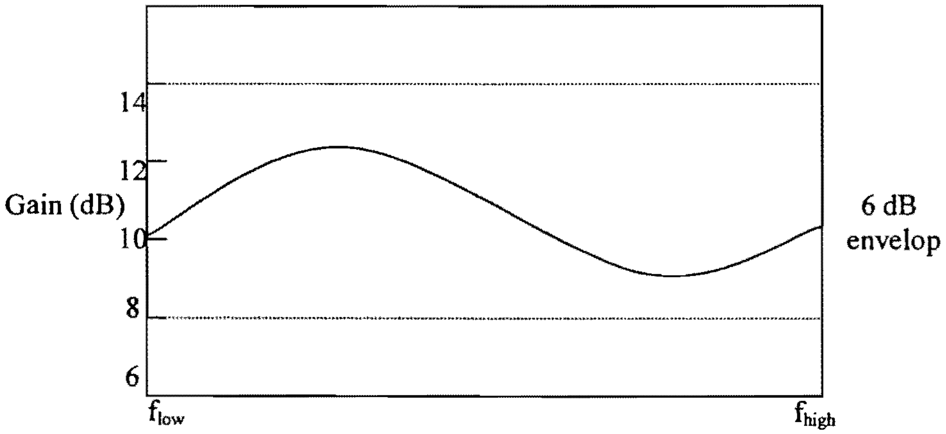

FIGURE 2 – EXAMPLE GAIN CURVE

5.2.1.2 FM Broadcast (87 to 108 MHz) – Measurements shall be taken with a measuring instrument which has an input impedance of 50 Ω. If the standing wave ratio(SWR) is greater than 2:1, an input matching network shall be used. Appropriate correction shall be made for any attenuation/gain of the matching unit.

5.2.2 Communication Bands (30 to 1000 MHz) – The test procedure assumes a 50 Ω measuring instrument and a 50 Ω antenna in the frequency range 30 to 1000 MHz. If a measuring instrument and an antenna with differing impedances are used, an appropriate network and correction shall be used.

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[5] Although there are several other short wave broadcast bands, this particular band has been chosen because it is most commonly used in vehicles. It is expected that other short wave bands will be protected by conformance to the limits in this band.

6. Method of Measurement – As a general principle, the disturbance voltage shall be measured at the terminal of the radio receiving antenna placed at the correct vehicle location(s).

   To determine the disturbance characteristics of individual disturbance sources or disturbance systems, all sources shall be forced to operate independently across their range of normal operating conditions (transient effects to be determined)

   The disturbance voltage shall be measured at the receiver end of the antenna coaxial cable using the ground contact of the connector as reference. The antenna connector shall be grounded to the housing of the on – board radio (center conductor of the antenna coax is not connected to the on-board radio). The radio housing shall be grounded to the vehicle body using the production harness. The use of a high quality double shielded cable for connection to the measuring receiver is required.

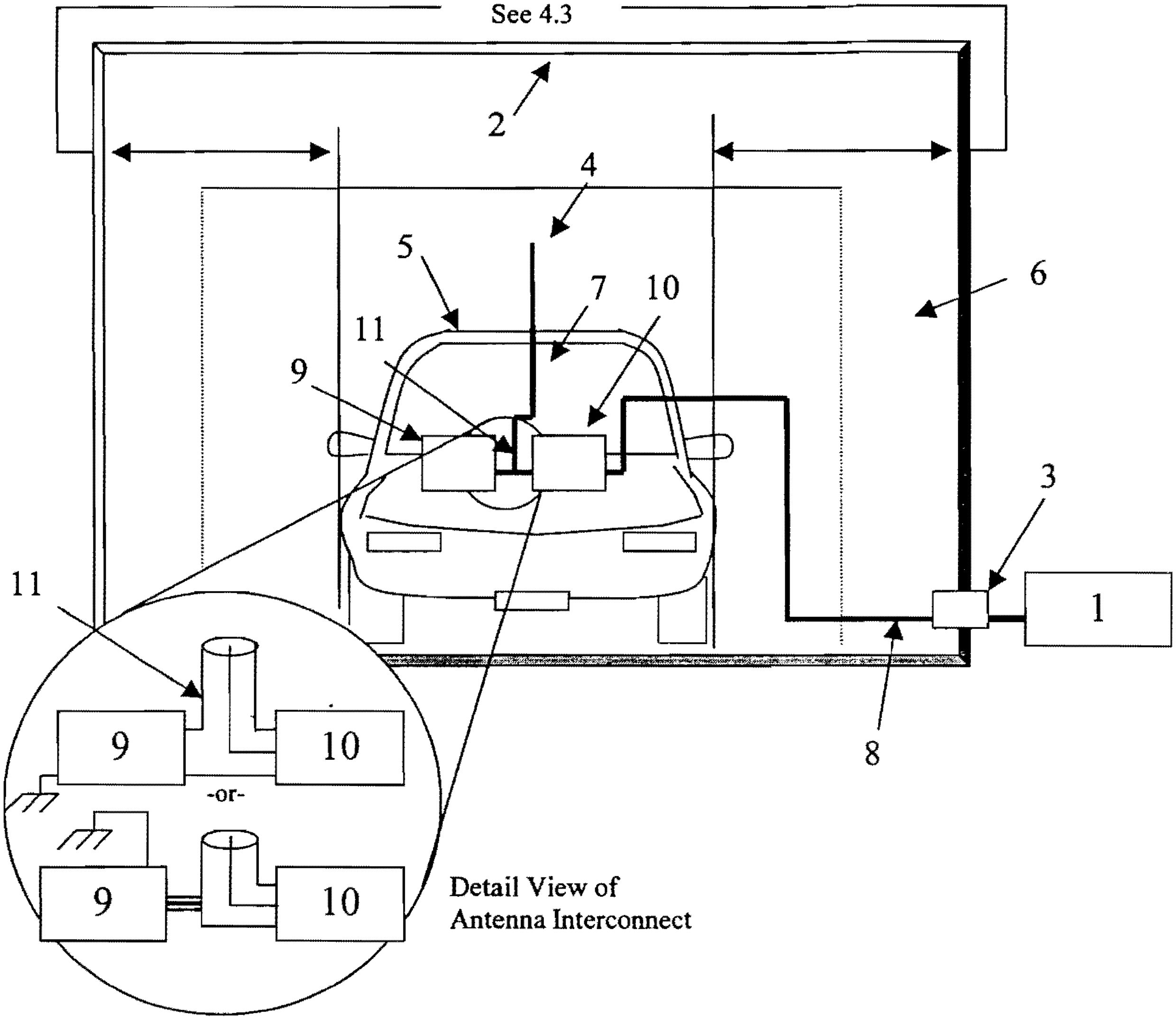
   NOTE – The use of ferrite or other suppression material on the coax is recommended, particularly below 2 MHz, for suppression of surface current.

   A coaxial bulkhead connector shall be used for connection to the measuring receiver outside the shielded room. See Figure 3.

   Some vehicles may allow a receiver to be mounted in several locations (e.g., under the dash, under the seat, etc.). In these cases a test shall be carried out as specified in the test plan for each receiver location.

7. Limit for Vehicle Radiated Disturbances – The limits of disturbance may be different for each disturbance source. Long duration disturbance sources such as a heater blower motor must meet a more stringent requirement than short duration disturbance sources. Short duration disturbance may be decided upon by the vehicle manufacturer. For example, door mirror operation may be allowed at a high level of disturbance, as it is operated for only 1 or 2 s at a time. Coherent energy from microprocessors is more objectionable because it resembles desired signal and is continuous.

   For acceptable radio reception in a vehicle, the disturbance voltage at the end of the antenna cable shall not exceed the values shown in table 5.



1. Measuring instrument
2. ALSE
3. Bulkhead connector
4. Antenna (see 5.1)
5. EUT
6. Typical absorber material
7. Antenna coaxial cable
8. High quality double shielded coaxial cable
9. Housing of on-board radio
10. Impedance matching unit (when required)
11. Optional tee connector with one leg removed

FIGURE 3. – VEHICLE RADIATED EMISSIONS – EXAMPLE FOR TEST LAYOUT
(END VIEW WITH MONOPOLE ANTENNA)

TABLE 5. – LIMITS OF DISTURBANCE – COMPLETE VEHICLE

Band	Frequency (MHz)	Terminal noise Voltage at Receiver Antenna Terminal dB(μV) Broadband Continuous QP	Terminal noise Voltage at Receiver Antenna Terminal dB(μV) Broadband Continuous P	Terminal noise Voltage at Receiver Antenna Terminal dB(μV) Broadband Short Duration QP	Terminal noise Voltage at Receiver Antenna Terminal dB(μV) Broadband Short Duration P	Terminal noise Voltage at Receiver Antenna Terminal dB(μV) Narrowband P
LW	0.15 – 0.3	9	22	15	28	6
MW	0.53 – 2	6	19	15	28	0
SW	5.9 – 6.2	6	19	6	19	0
VHF	30 – 54	6(15[1])	28	15	28	0
VHF	70 – 87	6(15[1])	28	15	28	0
VHF	87 – 108	6(15[1])	28	15	28	6
VHF	144 – 172	6(15[1])	28	15	28	0
UHF	420 – 512	6(15[1])	28	15	28	0
UHF	800–1000	6(15[1])	28	15	28	0

All broadband values listed in this table are valid for the bandwidth specified in Table 3.

Stereo signals may be more susceptible to interference than monaural signals in the FM – broadcast band. This phenomenon has been factored into the VHF (87 to 108 MHz) limit.

It is assumed that protection of services operating on frequencies immediately below 30 MHz will most likely be provided if the limits for services above 30 MHz are observed.

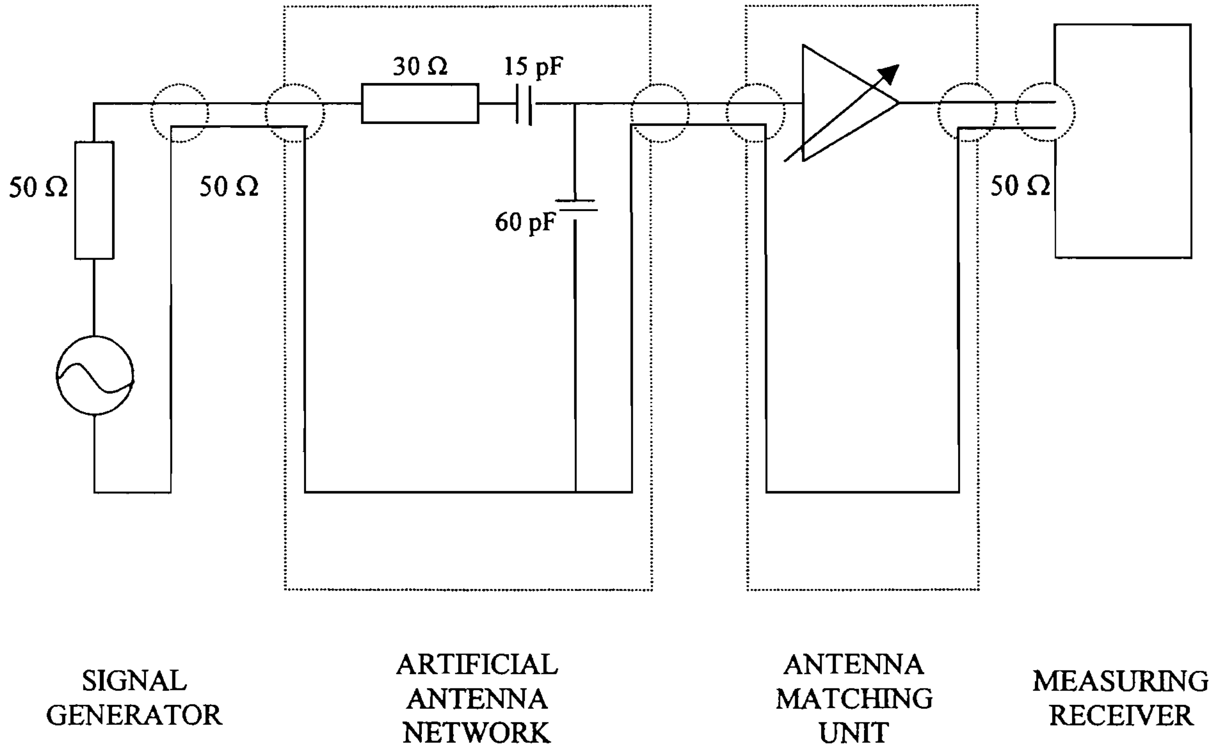
[1] Limit for ignition system only

APPENDIX I
(Normative)

ANTENNA MATCHING UNIT - VEHICLE TEST

I.1 Antenna Matching Unit Parameters (150 kHz to 6.2 MHz) – The requirements for the measurement equipment are defined in 5.2.1.

I.2. Antenna Matching Unit – calibration – the artificial antenna network of Figure A1 is used to represent the antenna including the coaxial cable. The 60 pF capacitor represents the capacitance of the coaxial cable between the car antenna and the input of the radio.



I.2.1 Gain Measurement – The antenna matching unit shall be measured to determine whether its gain meets the requirements of 5.2.1.1 using the test arrangement shown in Figure A.1

I.2.2 Test Procedure

a. Set the signal generator to the starting carrier frequency with 1000 Hz, 30 % amplitude modulation and 40 dB(µV)output level.
b. Plot the gain curve for each frequency segnment.

I.3 Impedance Measurement – Measurement of the output impedance of the antenna and antenna matching unit shall be made with a vector impedance meter (or equivalent test equipment). The output impedance shall be within a circle on a Smith chart crossing 100 + j0 Ω, having its center at 50 + j0 Ω (e.g., SWR less than 2 to 1).

APPENDIX II

(Informative)

NOTES ON THE SUPRESSION OF INTERFERENCE

II.1 Introduction – Success in providing radio disturbance suppression for a vehicle requires a systematic investigation to identify sources of interference which can be heard in the loudspeaker. This interference may reach the receiver and loudspeaker in various ways:

a. Disturbance coupled to the antenna
b. Disturbance coupled to the antenna cable
c. Penetration into the receiver enclosure via the power supply cables
d. Direct radiation into the receiver (immunity of an automobile radio to radiated interference)
e. Disturbance coupled to all other cables connected to the automobile receiver

Before the start of the investigation, the receiver housing, the antenna base, and each end of the shield of the antenna cable must be correctly grounded.

II.2 Disturbance Coupled to the Antenna – Most types of disturbances reach the receiver via the antenna. Suppressors can be fitted to the sources of disturbances to reduce these effects.

II.3 Coupling to the Antenna Cable – To minimize coupling, the antenna cable should not be routed parallel to the wiring harness or other electrical cables, and should be placed as remotely as possible from them.

II.4 Clock Oscillators – Radiation/conduction from on-board electronic modules may affect other components on the vehicle. Significant harmonics of the execution clock("E-Clock") must not coincide with duplex transceiver spacings, nor with receiver channel frequencies. The fundamental frequency of oscillator used in automotive modules/components shall not be an integer fraction of the duplex frequency of any mobile transceiver system in operation in the country in which the vehicle will be used

II.5. Other Sources of Information – Corrective measures for penetration by receiver wiring and by direct radiation are covered in other publications. Similarly, tests to evaluate the immunity of a receiver to conducted and direct radiated disturbances are also covered in other publications.

APPENDIX C

LIST OF FREQUENCIES USED BY TxDOT

Unit: MHz

Low Band	Low Band	High Band	High Band	High Band
45.680*	47.020	150.995	156.045	159.180
45.720*	47.040	151.010	156.060	159.225
45.800*	47.060	151.025	156.105	159.450
45.840*	47.080	151.040	156.120	162.400
	47.100	151.055	156.135	162.475
	47.120	151.070	156.180	162.550
	47.140	151.085	156.195	
	47.160	151.100		
	47.180	151.115		
	47.200	151.130		
	47.220	151.185		
	47.240	151.385		
	47.260	154.950		
	47.340	155.370		

* Note: these frequencies used only for mobile-radio transmission to repeater and not for mobile-radio reception

Appendix C: IEEE Symposium Paper

Testing for FM-Radio Interference in Motor Vehicles

Thomas F. Trost, Ye Jin, Jongsin Yun, Qianlin Zhou
Texas Tech University
Lubbock, TX 79409 USA

Abstract: A comparison has been carried out between two tests for predicting the effect of motor-vehicle RF emissions upon onboard FM receivers. The tests are Society of Automotive Engineers J551/4, an RF peak amplitude test, and State of Texas Tex-899-B, an FM receiver SINAD test. Tex-899-B would seem a natural choice because it employs an FM receiver like that used in the vehicle, but we have found that, by making judicious adjustments in the J551/4 limits, J551/4 can also be used, and this may afford an important testing option.

INTRODUCTION

The Texas Department of Transportation (TxDOT) has found that in some cases radio interference or noise is generated by the electrical system of a new fleet vehicle at such a level that it degrades the performance of the receiver in the two-way FM radio carried in the vehicle. In response, TxDOT has developed a test method to identify offending vehicles before they are put into service. TxDOT has also initiated the project described here as an independent investigation of the problem, focusing on testing methodologies and on cooperation with the vehicle manufacturers. The first portion of the project is covered in a TxDOT report [1], and the present paper includes the results from this report plus subsequent work to date.

Two EMC test standards were of primary interest, the test used by TxDOT and referred to above, Tex-899-B [2], and a Society of Automotive Engineers test, SAE J551/4 [3]. Both tests place limits on RF emissions. Tex-899-B specifies an RF emissions limit, indirectly, as the amount of noise that produces a 12 dB SINAD value [4] in the output of a TxDOT radio when an FM signal is present. J551/4 specifies direct limits on peak RF emissions for narrowband sources and for broadband sources. By design, Tex-899-B is well suited to uncovering potential TxDOT interference problems; but the applicability of J551/4 to the TxDOT situation was not known a priori.

OBJECTIVES AND APPROACH

Our objectives were to assess the degree of correlation between the two tests and to determine whether some modified form of the J551/4 test could be found that would be as effective as Tex-899-B and that the automakers would be willing to perform to qualify their vehicles for TxDOT service. J551/4 seemed like a better candidate than Tex-899-B for use by the automakers primarily because it appeared to be less time-consuming to carry out.

The range of frequencies where the TxDOT radios operate lies in the two-way radio low-band VHF range and extends from 47.02 MHz to 47.34 MHz. However our approach and our results are valid for automotive interference to wide-band FM radios operating at any frequency.

Our approach involved a two-pronged attack on the problem. First, we performed the J551/4 and Tex-899-B tests outdoors on a number of TxDOT vehicles. This work provided insight into the nature of the emissions produced. Second, we performed bench-top tests related to J551/4 and Tex-899-B on several TxDOT radios. Ten different types of RF noise sources were employed, including laboratory waveform generators simulating vehicle sources and actual vehicle components such as electric fuel pumps. This work gave us a chance to vary noise amplitudes and examine the effects on the radios.

VEHICLE TESTS

The test-equipment setup for the whole-vehicle tests was straightforward. For Tex-899-B, a magnetic-mount whip antenna was located on the vehicle roof and coupled, along with an FM signal generator, through a directional coupler to a TxDOT radio. The audio output of the radio was fed to a SINAD meter. For J551/4, the same antenna was connected instead to a CISPR-compliant EMI receiver (Rohde & Schwarz Model ESS) [5].

The test procedure was as follows: Vehicle electrical components that were potential noise sources were switched on and off. For the Tex-899-B test, while each component remained on, the FM signal amplitude required to achieve a 12 dB SINAD was noted. The specified limit is 0 dBμV, and the modulation is to have a frequency of 1.0 kHz and a frequency deviation of 3.3 kHz. For the J551/4 test, the peak noise reading on the EMI receiver was noted. The specified limits are 0 dBμV for narrowband and 28 dBμV for broadband noise, and the measurement bandwidths to be used are 9 kHz and 120 kHz, respectively.

The vehicles consisted of four Chevrolet, six Dodge, and three Ford pickup trucks. All had engines powered by gasoline or by gasoline and propane; and all were 1997 models, except for one of the Dodges which was a '96. Most of the trucks were tested by Southwest Research Institute in San Antonio [6,7], but some were tested by Texas Tech University at a field site near Lubbock and some by Professional Testing, Inc. at a site near Marble Falls, TX.

The three main sources of noise at low-band VHF were found to be the spark-ignition system, DC motors such as those in fuel pumps and HVAC fans, and electronic modules. The bandwidth of the spark-ignition and DC-motor noise is large, extending across the TxDOT range of frequencies. This is broadband noise. The bandwidth of the module noise is narrow, less than or comparable to the 15 kHz bandwidth of a TxDOT radio. This is narrowband noise. A discussion of the whole-vehicle test data is given below under Test Results and Analysis. A detailed presentation of the data is contained in [1].

BENCH TESTS

Our bench-top tests were conducted at Texas Tech University on five radio models, but concentrated on just two, the GE RANGR™ and the Motorola *MaraTrac*, which are the primary radios in the TxDOT fleet. A block diagram of the test-equipment setup is shown in Figure 1. The lines connecting the blocks represent coaxial cables. The noise sources are connected individually to the hybrid junction, which combines the noise and the FM signal and sends the combination to both the FM radio and the EMI receiver (Rohde & Schwarz Model ESS).

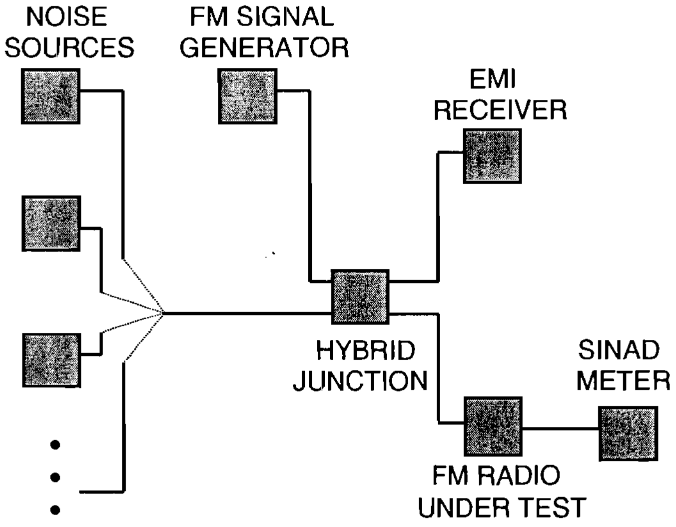


Figure 1. Block Diagram of Bench-Top Test System

The measurement procedure used with this setup contained a Tex-899-B component and a J551/4 component, thus allowing a comparison of the two test techniques for each radio. The procedure was as follows: (1) The FM signal was set to 0 dBμV, which is the Tex-899-B limit. (2) With a particular noise source connected, the noise amplitude was adjusted to produce a SINAD reading equal to 12 dB, which is the value used in Tex-899-B. (3) The FM signal was switched off and the amplitude of the noise was measured with the EMI receiver, as in the J551/4 test, thus giving the J551/4 value corresponding to the Tex-899-B limit.

Results show that the radios are very sensitive to narrowband noise but not to broadband. The radio IF noise blanker circuits are highly effective at removing the large, narrow pulses which are the basis of the broadband noise. A discussion of the bench-top test data is given below under Test Results and Analysis. A detailed presentation of the data is contained in [1].

TEST RESULTS AND ANALYSIS

Narrowband Emissions

Narrowband noise emissions were not found in the TxDOT frequency range (47.02 – 47.34 MHz) on the thirteen vehicles tested, although some were detected nearby at about 48 MHz.

The value needed for the J551/4 narrowband limit in order to achieve good correlation between the two tests was inferred from the bench test data. The resulting value is – 3 dBμV. It was obtained using a CW noise source and a *MaraTrac* radio, which is the newer of the two primary TxDOT radios. Thus the current J551/4 limit of 0 dBμV must be lowered a bit for application to the TxDOT situation. This result is not surprising since the maximum FM signal used in the Tex-899-B test (the Tex-899-B limit) has the same value, 0 dBμV; and the radios cannot tolerate an amount of noise that is equal to the amount of signal. That is, an FM detector requires that an interfering signal be at least a few dB below the desired signal for good reception [8].

Broadband Emissions

Broadband emissions were observed on the vehicles and were of such an amplitude as to cause the vehicles to pass the Tex-899-B test but to fail the J551/4 test. The emissions were due to DC motors and spark ignition. For the J551/4 measurements using the EMI receiver with 120 kHz bandwidth, the maximum DC-motor noise among all the vehicles was found to be 37 dBμV peak, and the maximum spark-ignition noise was 56 dBμV peak. Thus the current J551/4 limit of 28 dBμV must be increased to bring J551/4 into agreement with Tex-899-B.

Information on the required amount of increase comes from the bench test data. Here a slight complication is encountered, as it is found that a separate limit is needed for each kind of broadband noise. The reason for this is that not only the radios' FM detectors but also their noise blankers come into play, and the noise blankers are less effective against DC-motor noise than against spark-ignition noise. For DC-motor noise, the modified limit turns out to be 40 dBμV peak. This value applies to the *MaraTrac* radio, being slightly lower for the RANGR™. It comes from a bench test where a fuel pump, an HVAC fan, and a radiator fan were employed simultaneously as the noise source. The noise was coupled from the battery leads with a current transformer and connected to the hybrid junction (Figure 1) through an attenuator. There is an inherent randomness to DC-motor noise which gives the limit a statistical nature. Even for a long, two second, measurement time, we observed a 2 dB standard deviation in the peak noise readings.

For spark-ignition noise, the modified limit is very high. We used a laboratory pulse generator to simulate spark-ignition noise and applied up to 88 dBμV peak in a 120 kHz bandwidth to a TxDOT radio but still could not reduce the SINAD value below 28 dB, well above the required 12 dB value. The simulated noise consists of short, ringing pulses with low repetition rate (about 100 ns duration at 50 pps), and the radios display a refractory behavior to this kind of input. The maximum amplitude applied in these bench tests, 88 dBμV, measures 11 V peak-to-peak and is more than 30 dB above the highest value we observed in our vehicle tests. So it appears that although we do not know the value of the limit exactly, it is high enough that spark-ignition noise is not a threat to the radios, for the current generation of TxDOT trucks at least.

Combined Emissions

To test the radios' response to a combination of narrowband and broadband emissions we connected two of the bench-top noise sources in Figure 1 through a directional coupler to the hybrid junction. We used a CW source for narrowband and an HVAC fan for broadband and varied the relative amplitudes of the two while maintaining a 12 dB SINAD value on the radio (with 0 dBμV FM signal). The results are given in Figure 2 for a *MaraTrac* radio.

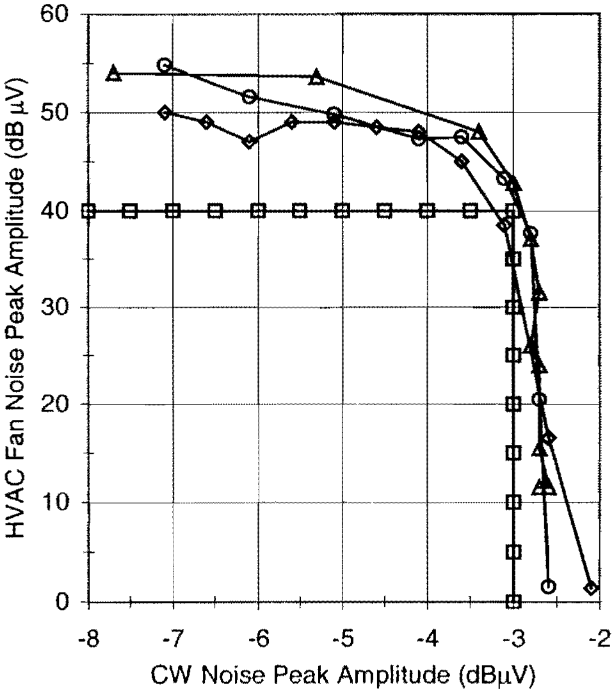


Figure 2. Comparison of Tex-899-B and Modified J551/4 Limits for a Combination of Narrowband and Broadband Noise

The same test was carried out three times to check repeatability, resulting in the three curves shown. The interpretation of these curves is that they mark the location of the Tex-899-B limit as a function of the amplitudes of the two noise sources. The horizontal and vertical lines drawn at 40 dBμV and –3 dBμV, respectively, give the location of our modified J551/4 limits. Hence the degree of correlation between the limits of the two tests can be visualized.

One might be inclined to argue that our 40 dBμV limit line in Figure 2 lies well below the left end of the curves and as such is too conservative. But, as a final step, the curves must be adjusted for the worst case in a vehicle, which means running a fuel pump and a radiator fan in addition to the HVAC fan, as mentioned above under Broadband Emissions. Our bench tests show that if two or three motors are running instead of just one, the radios are more strongly affected, and the curves in Figure 2 are displaced downward toward 40 dBμV. This will produce better agreement between the limits at the left end, although it will degrade somewhat the good agreement seen on the right at the knee of the curves.

Modified J551/4 Test

Shown in Table 1 is a suggested test plan for a J551/4-type test tailored to TxDOT needs. It contains the modified limits discussed above and also includes ambient limits, which are set 6 dB lower. The frequency range for the measurements is 46.9 MHz to 47.4 MHz, giving a slightly broader view than just the TxDOT range itself. Peak detection is to be used with a measurement time (or sweep time if using a spectrum analyzer) of 2 s.

All the limits in Table 1 were chosen to correspond to the limit of the Tex-899-B SINAD test conducted with a Motorola *MaraTrac* radio. A changeover to some other radio by TxDOT in the future might require adjustments to these limits.

Carrying out the test in Table 1 has advantages and disadvantages compared to carrying out Tex-899-B. The advantages stem from the use of an EMI receiver (or spectrum analyzer), as compared to a TxDOT radio, FM signal generator, and SINAD meter. With the receiver, the equipment setup is simpler; and, unlike the TxDOT radio, the EMI receiver is a common piece of calibrated laboratory instrumentation and one which admits computer control. The receiver also allows one to check not only the TxDOT frequencies for narrowband noise but also those frequencies in between and on either side. In this way, narrowband emissions that do not at the moment lie on a TxDOT frequency, but which are drifting and thus pose a potential threat, can be identified. On the other hand a disadvantage of the test in Table 1 is that, if new sources of RF noise arise in future vehicles and new TxDOT radios come into service, the Tex-899-B test will take these changes into account by simply changing to the new radio, while the modified J551/4 limits in Table 1 will have to be re-evaluated for the new situation.

Table 1. Modified J551/4 RF-Emissions Test for New TxDOT Vehicles

Test Configuration	Measurement Bandwidth (kHz)	Limit (dBμV)	Comment
1. Run engine until warm			
2. All OFF	9	– 9	Ambient
3. All OFF	120	34	Ambient
4. Engine OFF, key ON	9	– 3	Look for narrowband microcontroller emissions
5. Engine OFF, key ON, fuel pump, wipers, and HVAC fan ON (and radiator fan ON, if electric)	120	40	Look for broadband DC-motor emissions

Furthermore, the Table 1 test is fundamentally a less direct measure than Tex-899-B of the performance of FM radios in TxDOT vehicles.

CONCLUSIONS

Although the degree of correlation between the tests Tex-899-B and J551/4, with the original J551/4 limits, is poor, a series of changes in the J551/4 limits, as recommended here, would improve the correlation and allow J551/4 to be substituted for Tex-899-B. In addition, the EMI receiver or spectrum analyzer used with J551/4 provides testing flexibility unavailable from a TxDOT radio, such as fast measurements on many frequencies and computer control. If one can put up with a less direct method of predicting vehicle performance in the TxDOT setting, the modified J551/4 appears be an attractive alternative to Tex-899-B.

ACKNOWLEDGMENTS

This project was supported by the Texas Department of Transportation through Contracts 7-2995 and 7-4936. The project director was Don Lewis.

The EMI receiver, an RF signal generator, and a SINAD meter used extensively in this project were supplied by Rohde & Schwarz GmbH & Co. KG and Tektronix, Inc.

Valuable suggestions were contributed by B. Rehm of Professional Testing, Inc. and D. Mehrl of Texas Tech University. Research assistance was provided by Prasanna Bahukudumbi and Chad Bonner.

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Appendix D: MSEE Thesis by Prasanna Bahukudumbi

CHARACTERIZATION OF MOTOR VEHICLE RADIO INTERFERENCE USING AVERAGING DETECTORS

by

PRASANNA V. BAHUKUDUMBI, B.E.

A THESIS

IN

ELECTRICAL ENGINEERING

Submitted to the Graduate Faculty
of Texas Tech University in
Partial Fulfillment of
the Requirements for
the Degree of

MASTER OF SCIENCE

IN

ELECTRICAL ENGINEERING

Approved

Thomas F. Trost
Chairperson of the Committee

Thomas E. Krile

David Mehrl

Accepted

Interim Dean of the Graduate School

December, 2000

ACKNOWLEDGEMENTS

I would like to thank my family for their continuous support. I would like to thank Dr. Trost for his patience and guidance. His determination helped me to see through the problems and emerge successfully. His continuous assistance and involvement in the project made this possible. I would like to thank Dr. Krile for his persistence. I salute his amazing computing skill that helped me to back up my experimental findings with theoretical proof. I would like to thank Dr. Mehrl for his guidance, which helped me to proceed on my project with better thought.

I would like to extend my thanks to Mr.Yun who helped me with all my measurements and documentation. Finally, I would like to thank the people at the Texas Tech motor pool and the people of TxDOT whose cooperation helped me to complete the project.

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APPENDICIES

ABSTRACT

This research examined two different testing procedures for measuring the electromagnetic interference in a communication receiver in a motor vehicle. The procedures were analyzed, compared, and their differences were examined. The research found that by modifying one of the test procedures, the agreement between the two was improved.

The research also revealed the usefulness of an average detector in the estimation of one type of noise in the presence of other types. This led to development of a prototype of an auxiliary testing procedure. The prototype procedure takes advantage of a reduction in the ambient noise level in outdoor tests. This prototype gave good results when used in both laboratory and practical vehicle tests.

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CHAPTER I

INTRODUCTION

The last decade has shown a marked increase in the use of electronic products, which has also increased concern about electromagnetic interference. Electromagnetic Interference (EMI) is any electromagnetic disturbance that degrades the performance of any electronic equipment. The electronic industries are trying to minimize the interference problems by using suitable design measures [1, 2,3]. These industries have to produce electromagnetically compatible equipment to comply with the standards imposed by the government and to satisfy their customers. Organizations like the FCC [4], SAE [5], and CISPR [6] monitor product performance to maintain certain standards.

EMI testing is classified into four categories. These categories test various possibilities in both the control of emissions from the equipment and control of susceptibility of the equipment [3]:

1. Radiated emissions (RE),
2. Radiated susceptibility (RS),
3. Conducted emissions (CE), and
4. Conducted susceptibility (CS).

The radiated emissions test is used to measure the emissions radiated from the equipment and check it against a pre-defined limit set by the regulatory board. The radiated susceptibility test is used to measure the immunity of the equipment against radiated emissions from other electronic products. The remaining two categories are the same as the above except that they involve conducted phenomenon.

There are numerous sources that contribute to interference. They can be classified as natural and man-made. Some man-made interference sources are switching transients, DC motors, spark noise from ignition systems and harmonics of the clocks that are used in micro-controllers. Switching transients and ignition noise affect a huge spectrum because of their many spectral components.

1.1 Standard units used in measurements

The amplitude units used for the measurement of EMI are usually variants of the decibel [3]. The commonly used units are the dBm and dBμV. The unit dBm is the ratio of power with reference to 1mW:

$$\text{dBm} = 10 \log_{10} [\text{signal strength (mW)} / 1\text{mW}].$$

The unit dBμV is a ratio of voltage with reference to 1μV:

$$\text{dB}\mu\text{V} = 20 \log_{10} [\text{signal strength} (\mu\text{V}) / 1\mu\text{V}].$$

These units are related by the following expression in a 50-ohm EMI measurement system:

$$0 \text{ dBm} = 107 \text{ dB}\mu\text{V}.$$

The signals received as input to the receiver will be in the range of 1μV so these units suit the measurement range. Other less popular units are dBμV/MHz and dBμA [3].

1.2 Problems in vehicles

Nowadays automobiles contain a lot of electronic/electric equipment. Sometimes one piece of equipment causes significant interference to another. The main interference sources for a communication receiver in an automobile [7, 8] are the following:

1. Spark ignition noise produced from the spark plug. This noise is impulsive and extends across many MHz.

2. DC motor noise (from motors like fuel pump, HVAC fan, light bar, wipers and washer motors, etc.). This noise is due to the sparks produced at the brushes of motors.

3. Micro-controller noise. This noise is primarily due to the clocks and their harmonics.

These noise sources contribute to broadband and narrow-band noise. The communication receiver reacts differently to each. There are two standard testing procedures available for testing a communication receiver in a vehicle for electromagnetic interference:

1. Tex-899-B proposed by the Texas Department of Transportation (TxDOT) to test the two-way radios installed in their trucks. It has been recently renamed as Tex-1160-T (Appendix A).

2. J551 proposed by SAE (Society of Automobile Engineers) to test any communication receiver installed in a motor vehicle. Major vehicle manufacturers in the US use the J551 test (Appendix B).

These standards are used to quantify, and set limits on, the emissions from vehicles. They have different procedures and different results for the same communication receiver in the same automobile. This thesis intends to propose some changes, which will bring some agreement between the two standards. There are also proposals for an auxiliary testing procedure to test for interference in automobiles along with the J551 tests. The forthcoming chapters discuss the calibration tests made to assert the accuracy of the two test instruments used (Rohde & Schwarz EMI receiver and HP EMC analyzer), the standard testing procedures and their results, and then the use of average-detector measurements, the auxiliary testing procedure, and a comparison with the existing procedures. In arriving at the results, several trucks belonging to TxDOT were tested.

CHAPTER II

EVALUATION OF HP E7401A EMC ANALYZER

The first step in EMI measurement is calibration and testing the accuracy of the instrument to be used with a standard instrument. In this chapter an HP E7401A analyzer is compared with a Rohde& Schwarz ESVP receiver as the standard. The ESVP receiver has a CAL button which when pressed for 3 seconds calibrates the receiver with an internal generator as a reference [9]. The HP E7401A is a new product on the market, and it has both the features of an EMI receiver and a spectrum analyzer, i.e., the measurement capabilities of the receiver and the visual representation of the spectrum analyzer.

There are several new features in this analyzer, which make it suitable for pre-compliance tests. The limit disk gives the limits for the EMI testing for several applications [10]. The analyzer determines the result of a measurement based on the limit and displays pass or fail. The limits can be changed and corrections can also be added for different types of antenna and loads to minimize error in the measurement [11]. This analyzer has all the detectors of an EMI receiver (peak, quasi-peak and average). It has an internal memory to store waveforms, screens, traces and states. It runs on a 12 V battery, which makes it ideal for open area testing. The analyzer is much cheaper than the EMI receiver.

2.1 Internal noise level comparison

The internal noise levels of both the receiver and the analyzer were measured and listed in Table 2.1. The center frequency was 47.18 MHz and the RF attenuation was 0 dB.

Table 2.1: Internal noise levels of ESVP receiver and E7401A analyzer

	Pre-amp ON		Pre-amp OFF	
	BW=120 kHz	BW=9 kHz	BW=120 kHz	BW=9 kHz
ESVP Peak (dBμV)	0	-11.5	9.5	-2.1
ESVP Average (dBμV)	-12.3	-23.5	-4.6	-15.7
E7401A Peak (dBμV)	-0.2	-13.8	16.5	3.1
E7401A Average (dBμV)	-10.8	-22.3	2.9	-8.5

It is found that, with the pre-amp switched on, the noise level of the E7401A analyzer becomes comparable to that of the ESVP receiver.

2.2 Narrow-band comparison

Noise sources are divided into narrow-band and broadband. A comparison was done for each and the results were tabulated. The narrow-band comparison was conducted using a Fluke 6060B signal generator as a CW source at 47.18 MHz. Table 2.2 gives the receiver and analyzer settings, and Table 2.3 gives a comparison of their measured values for the CW signal using a sine-wave source. Table 2.3 also compares both conditions of pre-amp ON and OFF, so it is also used to determine the effect of the pre-amp on narrow-band signals.

Table 2.2: Measurement setting on the receiver and the analyzer

	ESVP	HP E7401A
Attenuation	0 dB (Auto attenuation ON)	0 dB (Auto attenuation ON)
Bandwidth	10 kHz	9 kHz (span 0 Hz)
Sweep Time/ Measurement Time	2 sec	2 sec

The table shows good agreement for a peak measurement between the receivers and the source at strong signal levels (-90 to –30 dBm). The agreement in the peak measurement improves when the pre-amplifier is on at low signal levels (-120 to –100 dBm). The dynamic range in the case of the ESVP can be chosen from one of the three available ranges (20, 40 and 60 dB). We can see that at low signal levels the measured value is limited by the internal noise of the receivers.

Table 2.3: Comparison of the receiver and the analyzer for a CW signal input

Source (dBm)	Pre-amp ON (dBm)				Pre-amp OFF (dBm)			
	ESVP		E7401A		ESVP		E7401A	
	Peak	Avg	Peak	Avg	Peak	Avg	Peak	Avg
-30	-30.2	-30.5	-30.65	-30.72	-30.4	-30.5	-30.47	-30.38
-40	-40.5	-40.5	-40.71	-40.67	-40.3	-40.5	-40.43	-40.31
-50	-50.3	-50.6	-50.67	-50.61	-50.1	-50.5	-50.35	-50.21
-60	-60.5	-60.2	-60.71	-60.46	-60.5	-60.2	-60.2	-60.17
-70	-70.2	-70.2	-70.46	-70.35	-70.3	-70.5	-70.13	-70.15
-80	-80.5	-80.6	-80.29	-80.3	-80.1	-80.5	-79.87	-80.13
-90	-90.2	-90.5	-89.86	-90.3	-89.97	-90.3	-89.2	-90.17
-100	-99.6	-100.6	-99.6	-100.3	-98.1	-100.5	-97.8	-100.2
-110	-107.9	-110.7	-107.8	-110.4	-103.9	-110.3	-101.9	-109.9
-120	-113.3	-120.4	-115.2	-120.3	-108.8	-118.8	-105.4	-114.6

2.3 Broadband comparison

The broadband source used for the receiver-analyzer comparison was an EH 139B pulse generator. It was set for a pulse width of 10 ns and a repetition rate of 1500 pps. The bandwidth of the receiver and analyzer was changed to 120 kHz. Other settings remained the same as the narrow-band settings.

Table 2.4: Comparison of the peak measurement for a pulse source

E7401A (dBμV) Pre amp OFF	ESVP (dBμV)	E7401A (dBμV) Pre amp ON
15.62	9.5(Pre amp ON)	10.7
20.2	18.6	18.9
25.3	24.5	24.7
34.5	33.7	33.3
43.5	42.9	39.2
54.4	53.8	37.5
64.1	64.7	41.1

From Table 2.4, the E7401A with pre-amp OFF has higher peak values than the ESVP. The pre-amp had to be switched on for the 9.5 dBμV measured on the ESVP because it was close to the noise level (refer to Table 2.1). The rest of the measurements taken using the ESVP had the pre-amp OFF. The pre-amp of the HP seems to saturate around 34 dBμV. This seems to be a limiting factor with the HP analyzer because usually the pre-amp is switched on during measurements on vehicles, where the signal varies widely from a couple of dB to several of tens of dB.

2.4 Comparison of filter shapes

Using a fixed source and varying the center frequency of the receivers the filter shapes of the receiver and analyzer were determined. The input amplitude of the signal generator was set at -70 dBm and the frequency at 47.18 MHz. The center frequency of the receivers was changed in steps of 1 kHz.

From Figures 2.1 and 2.2, it is evident that the filter shapes of the receiver and analyzer are different. The ESVP has a filter with very low skirts. The filters are designed based on the CISPR specification [12], and it is evident that both filters satisfy these specifications. However the ESVP has a higher rejection level outside the pass band and so a better filter shape than the E7401A.

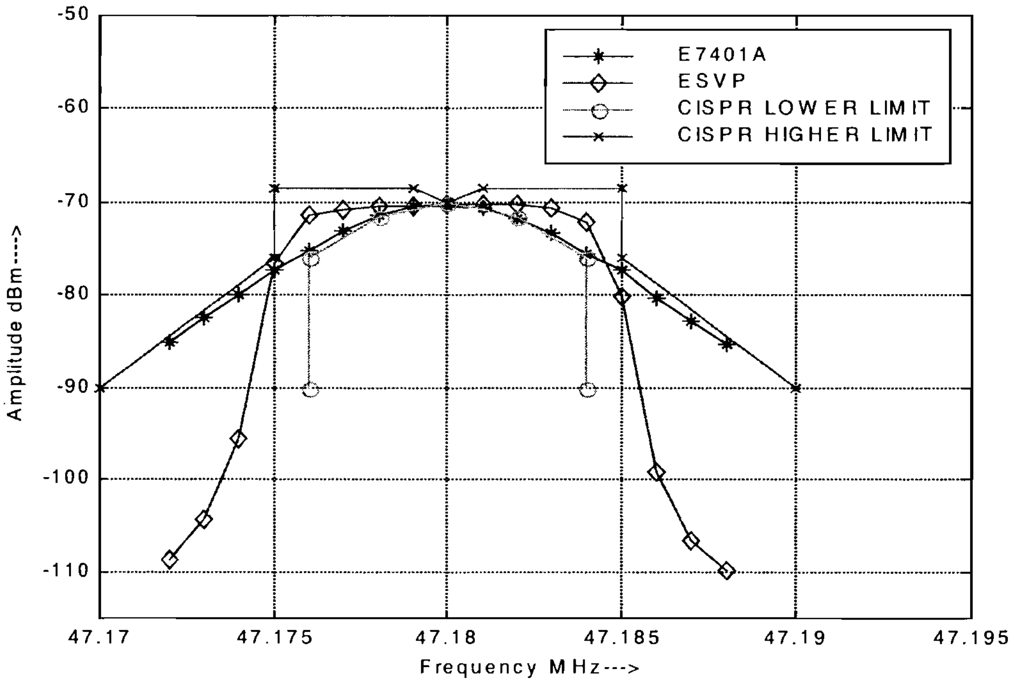


Figure 2.1: Comparison of filter shapes for BW = 9/10 kHz

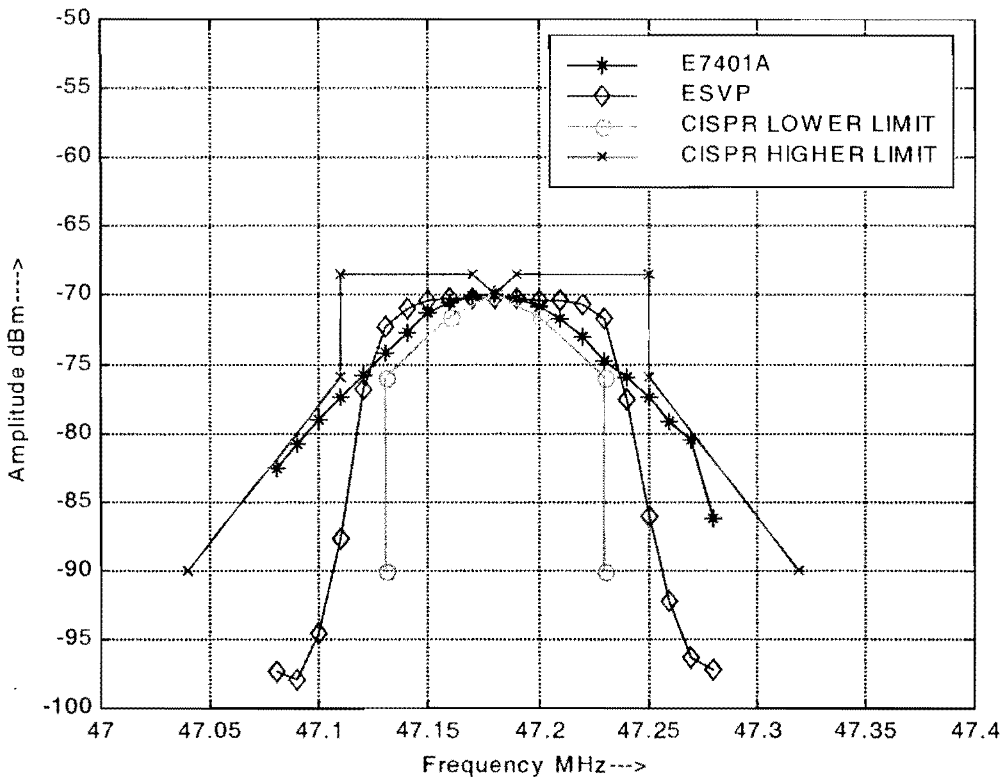


Figure 2.2: Comparison of filter shapes for BW = 120 kHz

2.5 Comparison of average measurements

The receiver and the analyzer employ average detectors which, unfortunately, display a somewhat non-ideal behavior. The ESVP has an average detector that in some cases gives different results for different operating ranges (20, 40 and 60 dB). The E7401A has an average detector that gives different results when the pre-amp is switched on. It also has another averaging technique called video averaging. In this kind of averaging the analyzer changes its mode to sample detect, and it averages the amplitudes at particular frequencies for a specific number of scans set by the user. The trace obtained as a result is essentially the geometric average amplitude. The EH 139B pulse generator was used for comparing average detectors. The pulse repetition rate was varied while the amplitude and the pulse width were fixed. The pulse width was 10 ns and amplitude was 38.5 dBμV at 47.18 MHz.

Table 2.5: Measured peak values at 9/10 kHz bandwidth

ESVP 20 dB range (dBμV)	ESVP 40 dB range (dBμV)	ESVP 60 dB range (dBμV)	E7401A Pre-amp OFF (dBμV)	E7401A Pre-amp ON (dBμV)
38.5	38	38.5	39	27

Tables 2.5 and 2.6 show the measured peak and average values. These are used to plot a peak-to-average ratio graph for comparison with theoretically calculated peak-to-average values (refer to Chapter V, section 1). It is found that the HP peak with the pre-amp ON has a different value which is around 11 dB less than all other peaks. That effect is mainly due to saturation of the pre-amplifier. VA in Table 2.6 means video averaging.

Table 2.6: Measured average values at 9/10 kHz bandwidth

Repetition Rate (Hz)	ESVP 20 dB range (dBμV)	ESVP 40 dB range (dBμV)	ESVP 60 dB range (dBμV)	HP Pre-amp OFF (dBμV)	HP Pre-amp ON (dBμV)	HP VA Pre-amp OFF (dBμV)
50	-12.5	-19.2	-19.2	-4.11	-20.5	-8.7
100	-8	-15.8	-15.4	-1.02	-20.1	-5.6
500	17.2	8.1	10.2	10.7	-13.85	-4.5
1000	19	18.8	18.9	17.16	-8.45	10.5
2000	28.7	28.5	28.5	22.7	-4.88	16.89
3000	29.6	29.5	29.5	26.7	-0.34	25.6
4000	33.1	32.9	32.9	28.87	2.77	25.6
5000	34.1	34	33.5	31.3	4.787	28.5
7000	35	35.8	36.1	33.54	7.1	32.9
10000	37.2	37.1	37.2	35.39	8.5	32.8

Figure 2.3 shows a graph of all the peak-to-average ratios.

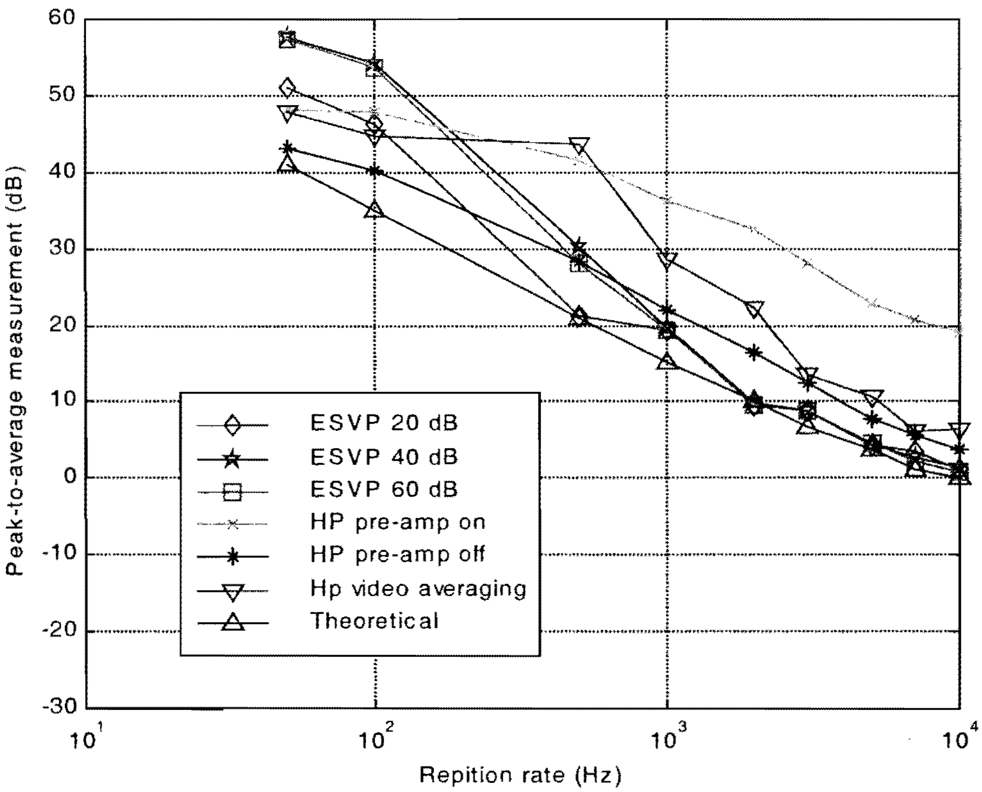


Figure 2.3: Comparison of different averaging techniques (9/10 kHz)

From the graph, it looks like the measurements from the ESVP fit the theoretical curve after 1 kHz. The ESVP readings (40 and 60 dB) for 50 Hz are approximately 4 dB above the noise level so it may not be accurate. The HP pre-amp OFF is also close to the theoretical curve. The HP video averaging is many dB greater than the theoretical curve but comes close to the theoretical curve as the frequency increases (after 1 kHz). The shape of the HP average with pre-amp ON looks similar to the theoretical curve but shifted by 20 dB. The points in the graph close to 60 are only about 4 dB above the noise level of the receiver.

Tables 2.7 and 2.8 contain the peak and average values measured at 120 kHz bandwidth. From these are plotted the peak-to-average ratio to compare with theoretically calculated peak- to-average values. It is clear from the table that the peak and the average of E7401A pre-amp ON are low due to the saturation of the pre-amp.

Table 2.7: Measured peak values at 120 kHz bandwidth

ESVP 20 dB range (dBμV)	ESVP 40 dB range (dBμV)	ESVP 60 dB range (dBμV)	HP Pre-amp OFF (dBμV)	HP Pre-amp ON (dBμV)
61.4	59.9	60.1	60.56	40.8

Table 2.8: Measured average values at 120 kHz bandwidth

Repetition Rate (Hz)	ESVP 20 dB range (dBμV)	ESVP 40 dB range (dBμV)	ESVP 60 dB range (dBμV)	E7401A Pre-amp OFF (dBμV)	E7401A Pre-amp ON (dBμV)	E7401A VA (dBμV)
50	-8.9	-11.2	-10.6	3.3	-10.5	2.4
100	-6.8	-10.5	-9.3	3.4	-10.2	3.7
500	1.9	-4.4	1.4	8.9	-7.3	3.8
1000	4.4	0.2	4.6	12.3	-5.7	3.9
2000	28.1	28.4	27.4	21.8	-1.3	3.8
3000	29	29.9	29.2	22.6	1.8	3.4
4000	35.7	34.1	35.1	27.4	4.1	7
5000	36.3	37.3	36	30.7	5.7	6.8
7000	38	38.2	38	33.8	7.6	13.5
10000	43.3	41.6	42.7	36.8	10.8	23.5
20000	48.4	48.4	48.4	42.5	16.6	32
30000	51.6	51.4	51.3	46.5	19.8	42
40000	53.5	53.2	53.3	49.1	22.5	44.2
50000	55.3	55.6	55.7	52.3	25.5	48.3

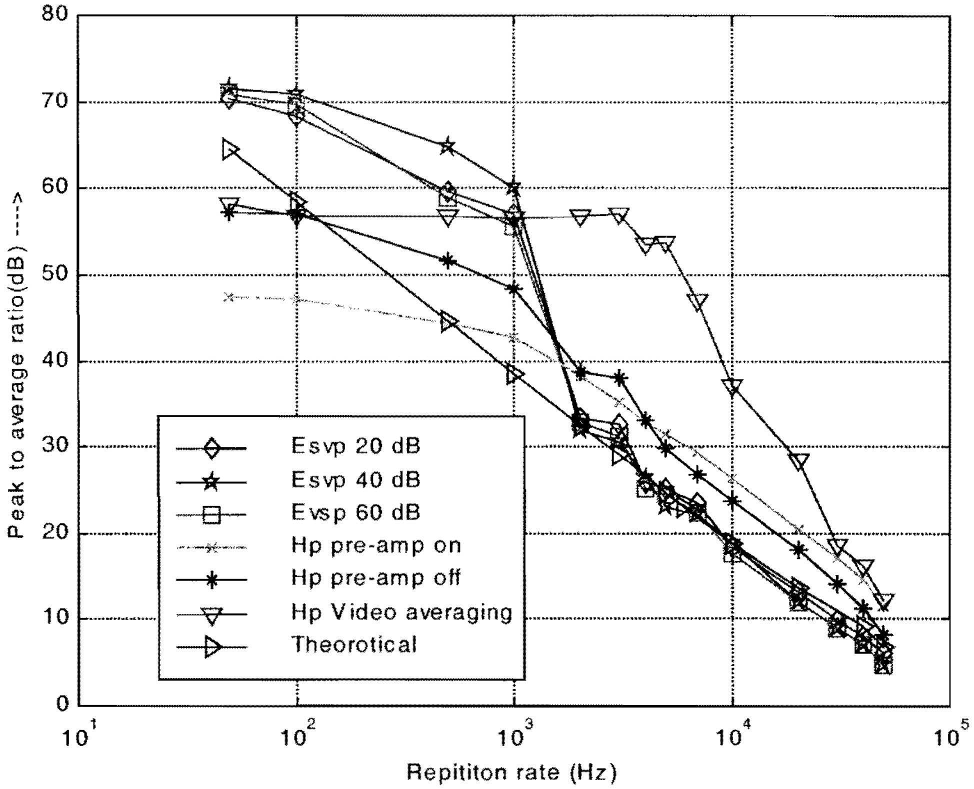


Figure 2.4: Comparison of different averaging techniques (120 kHz)

The graph in Figure 2.4 compares peak-to-average of different averaging techniques from the receiver and analyzer with the theoretical (refer to Appendix C). The ESVP readings for 50 Hz are approximately 4 dB above the noise level so they may not be accurate. From the graph, it looks like the measurements from the ESVP fit the theoretical curve after 1 kHz. The E7401A pre-amp OFF is consistently several dB above the theoretical curve. The E7401A video averaging curve does not have a shape similar to the theoretical curve but comes close to the theoretical curve at the highest frequency. The E7401A average with pre-amp ON looks similar to the E4701A pre-amp OFF. Note that while the peak and the average of the E7401A are both low, peak-to-average ratio is compensated and is close to the theoretical curve. The calculation of the theoretical peak- to-average ratio is discussed in Chapter V.

2.6 Noise emissions from the ESVP and E7401A

Our measuring instruments were not perfectly quiet. Weak emissions from the ESVP receiver were measured with the E7401A analyzer, and vice versa. The receiver radiated in a narrow band from 47.099 to 47.105 MHz and the amplitude was around -5 dBμV. The analyzer had harmonic emissions at 46.99, 47.205, 47.4 and 47.62 MHz. The amplitude was around 0 dBμV.

2.7 Summary

The data examined above suggest that the E7401A analyzer is good but has some deficiencies. There is pre-amp saturation, and the filters should have a higher order to give better rejection outside the band. The average measurement of pulses has a problem when the pre-amp is switched on. The E7401A analyzer has several advantages as listed in the beginning of this chapter.

CHAPTER III

Tex-899-B TEST

The Tex-899-B procedure was proposed by the Texas Department of Transportation. It was developed to support their network of two-way radios installed in their trucks. This procedure is listed in Appendix A. Results have been reported by Zhou [13]. The instruments we used to perform this procedure are the following:

1. Radio communication monitor (Rohde & Schwarz CMS 54),
2. Directional coupler (Synergy Microwave KDK-702),
3. 50 ohm load,
4. Antenna with coaxial cable (Larsen NMO 50 whip with Maxrad magnetic mount), and
5. Two way radio (Motorola MaraTrac).

The radio communication monitor is used to generate the FM signal and is also used as a SINAD meter to measure the SINAD value at the output of the radio.

3.1 TxDOT Dodge trucks 2-5643-G and 2-5649-G

We tested two TxDOT trucks. They were both Dodge 1999-model trucks, and both had dual fuel systems (gasoline and propane). These trucks had a Motorola MaraTrac radio installed behind the seat. The microphone, speaker and the control box were installed near the cigarette lighter. A light bar was installed on the roof of one of the trucks and on the headache rack of the other.

The radios in the trucks were scanned to find the frequencies (modes) programmed in them. Eight different modes were found and their respective frequencies were noted down. They are listed in the table below. The frequency 47.18 MHz is a special frequency since it is the only frequency that is common to every Department of Transportation office in Texas.

Table 3.1 Mode number and its respective center frequency, TxDOT trucks

Mode Number	Frequency (MHz)
1	47.18
2	47.06
3	47.24
4	47.26
5	47.34
6	47.02
7	47.04
8	47.08

An antenna was installed at the center of the roof of each truck. The antennas were tested at Texas Tech University to determine their VSWRs. A network analyzer was used for this purpose and was scanned from 30 to 80 MHz. Both antennas were found to be acceptable.

Both the trucks from TxDOT were tested at the same test site (west of Abernathy) one after other. The eligibility of the test site was determined by the following measurements listed in Table 3.2. The receiver sensitivity SG_R represents the lower limit for measurement using the receiver (refer to Figure A.1, Appendix A). The load and coupler was connected and the amplitude of the FM signal was adjusted to get 12 dB

SINAD, This represents the noise level of the receiver for a 12 dB SINAD reading (SG_L) (refer to Figure A.2, Appendix A). The load was removed and the antenna was connected. The amplitude of the input FM signal was adjusted to obtain the amplitude value corresponding to 12 dB SINAD (SG_A). This represents the ambient noise level. The difference between SG_A and SG_L gives the ambient noise level relative to internal noise level. This also compensates for the 20 dB attenuation of the direction coupler on the input FM signal. The difference is added to the receiver sensitivity to add the effect of the receiver (SG_E). SG_E has to be less than -6 dBμV for a site to pass (refer to Site Qualification Standards, Appendix A).

Table 3.2 Ambient noise levels

	Mode 6 47.02 MHz	Mode 1 47.18 MHz	Mode 5 47.34 MHz
SG_R Receiver sensitivity	-12 dBμV		
SG_L 12 dB with load	8 dBμV		
SG_A 12 dB with antenna	12.3 dBμV	12.3 dBμV	12.3 dBμV
$SG_{AL}=SG_A-SG_L$	4.3 dB	4.3 dB	4.3 dB
$SG_E= SG_{AL}+ SG_R$	-7.7 dBμV	-7.7 dBμV	-7.7 dBμV

The test site passes if SG_E is less than -6 dBμV. From the above table the site passes for testing the trucks since it has -7.7 dBμV.

After checking the level of ambient noise, measurements were conducted on the noise produced by the truck, and the results are summarized below

Table 3.3 Summary of Tex-899-B test on the Dodge truck from TxDOT (2-5649-G)

EVENT	Amplitude level for 12 dB SINAD value (dBμV)		
	47.02 MHz	47.18 MHz	47.34 MHz
Key on (gasoline)	13.2	12.9	15.8
Key on (propane)	13.1	12.7	17.7
Light bar	12.2	11.9	13.7
Wipers	13	15.3	16.7
Fan	12.5	12.5	15.9
Fuel pump	13.2	12.9	12.5
Fan and fuel pump	13.8	13.2	17.9
Turn signals	12.2	11.9	12.3
All systems (gasoline)	16	16	20.1
All systems (propane)	16.2	16	19.5

Referring to Appendix A, we can see that the limit that determines the pass or failure is 0 dBμV. We used a directional coupler, which adds 20 dB attenuation, so the limit in Table 3.3 is 20 dBμV. That is, the system passes if the amplitude level for a 12 dB SINAD is less than 20 dBμV.

Analyzing the above data it is found that this truck failed the Tex-899B test at 47.34 MHz when all systems were running in gasoline by 0.1 dB. Since the difference is very small, we can consider that this truck passed the test.

A new type of noise was noticed at 47.34 MHz when the key was switched on. Usually key-on measurements reveal micro-controller narrowband noise, but this new noise type was found using our EMI receiver to be broadband (refer to Figure 4.1).

Table 3.4 Summary of Tex-899-B test on the Dodge truck from TxDOT (2-5643-G)

EVENT	Amplitude level for 12 dB SINAD value (dBμV)		
	47.02 MHz	47.18 MHz	47.34 MHz
Key on (gasoline)	14.7	14.3	18.3
Key on (propane)	15	14.7	18.4
Light bar	16	15.6	19.9
Wipers	16.2	15	18
Fan	15	14.8	18.6
Fuel pump	13.9	13.6	15.1
All systems (gasoline)	17.4	18.2	19.6
All systems (propane)	17.4	17.6	19.6

Table 3.4 shows the Tex-899-B data for the other TxDOT truck. Analyzing the data reveals that this truck passed the Tex-899-B test (20 dBμV limit). The new type of noise was noticed in this truck also when the key was switched on.

3.2 Texas Tech University Dodge truck

We also performed the Tex-899-B test on a 1999 Dodge truck belonging to Texas Tech University. This had no radio and antenna. We used a Larsen antenna with magnetic mount and a MaraTrac radio, which was programmed for 60 modes. Table 3.5 lists the modes that were used for the Tex-899-B testing.

Table 3.5: Mode number and its respective center frequency, TTU trucks

MODE NUMBER	FREQUENCY (MHz)
6	47.02
12	47.14
14	47.18
22	47.34
23	47.36
24	47.38
26	47.42

The ambient noise levels were measured to determine the eligibility of the test site. The test site passes if SG_E is less than -6 dBμV. As noted from the data in the Table 3.6 this site passed the test.

Table 3.6: Ambient noise levels

	Mode 6 47.02 MHz	Mode 14 47.18 MHz	Mode 22 47.34 MHz
SG_R Receiver sensitivity	-12 dBμV		
SG_L 12 dB with load	8 dBμV		
SG_A 12 dB with antenna	12 dBμV	10.7 dBμV	11.7 dBμV
$SG_{AL}=SG_A-SG_L$	4 dB	2.7 dB	3.7 dB
$SG_E= SG_{AL}+ SG_R$	-8 dBμV	-9.3 dBμV	-8.3 dBμV

The Tex-899-B results for this truck are tabulated in the Table 3.7. The truck did not have the light bar or an alternative fuel system. The key-on test was also repeated at two different frequencies, 47.38 MHz and 47.42 MHz. As shown in Table 3.8, the micro-controller noise registered up to 35.3 dBμV. The measurements were not conducted at 47.18 MHz because of a high ambient noise in that frequency.

Table 3.7: Summary of Tex-899-B test on the Dodge truck from Texas Tech

EVENT	Amplitude level for 12 dB SINAD value (dBμV)	
	47.02 MHz	47.34 MHz
Key on	16.3	21
Wipers	15.4	22.1
Fan	16.3	21.2
Fuel pump	14.9	14.4
Fan, fuel pump and wipers	17	22.3
Fan, fuel pump, wipers and washer	18	24
Engine idle	18	21.2
Engine idle, and all motors except washer	14.9	-
All systems (gasoline)	17.4	21.4

Table 3.8: Tex-899-B key-on test for other frequencies

EVENT	Amplitude level for 12 dB SINAD value (dBμV)	
	47.38 MHz	47.42 MHz
Key on	35.3	24.5

This truck failed the test at 47.34 MHz, which is the last frequency in the TxDOT range. Here the DC motor noise is heavily contaminated by the micro-controller noise, while at the lower frequency, where the micro-controller noise is low, we can see that the noise from the DC motors is below the limit.

3.3 Texas Tech University Chevrolet truck

This was a Chevy '99-model truck. It did not have a radio or an antenna, so we used the same MaraTrac radio used before and the same Larsen antenna. This truck did not have any extra electrical components installed after purchase from the manufacturer (like the light bar or the alternate fuel system).

From Table 3.9, we can see that the location selected for the open area testing of this truck passed the test since its SG_E is less than -6 dBμV.

Table 3.9: Ambient noise levels

	Mode 6 47.02 MHz	Mode 1 47.18 MHz	Mode 5 47.34 MHz
SG_R Receiver sensitivity	-12 dBμV		
SG_L 12 dB with load	8 dBμV		
SG_A 12 dB with antenna	10.4 dBμV	10.74 dBμV	10.4 dBμV
$SG_{AL}=SG_A-SG_L$	2.4 dB	2.4 dB	2.4 dB
$SG_E= SG_{AL}+ SG_R$	-9.6 dBμV	-9.6 dBμV	-9.6 dBμV

The measurements were conducted on the noise from the truck and the results are tabulated below in Table 3.10. From the table, it is concluded that this truck is extremely silent and passed the TxDOT test. EI means engine idle.

Table 3.10: Summary of Tex-899-B test on the Chevrolet truck from Texas Tech

EVENT	Amplitude level for 12 dB SINAD in dBμV		
	47.02 MHz	47.18 MHz	47.34 MHz
Key on	11.2	10.8	10.8
HVAC fan	11.6	11.3	11.1
Wipers	11.6	11.8	11.8
Fuel pump	10	9.8	10.8
All above + washer	12	11.9	12
Engine idle	16.3	16.3	16.5
Washer + engine idle	15.4	15.4	15.7
EI + all motors but no washer or wipers	13.8	13.7	13.9
EI + all motors but no washer	16.7	-	-
All systems	19.2	19.2	-

3.4 Texas Tech University Ford truck

This truck is a '98-model Ford truck. The antenna used before was not suitable, so we used a different length antenna for testing this truck. The same radio was used for testing. From Table 3.11, SG_E is below -6 dBμV, so the site passes the test and is fit for testing.

Table 3.11: Ambient noise levels

	Mode 6 47.02 MHz	Mode 1 47.18 MHz	Mode 5 47.34 MHz
SG_R (receiver sensitivity)	-12 dBμV		
SG_L (12 dB with load)	7.9 dBμV		
SG_A (12 dB with antenna)	9.9 dBμV	9.9 dBμV	9.9 dBμV
$SG_{AL}=SG_A-SG_L$	2 dB	2 dB	2 dB
$SG_E= SG_{AL}+ SG_R$	-10 dBμV	-10 dBμV	-10 dBμV

The measurements were conducted on the truck noise, and results are tabulated in Table 3.12.

Table 3.12: Summary of Tex-899-B test on the Ford truck from Texas Tech

EVENT	Amplitude level for 12 dB SINAD value (dBμV)		
	47.02MHz	47.18MHz	47.34MHz
Key on (gasoline)	9.9	10	10.3
Wipers	10.3	10.5	10.5
Fan	12.5	12.4	12.4
Fuel pump	10.6	10.6	10.7
Fan, wipers and fuel pump	13.3	12.8	13.5
Fan, wipers, fuel pump and washer motors	13.9	13.8	13.8
Engine idle and all motors on except washers	14.6	-	-
All systems (gasoline)	15.6	15.6	15.9

All the values in the table above are much less than the 20 dB limit so we can conclude that this truck is extremely quiet.

The next chapter discusses the details of J551/4 tests on the trucks previously tested under Tex-899-B. By comparing the test results, the validity of the J551/4 limits is assessed.

CHAPTER IV

J551/4 TEST

The Society of Automotive Engineers proposed the J551/4 test. It was devised to check for interference on a communication receiver in an automobile. The test procedure is given in Appendix B. The instruments used by us for this test are listed below:

1. EMI receiver (Rohde & Schwarz ESVP),
2. Antenna with coaxial cable (Larsen NMO 50 whip with Maxrad magnetic mount), and
3. 50 Ω load.

Table 4.1 contains the internal noise values of the receiver. These values limit the sensitivity of the receiver.

Table 4.1: Noise level of EMI receiver at 47.18 MHz

	Pre-amp ON		Pre-amp OFF	
Bandwidth (kHz)	120	10	120	10
Peak (dBμV)	0.6	-11.5	8.6	-3.6
Average (dBμV)	-12.5	-23.3	-3.6	-15.7

4.1 TxDOT Dodge trucks: 2-5649-G and 2-5643-G

The site where the open area testing was conducted was first tested for ambient noise, and its suitability was determined. The antenna was mounted on the vehicle and the ambient noise levels were noted down. The requirement for the site to be suitable for measurements of vehicle emissions is that the ambient level should be at least 6 dB less than the limit of the vehicle noise to be measured. For CW noise, the limit when using 10 kHz BW and a peak detector is -3 dBμV [14]. From Table 4.2, the ambient noise was -6.4 dBμV. Since this was not at least 6 dB down from -3 dBμV, the site was not suitable. For DC motor noise, the limit when using a 120 kHz bandwidth and a peak detector is 50 dBμV or 40 dBμV [14, 15]. From Table 4.2, the ambient noise was 5.4 dBμV. Since this was well beyond the 6 dB margin, the site was suitable.

Table 4.2: Ambient noise levels at 47.18 MHz

	Pre-amp ON		Pre-amp OFF	
Bandwidth (kHz)	120	10	120	10
Peak (dBμV)	5.4	- 6.4	9.7	- 2.5
Average (dBμV)	- 7.2	-18	-3.5	-14.5

Each noise source was switched on and the peak value at 120 kHz bandwidth was noted. The summary of the test results is shown in the Table 4.3.

Table 4.3: Summary of J551/4 test on TxDOT truck (2-5649-G)

EVENT	Amplitude at 47.02 MHz (dBμV)	Amplitude at 47.34 MHz (dBμV)
Light bar	43.3 to 47	44 to 46
Fan	10.5 to 11.7	15.7 to 17
EI + fan	48 to 54.2	52.7 to 54.8
EI + fan + light bar	51.2 to 53.9	52.2 to 53.4
EI + light bar	51.3 to 53.9	50.4 to 52.1
Fuel pump	11 to 13.5	10.3 to 12.4
Wipers	31.3 to 35.2	28.9 to 32.4
Wipers + washer	52 to 54.9	49.1 to 54.3
EI + wipers	53.4 to 54.3	53.2 to 55.2
EI	49.7 to 54.5	52 to 53.9

The limit for a single DC motor is 50 dBμV [14] and for 2 or more DC motors is 40 dBμV [14]. From Table 4.3 the truck fails in the cases where the washers were on. This is different from the result of the Tex-899-B test (refer to Table 3.3). Engine idle (EI) produces spark ignition noise which often has higher peak noise and for which there is no limit because of noise blanker effectiveness.

Looking at the narrow-band key-on scan, Figure 4.1 shows the TxDOT range (47.02 to 47.34 MHz) and beyond. The scan reveals the existence of broadband noise extending from 47.3 to 47.5 MHz (around 200 kHz). The narrow spikes are interference from vehicles passing near the test site. The micro-controller broadband noise is discussed in more detail in Chapter V. The noise has no pre-defined limit, so in Chapter V the limit is defined and the procedure used for obtaining the limit is explained. The peak of the micro-controller noise is very high but its average is less. The micro-controller noise is strongest at 47.37 MHz, which is outside the TxDOT range.

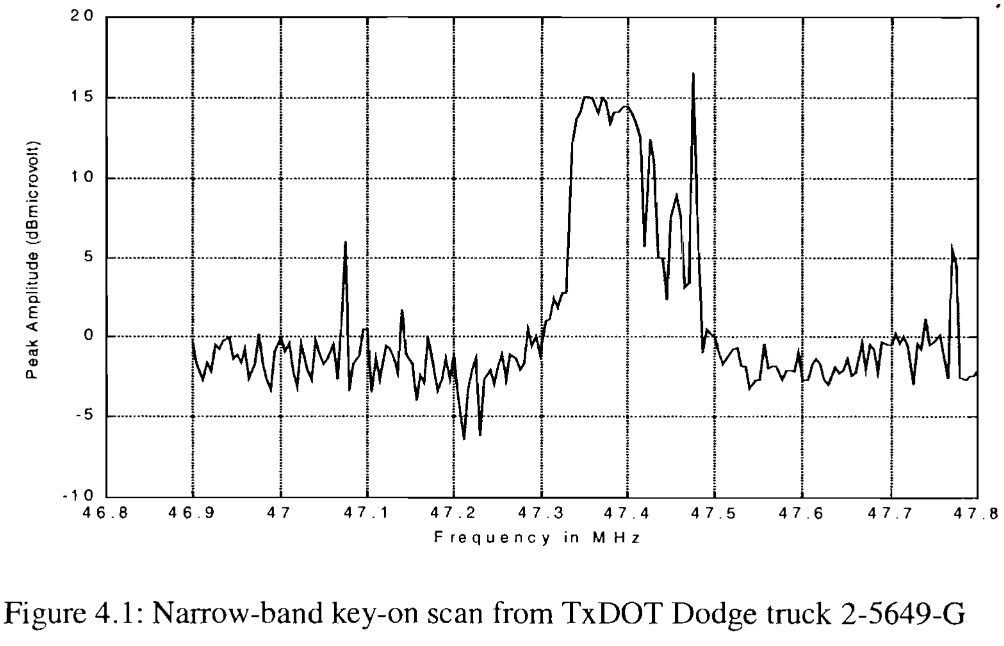


Figure 4.1: Narrow-band key-on scan from TxDOT Dodge truck 2-5649-G

The truck 2-5643 was tested after testing the previous trucks at the same spot, and the ambient conditions remained stable (refer to Table 4.4).

Table 4.4: Summary of J551/4 test on TxDOT truck (2-5643-G)

EVENT	Amplitude at 47.02 MHz (dBμV)	Amplitude at 47.34 MHz (dBμV)
Light bar	26.1 to 30.1	30 to 34.8
Fan	9.6 to 11.3	19.5
EI + fan	55.3 to 57	54.3 to 56.2
EI + fan + light bar	55.6 to 59.4	56.1 to 59
EI + light bar	53.1 to 58.2	55.1 to 59.2
Fuel pump	6.3	4 to 6
Wipers	22.7 to 29.8	29.8 to 34.2
Wipers + washer	55.9 to 60.6	52.8 to 56.2
EI + wipers	52.4 to 53.8	53.8 to 54.6
EI	52.5 to 56.3	53.2 to 55.6

The limit for a single DC motor is 50 dBμV [14] and for 2 or more DC motors is 40 dBμV [14]. From Table 4.4, the truck fails in the cases where the washer was ON. From Table 3.4, we can see that this result does not agree with the Tex-899-B test, where the truck just passed. This creates a requirement for a new limit on DC motors.

Let's look at the narrow-band scan. Figure 4.2 shows a result similar to Figure 4.1. The spike is interference from a vehicle passing near the test site. It was found that the micro-controller level was about 5 dB lower than that of the previous truck. In this truck, the micro-controller noise starts at 47.34 MHz frequency which is the highest frequency used by TxDOT.

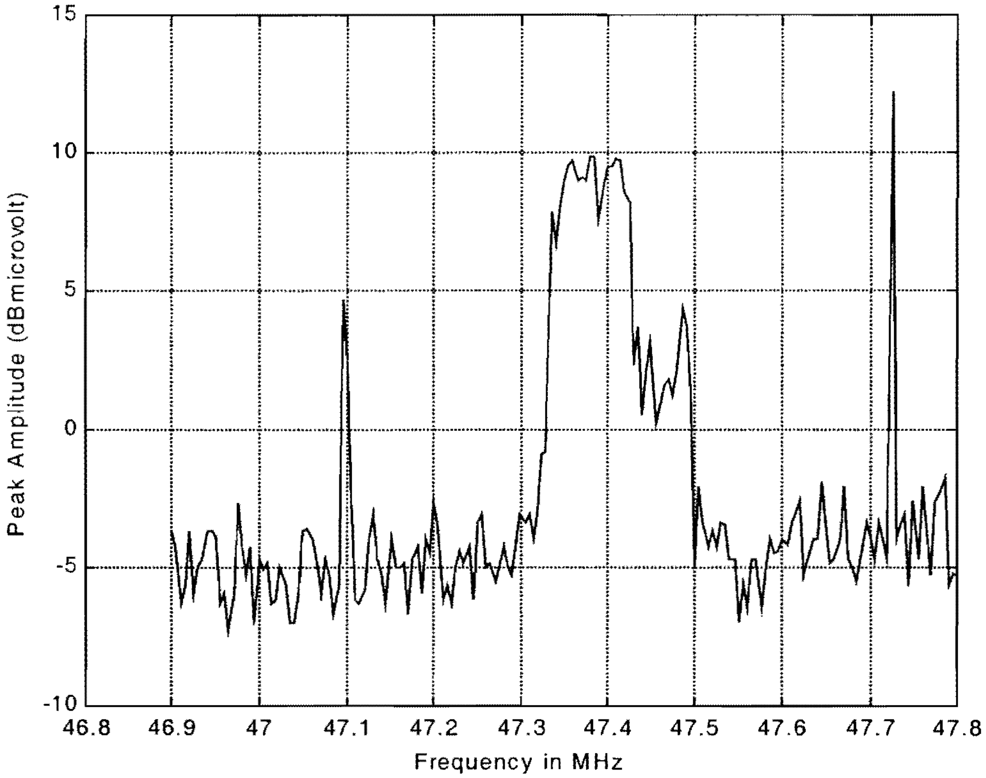


Figure 4.2: Narrow-band key-on scan from TxDOT Dodge truck 2-5643-G

This micro-controller noise can originate from any of the micro-controllers in the truck. There were five micro-controllers in the trucks we tested ('99 Dodge). The micro-controller noise was also recorded on a portable oscilloscope, and this is described in Chapter V.

4.2 Texas Tech University Dodge truck

As described in Chapter III, a 1999 Dodge truck was obtained from Texas Tech and a Larsen antenna was mounted on it. The ESVP receiver was used for broadband and narrow-band measurements as just described for the TxDOT Dodge trucks. The measurements were conducted at 47.18 MHz, and the results are tabulated below in Tables 4.5 and 4.6.

Table 4.5: Ambient noise levels (Pre-amp ON)

Bandwidth (kHz)	120	10
Peak (dBμV)	9.6 to 11.2	-6
Average (dBμV)	-5	-16.5

Table 4.6: Summary of J551/4 test on Dodge truck from Texas Tech

EVENT	PEAK (dBμV)	AVERAGE (dBμV)
Fan	12.8	-2.3
Fuel pump	10.3	-6
Wipers	33	-2.47
All the above	31 to 37	-2.3
All above + washer	53.5	-2.2
Engine idle and all motors on except the washer	51.2	-3.9
All systems on	52.5	-2.1

Analyzing the above, results we conclude that the truck failed in the case of the washer when we consider the 40 dBμV [14] suggested limit. From Table 3.7, we can see that this result does not agree with the Tex-899-B test. This creates a requirement for a new limit on DC motors.

Looking at the narrow-band scan, the graph in Figure 4.3 shows a key-on scan that also reveals the existence of the broadband micro-controller noise in this truck as seen in the trucks before. Since the ambient level (refer to Table 4.5) for the 10 kHz bandwidth was not 6 dB below the limit, we were not able to determine the result for narrow-band or CW emission. The micro-controller noise is discussed in the next Chapter and its limits are found, and the truck was failed because of micro-controller noise at the highest frequency, 47.34 MHz. Vehicles driving past the test site contaminated the band of frequencies from 47.22 to 47.28 MHz.

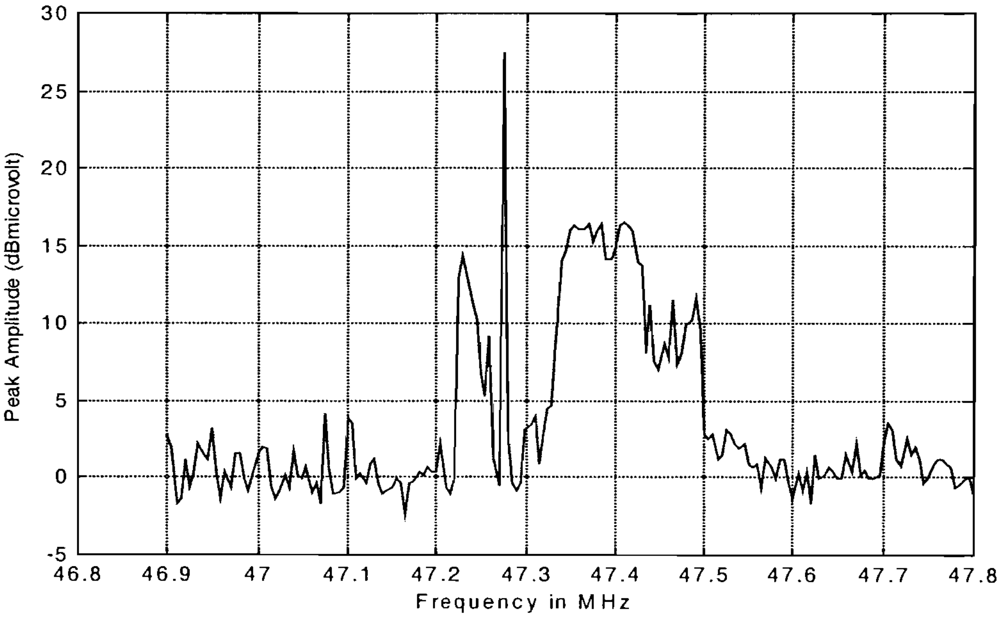


Figure 4.3: Key-on noise from Texas Tech Dodge truck

4.3 Texas Tech University Chevrolet truck

The same Chevy truck discussed in Chapter 3 was borrowed from Texas Tech and a Larsen antenna with magnetic mount was mounted, and the truck was tested. The truck was tested at 47.18 MHz at 120 kHz bandwidth

The results are tabulated in Tables 4.7 and 4.8. From Table 4.8, we can see that the average value of the DC motors changes when the engine is switched on. This truck fails if we consider the DC-motor peak limit [14] of 40 dBμV when we look at all motors running because of the washer. From Table 3.10, we can see that this result does not agree with the Tex-899-B test. This creates a requirement for a new limit on DC motors.

Table 4.7: Ambient noise levels

	Pre-amp ON	
Bandwidth (kHz)	120	10
Peak (dBμV)	5.2	-7.4
Average (dBμV)	-9	-19.8

Table 4.8: Summary of J551/4 test for Chevrolet truck from Texas Tech

Noise Source	Peak amplitude (dBμV)	Average amplitude (dBμV)
HVAC fan	24.7	-8.7
Fuel pump	16.3	-8.5
Wipers	8.1	-8.1
All above	25	-7
Wipers and washer	49	1.9
All above	54	1.5
Engine idle	61.8	-0.9
Engine idle and all motors on except the washer	62.2	-4.7
All above	65.8	3

The narrow-band key-on scan along with the ambient is shown in Figure 4.4. The strange looking high peaks are due to vehicles passing near the test site. From the graph, we can conclude that there is no broadband micro-controller noise as we saw in the Dodge trucks.

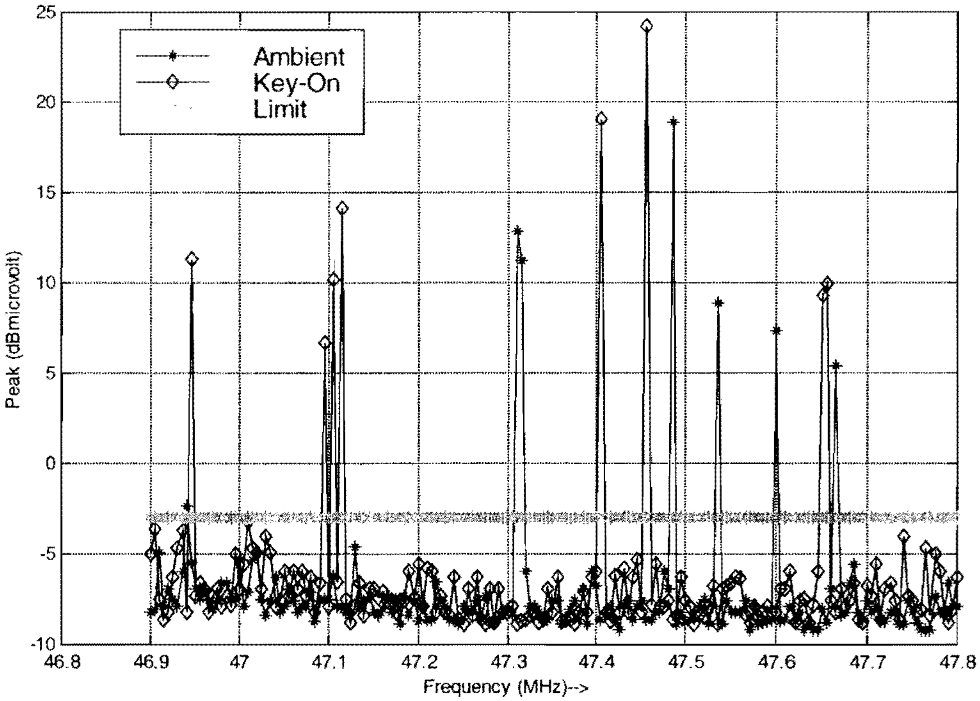


Figure 4.4: Key-on and ambient noise on the Chevy truck

The –3 dBμV limit [14] is also plotted in the graph and shows that except for the frequencies with high peaks, due to vehicles passing near the test site, all others are less than the limit, so this truck passes the narrow-band noise test.

4.4 Texas Tech University Ford truck

As mentioned in Chapter III, the Texas Tech Ford truck required a different antenna to adjust the center frequency to around 47 MHz. The testing was done at the same spot as before. The ambient was quiet at first (refer to Table 4.9), but it got worse due to lightning so the narrow band scan was abandoned. The broadband test was conducted at 47.02 MHz at 120 kHz bandwidth, and the results are shown in Table 4.10. This truck passed the test considering the limit [14] for DC motors. The ignition system produced less noise compared to the washer motors. The truck was extremely quiet.

Table 4.9: Ambient noise levels

	Pre-amp ON	
Bandwidth (kHz)	120	10
Peak (dBμV)	14.8	-8.1
Average (dBμV)	-7.8 to -10.8	-19.8

Table 4.10: Summary of J551/4 test on Ford truck from Texas Tech

EVENT	PEAK (dBμV)	AVERAGE (dBμV)
Fan	32.7 to 35.7	-2.2
Fuel pump	20 to 22	-7.4
Wipers	29.8	-7.9
All of the above	41.9	-2.9
Wipers + washer	42.7 to 45	0.5
All above	39.6	-1.5
Engine idle	33.2	-7
Engine idle and all motors on except the washer	40	0.3
All above	38.2	-4.3

In the next chapter, we shall discuss the average measurements, micro-controller noise and new limits for DC motors and broadband micro-controller noise. The analysis of average data tabulated in Tables 4.6, 4.8, and 4.10 are discussed in Chapter V.

CHAPTER V

AVERAGE MEASUREMENTS

The measurements discussed in the previous chapter involve a peak detector. There are several other detectors that can be used and that have their advantages over peak detectors depending on the characteristics of the signal detected. Quasi-peak detectors can be used to separate two signals that have almost equal peaks but different duty cycle. Average detectors are used to separate narrow-band signals from broadband signals.

The problem that led us to the consideration of detectors other than peak was how to detect DC motor noise in the presence of ignition noise. The average detector seemed like a good candidate because it gives a low output for low repetition rate pulses like ignition noise. Figure 5.1 illustrates a test conducted in the laboratory, which shows a comparison of detectors as a function of repetition rate [16].

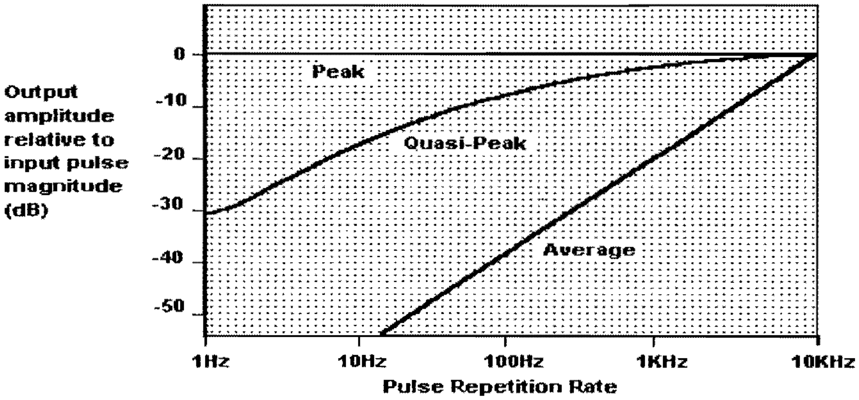


Figure 5.1: Comparison of various detectors used for EMI measurements

There are several advantages of average detectors:

1.The noise floor (both receiver and ambient) is very low compared to that of peak (refer to Table 4.1 and Table 4.2).

2. In open area testing, an average detector is more immune to the noise from other vehicles.

3. The variations in average are less than the variations in the peak. This leads to a stable limit.

A comparison was conducted in our laboratory to test the different detectors and their effectiveness in separating the DC motor noise and ignition noise. The experiment was set up such that the ignition noise was simulated with a pulse generator with a constant peak amplitude of 55 dBμV. A DC HVAC fan was adjusted in steps and the peak, quasi-peak and average values were noted. The combined noise was also measured. The figure below plots the fan noise and the fan-plus-ignition noise. We can see that the quasi-peak of the total noise does not follow the quasi-peak of the fan, but the average of the total noise more or less follows the fan average. This proves that the average detector can be used to estimate the fan noise in the presence of ignition noise.

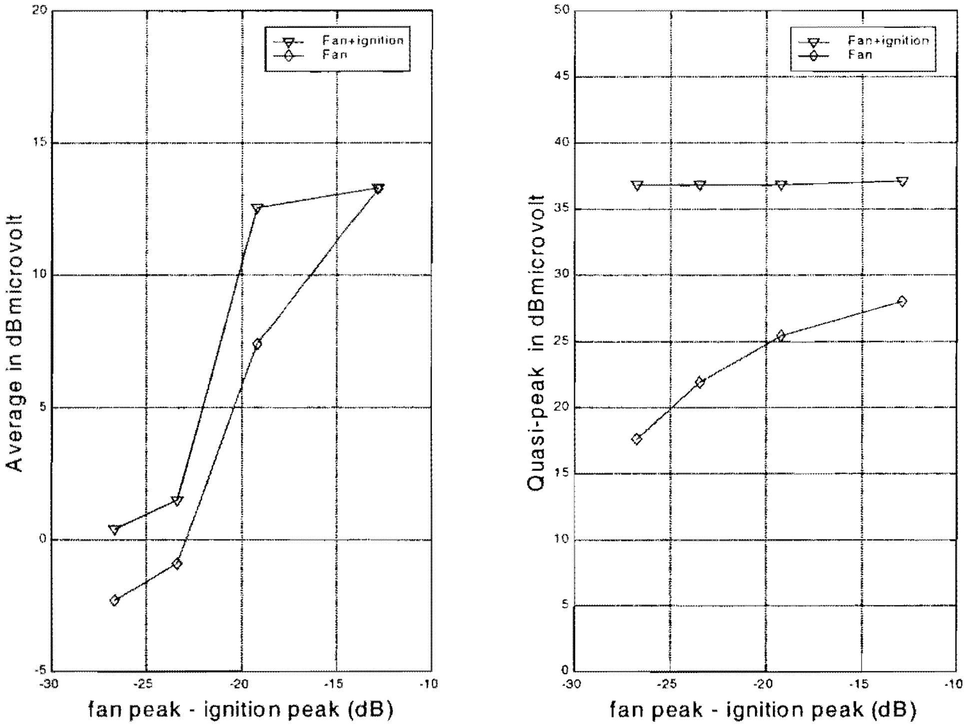


Figure 5.2: Comparison of different detectors to separate different noise sources

The reasons for choosing the average detector were described above. However, the average detector turned out to provide other advantages also. These include measuring broadband micro-controller noise and DC-motor noise without ignition noise in vehicles. In forthcoming sections we discuss these measurements.

5.1 Computation of theoretical peak-to-average ratio

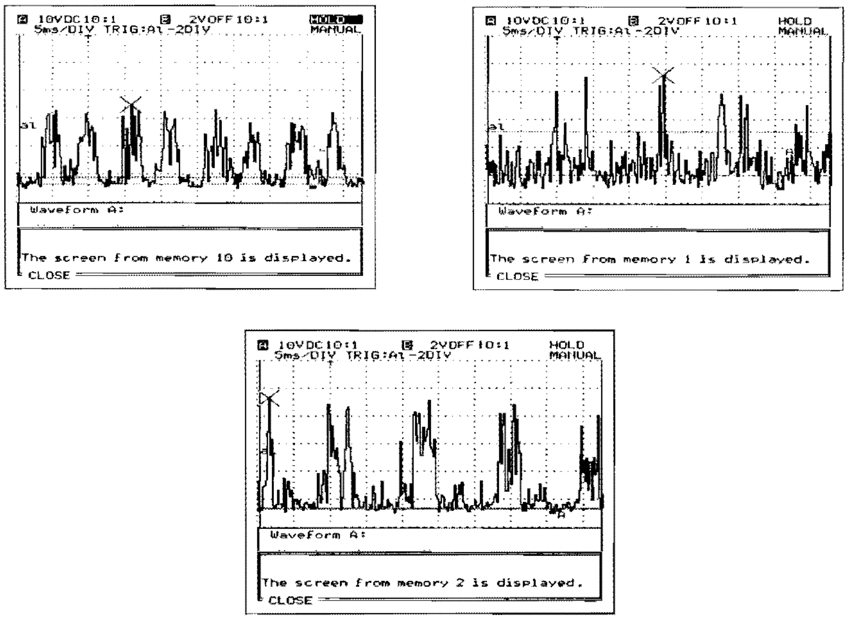
The theoretical peak-to-average ratio was used as a reference to compare different averaging techniques (refer to Appendix C for a sample computer program). The pulse used for the periodic pulse train was approximated as a trapezoidal function. The width of the pulse at the half-peak amplitude was considered to be 10 ns. A fifth-order Butterworth bandpass filter was chosen, with a version having a 6 dB bandwidth of 120 kHz shown in the sample program. This filter was designed to match closely the shape of the ESVP receiver filter used in the measurements. The input pulse train's Fourier transform, consisting of a periodic series of spectral lines, was multiplied by the gain of the filter at each spectral line frequency. The spectral lines used spanned a frequency range of about +/- 6 times the bandwidth of the filter, centered at the filter's mid-frequency point.

The complex coefficients of the filter output spectral lines are phasors. These were then each put back into the time domain as a cosine function whose amplitude and phase came from the phasor value and whose frequency was that of the particular spectral line. When the results from all the spectral lines were added, the output pulse for a particular time sample was obtained. In the same way, the outputs of all other time samples (500 samples) were calculated to produce the total output pulse as a function of time over one period or fraction of a period, depending on the resolution desired. While calculating the output, full-wave rectification was performed (as in the ESVP), i.e., the negative coefficients were converted to positive values and stored. The maximum value among the 500 samples was found and stored as the peak value of the pulse.

The area under the output pulse was calculated by multiplying the sample values by their time resolution factor and summing the results. The sum was divided by the period of the pulse train to give the average of the pulse train. The peak of the pulse was then divided by the average of the pulse train to give the peak-to-average ratio, which was then converted to dB. This process was repeated for different rep rates, which changed the values of the period (and hence the average) of the pulse train. Thus the theoretical peak-to-average ratio was calculated as a function of pulse repetition rate. For the narrower bandwidth case (9/10 kHz), the filter was changed and the calculations were repeated. The theoretical average was fairly accurate because it can be seen that the peak-to-average ratio measured from the ESVP receiver matches the calculated peak-to-average ratio over a range of repetition rates (Figures 2.3 and 2.4).

5.2 Broadband micro-controller noise

This noise was first observed in the TxDOT Dodge trucks tested with key ON (refer to Figures 4.1, 4.2 and 4.3). This noise is broadband and extends around 150 to 200 kHz. The figure below shows the micro-controller noise at 47.38 MHz recorded through a portable oscilloscope connected to the AM output of the EMI receiver. As the figure illustrates, the noise waveform changes with time. The micro-controller noise is centered at 47.38 MHz. It was observed only on the Dodge trucks.



The screen from memory 10 is displayed.

The screen from memory 1 is displayed.

The screen from memory 2 is displayed.

Figure 5.3: Micro-controller noise at different instances

The micro-controller noise did not have any pre-defined pass-fail limit for use with the TxDOT trucks. To investigate further, a special scan was conducted on the Texas Tech Dodge truck showing the peak and the average of the micro-controller noise at 10 kHz bandwidth. From Figure 5.4, we can see that the peak is almost constant with frequency but the average varies. This data together with Tex-899-B data was then used to determine the limit for the micro-controller noise.

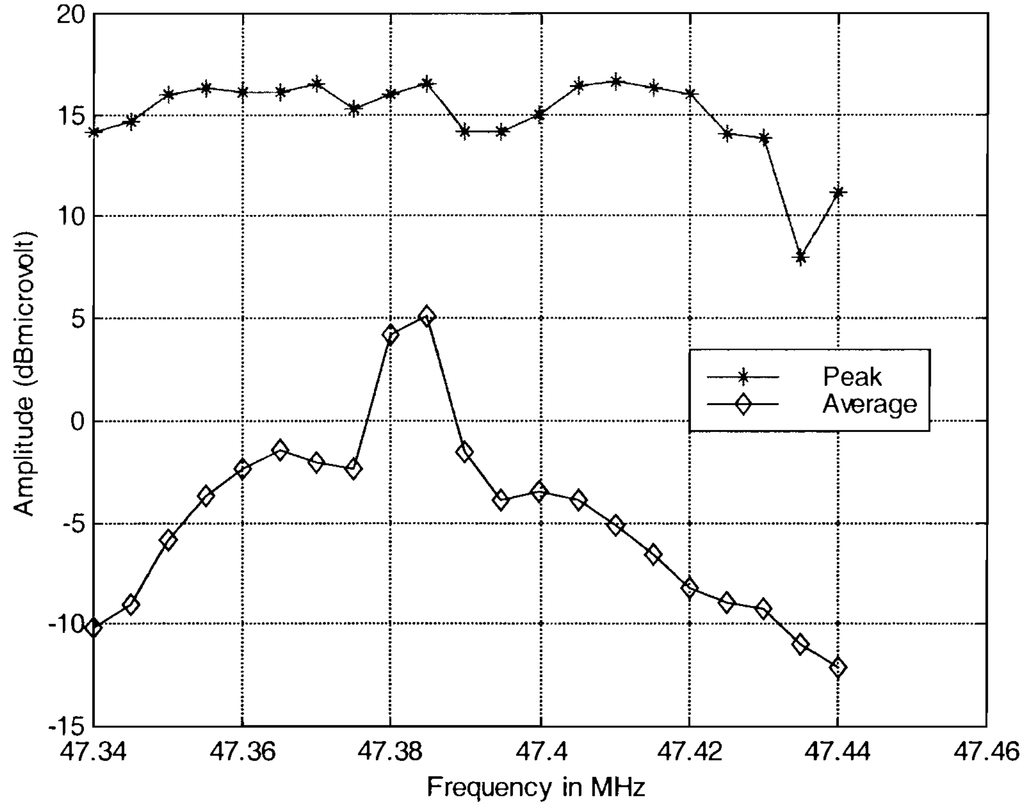


Figure 5.4: Peak and average plot of the micro-controller noise

Tables 3.7 and 3.8 give Tex-899-B SINAD key-on data at 47.34 MHz, 47.38 MHz, and 47.42 MHz. This data is plotted in Figure 5.5 (after subtracting 20 dB for the coupler) along with the data at these same frequencies from Figure 5.4. From the graph in Figure 5.5, it is evident that the SINAD value of the micro-controller noise follows the average, not the peak, so the limit should be set based on the average value of the micro-controller noise. At 47.34 MHz the SINAD value lies at 1 dBμV, which is very close to the limit of 0 dBμV. At this frequency the average value is about -10 dBμV. Thus the average limit was found to be -10 dBμV, at 10 kHz bandwidth. This limit could not be verified with other trucks because only Dodge trucks seem to have this strange microcontroller noise.

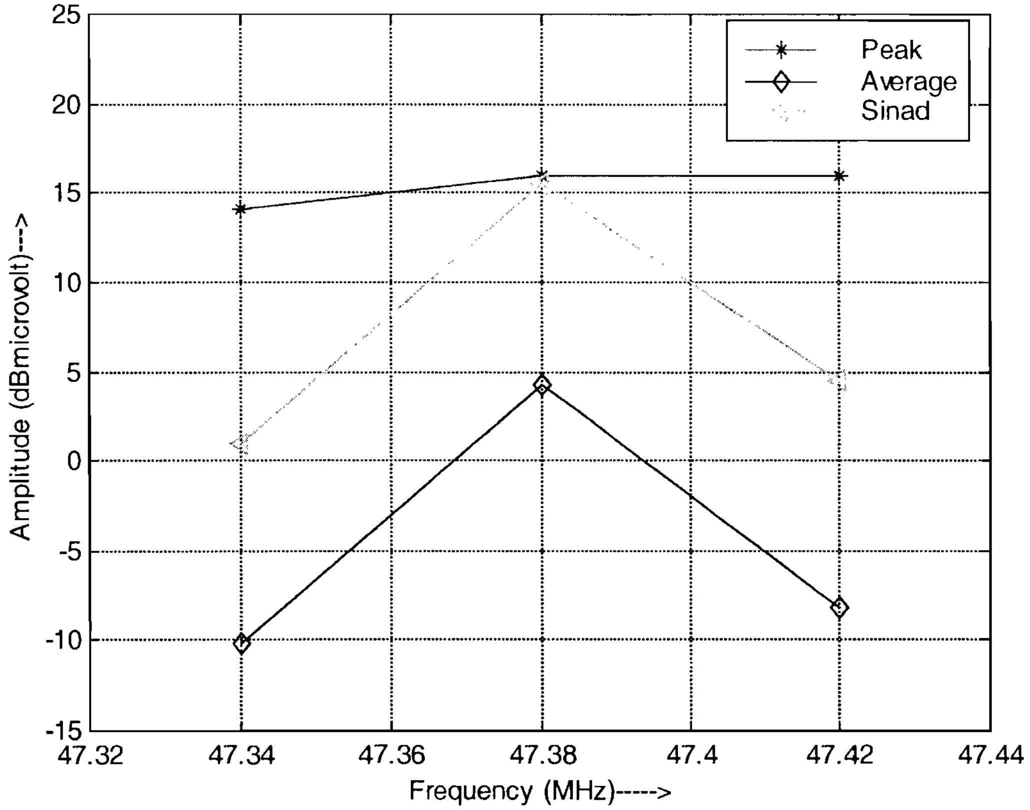


Figure 5.5: Comparison of peak and average noise amplitude with 12-dB SINAD signal amplitude

5.3 Average limit for DC-motor noise

DC motor noise requires different peak limits depending on the number of motors [14]. Furthermore the limits do not suit the testing of DC motors when windshield washer motors are involved. In the hope of finding a single limit we investigated average measurements. As described before, the possibility of measuring DC motor noise in the presence of ignition noise also seemed to be a good reason to explore the use of average measurements.

We conducted a laboratory test where the DC motor noise was added to an FM signal and was connected to the radio. The SINAD meter was connected to the output of the radio. The values of peak and average of the DC motor noise were recorded for a 12 dB SINAD value.

Table 5.1: Peak and average for DC motors for 12 dB SINAD using ESVP receiver

	Fan		Fuel pump		Fan + Fuel pump	
Bandwidth	Peak dBμV	Average dBμV	Peak dBμV	Average dBμV	Peak dBμV	Average dBμV
120 kHz	49 to 53.5	2.9 to 3.7	44.6 to 49.2	2.7 to 3.6	49.6 to 54.8	2.9 to 4.1
10 kHz	27.7 to 31.3	-2.8 to –3.8	26.6 to 29.1	-2.6 to – 4.4	27.7 to 32.7	-2.8 to -3.7

From Table 5.1, we can conclude that the average limit should be 3 dBμV at 120 kHz bandwidth. (The average limit is about –3 dBμV at 10 kHz bandwidth.) This has been tested in vehicles before (refer to Tables 3.7, 3.10, 3.12, 4.6, 4.8 and 4.10) and is found to be fairly accurate. In all those tables, the events concerned with washer motors did not fit in the peak limit. The average limit of 3 dBμV seemed to be better correlated than the peak. The washer in the Chevy truck produced a lot of noise. We can see that the average limit was good even in this case. So it was found that a single limit could be set for the DC motors. This new limit plus the one for micro-controller noise lead to an auxiliary testing procedure that could be coupled with the J551/4 test to produce a more effective procedure for testing the vehicles. This is described in the following section.

Table 5.2: Peak and average for DC motors for 12 dB SINAD using HP analyzer

	Fan		Fuel pump		Fan + Fuel pump	
Bandwidth	Peak dBμV	Average dBμV	Peak dBμV	Average dBμV	Peak dBμV	Average dBμV
120 kHz	43 to 48.5	.54 to 0.7	48 to 51	-2 to –3.2	53 to 55	-0.4 to -1
10 kHz	23 to 26	-1.1 to –1.6	28 to 32	-5 to –6.3	31 to 35	-3 to -5

Table 5.2 shows the same measurements recorded using the HP analyzer. The limits do not match those of the ESVP, but this is expected because we saw a difference in Figure 2.3 and Figure 2.4.

5.4 Comprehensive test procedure

The following procedure describes the J551/4 test along with the auxiliary testing procedure:

1. The first step is to test for the key-on noise. A narrow-band peak scan, which is the same as the J551/4 test, is conducted. It is followed by a narrow-band average scan. The peak limit for narrow-band (or CW) micro-controller noise is –3 dBμV [14], so check this limit outside the broadband micro-controller noise. (Usually the broadband noise is a band of frequencies that has very high amplitude mostly above 5 dBμV peak). Check for the average limit of –10 dBμV in the band of frequencies that has the broadband noise noted from the peak scan.

2. The next step is to determine the noise from DC motors. Turn the motors on one at a time and measure the peak and average at a 120 kHz bandwidth. Check for a limit of 3 dBμV in the average value and determine the pass or fail based on the average limit.
3. Turn all motors on at the same time and measure the peak and the average at a 120 kHz bandwidth. Check for a limit of 3 dBμV in the average value and determine the pass or fail based on the average limit.
4. Turn everything on in the vehicle including engine and all DC motors. Do a 120 kHz average scan. Look for spots from step 1 where the micro-controller noise is the least and check for a 3 dBμV average limit. Compare it with the value from the previous step. This gives an estimate of the DC motor noise when the engine is running, which might be different than when the engine is switched off (refer to Table 4.8).
5. Turn on the engine only, and note down the peak value. There is no limit on ignition noise [14] because of the effectiveness of the noise blanker in the TxDOT radios. This measurement is done to get a complete set of data on a truck.

The procedure described here has both J551/4 and its modifications that make it more effective for DC-motor noise and more complete by including broadband micro-controller noise.

CHAPTER VI

CONCLUSIONS

The requirement of synchronizing the limits of two testing standards led to several results along the course of the research. Assuming Tex-899-B as the reference standard, efforts were made to modify the limits of the J551 test to make it more comparable to the Tex-899-B test. Different makes of trucks were tested to help us arrive at several conclusions. We encountered a new kind of micro-controller noise, which was broadband in nature.

The Dodge trucks had micro-controller noise generated when the key was turned on. This noise is broadband and extends to a couple of hundred kHz. There was no pre-defined limit on this kind of noise. The average limit was determined by us to be -10 dBμV at 10 kHz bandwidth to give a comparable result to Tex-899-B. In the Dodges, it contaminated all other noise sources in its band of frequencies.

The Chevy truck had a noisy windshield washer, which proved that the peak limit previously set on DC motors is not suitable for small motors like the washer. It was found that the average detector gave a good stable limit, which gave a comparable result to that of the Tex-899-B test. It was determined in our laboratory tests that the limit of the DC motors should be set at 3 dBμV at 120 kHz BW irrespective of single motor or multiple motors. This was verified in the truck testing (refer to Tables 3.7, 3.10, 3.12, 4.6, 4.8 and 4.10).

Testing with the engine running and with all motors except washer ON showed that the average noise measured corresponded to the average of DC motors (refer to Tables 4.6, 4.8 and 4.10). Thus an average measurement can be used to detect the DC motor noise in the presence of the ignition noise.

Comparing the results from the three Texas Tech University trucks, we find that there seems to be a correlation between the average detector value and the 12 dB SINAD value. Figure 6.1 compares the different trucks for the Tex-899-B test and J551/4 test for the case of all motors except the washer ON. We can see that the average curve is similar to the Tex-899-B curve whereas the peak curve is not. The Tex-899-B curve is not only similar to the average curve but also overlaps the average curve.

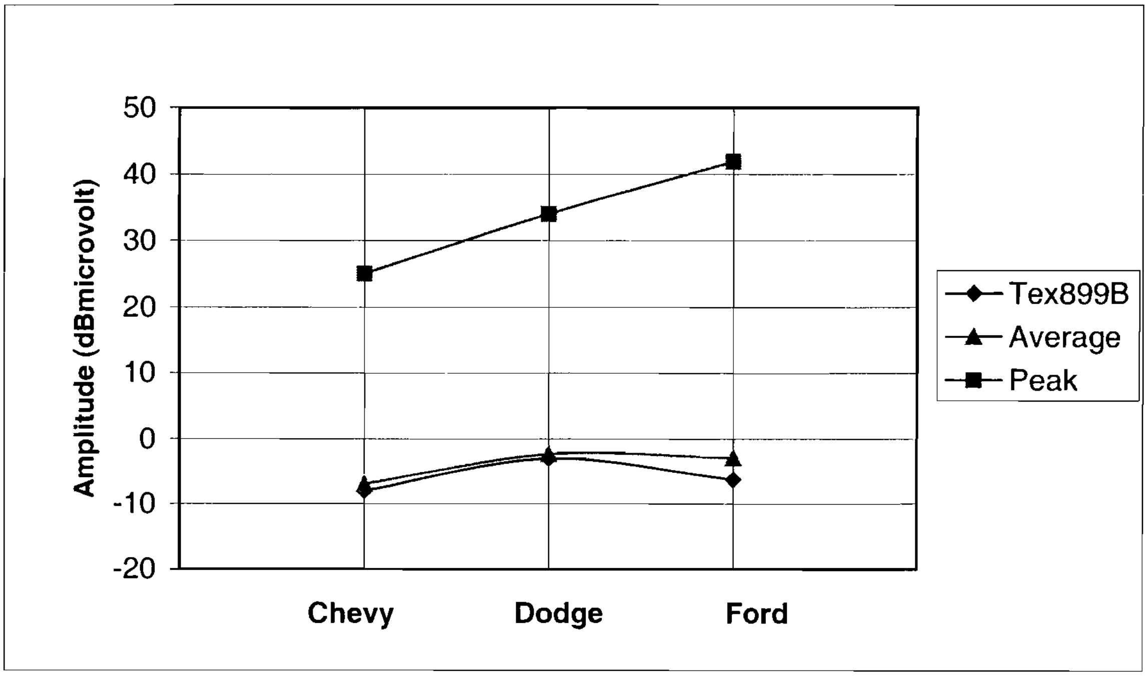


Figure 6.1: Comparison of peak, average and SINAD values of different trucks

The modified J551/4 test discussed in Chapter V includes the usage of average detectors along with peak detectors to form a more effective method of testing. The addition of average limits to the existing J551/4 test brings the results of both tests in closer agreement.

6.1 Future research

In the future the application of average measurements for EMI measurements should be considered more seriously. From Table 4.8, the average values of the motors changes when the engine is switched on, so the possibility of measurement of noise in the presence of other noise sources should be studied carefully. It would be better to separate the noise sources when everything is running in the vehicle. The noises could be separated as ignition, DC motors, micro-controllers and narrow-band noises. Modeling of the micro-controller noise could lead to better understanding and would allow us to develop better noise suppression techniques.

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APPENDIX A

TxDOT Tex-899-B TEST

RADIO FREQUENCY INTEFERENCE (RFI) TESTING

This test method assures the compatibility of Texas Department of Transportation (TxDOT) fleet vehicles and VHF FM radio equipment operating in the frequency ranges of 30 to 50 MHz and 150 to 174 MHz, but not inclusive. It is intended to identify 90% or more ingress and egress problems.

Definitions

Ingress – any action, reaction, indication, failure to perform or comply, by vehicle equipment and/or accessory items, caused by the activation of the VHF FM radio transmitter in any mode of operation.

Egress – any mode of operation, action, reaction or indication or by the vehicle equipment and/or accessory equipment which degrades the VHF-FM radio receiver effective sensitivity performance by more than six dB.

Equipment

1. 100 W VHF FM communications transmitter and receiver capable of operating on all TxDOT frequencies.
2. 12 V regulated DC power supply
3. RF FM signal generator with a calibrated attenuator
4. Signal-to-noise audio distortion (SINAD) meter
5. Receiver audio termination load
6. RF directional coupler rated at 40 dB directional, minimum
7. RF termination load
8. Magnetic-mount antenna for the testing frequencies
9. RF isolation choke, a (6 ft. by 6 ft.) sheet of hardware cloth, laid flat on the test area floor with the coaxial cable making one complete loop approximately four feet in diameter under it
10. RF wattmeter

Facilities

1. Free of high ambient RF noise (receiver test)
2. Equipped with lift capable of raising vehicle tires six inches above floor (transmission test)

Safety notes

Safety be must never be compromised during tests. Hazards due to vehicle parts moving and radio frequency/electrical burns exist. Strict compliance with accepted work practices must be observed at all times. Sudden actions may result when the radio transmitter is activated. Stay clear of vehicle and antenna. One person should operate the vehicle, and another the radio.

Egress compatibility

- Receiver qualification

Step	Action
1	Assemble a test set-up as shown figure 1.
2	Generate a standard test signal and establish 12 dB SINAD.
3	Record receiver basic sensitivity.
4	Increase signal 6 dB above step 3.
5	Increase peak deviation until SINAD is degraded to 12 dB SINAD.
6	Record modulation acceptance (Bandwidth).

Compliance of the test setup qualifies the receiver for acceptance testing if:

- The receiver basic sensitivity is less than 0.4 μV (-114 dBm) for 12 dB SINAD
- The receiver bandwidth shall be a minimum of ± 6.5 kHz and a maximum of ± 8.0 kHz.

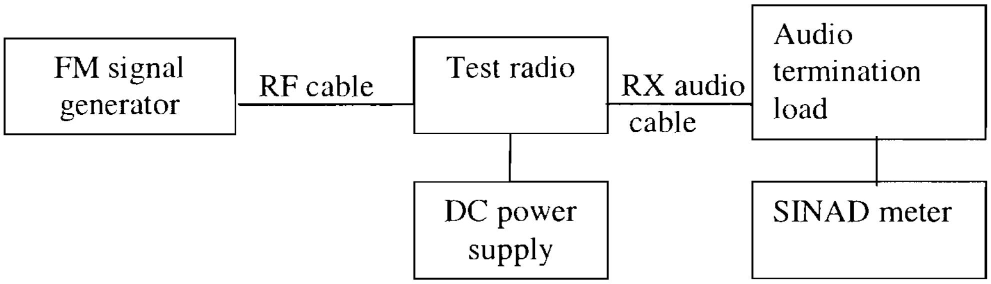

Figure A.1 Site Qualification.

- Site Qualification

Step	Action
1	Assemble a test set-up as shown in figure 2.
2	Move test vehicle into radio frequency interference shield room or onto site.
3	Temporarily install the magnetic mount antenna on the center of the vehicle loop.
4	Disconnect the battery cable.
5	Terminate the RF line into the RF load terminal.
6	Generate a standard test signal of on-channel center frequency FM modulated with a 1 kHz sine wave tone at ±3.3 kHz deviation.
7	Increase the signal generator RF output level until a 12 dB SINAD indication is achieved.
8	Record sensitivity into RF road termination in dBm.
9	Remove the RF load termination and terminate the RF line into the temporary antenna.
10	Increase signal generator RF output level until a 12 dB SINAD indication is achieved.
11	Record sensitivity into antenna in dBm.
12	Compute the effective sensitivity and determine if the site is qualified.
13	Repeat site qualification at all test radio channels/frequencies to be used.

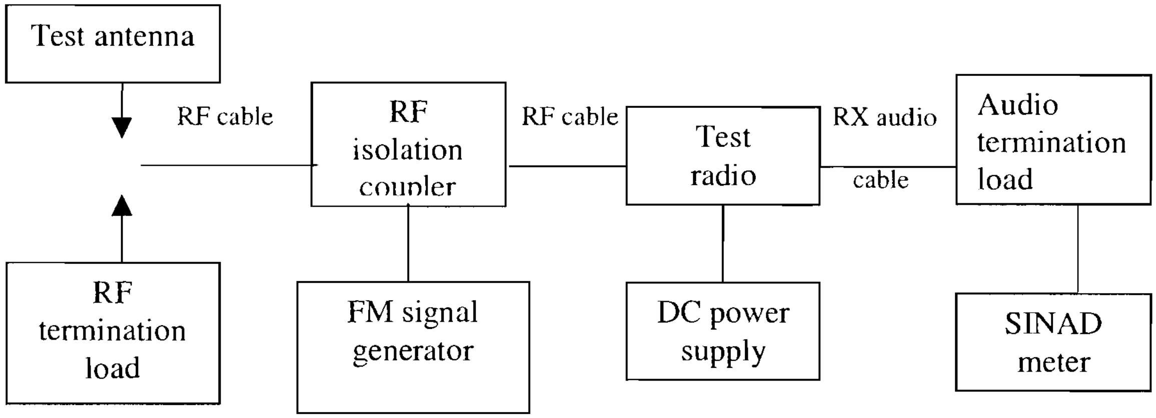

Figure – A.2 Test Setup

- Effective Sensitivity Calculation

Step	Action
1	Subtract the sensitivity into antenna from sensitivity into RF load termination.
2	Record this difference.
3	Subtract this difference from the basic receiver sensitivity.
4	Record the effective receiver sensitivity in dBm.
5	Convert the effective receiver sensitivity to microvolts.

- Site Qualification Standards

The site is qualified if the effective receiver sensitivity is less than 0.5 μV (-113 dBm)

Egress compatibility

- Egress compliance test for test for test vehicle

Step	Action
1	Reconnect vehicle battery.
2	Increase the signal generator RF output level until a 12 dB SINAD indication is achieved.
3	Record the signal generator RF output level.
4	Activate one vehicle system or accessory.
5	Increase the signal generator output level until a 12 dB SINAD indication is achieved.
6	Record the signal generator RF output level.
7	Repeat Steps 4 through 6 until all vehicle systems and accessories are activated.
8	Compute total degradation. See NOTE.
9	Repeat compliance test for all test radio channels/frequencies to be used.
10	Turn off engine.

NOTE: The electrical system should be designed so the effective sensitivity of the VHF FM receiver requires not more than 1 μV (-107 dBm) to produce 12 dB or greater SINAD. The effective sensitivity should not exceed 1 μV for all modes of operation, which should include engine off, engine on, (from idle to full throttle), and all vehicle systems or any combination thereof.

- Test vehicle qualification

The test vehicle passes the egress compliance test when the total degradation does not exceed 6 dB.

Ingress compatibility

- Antenna qualification

Step	Action
1	Assemble a test set-up as shown in Figure 3.
2	Verify engine is OFF.
3	Raise test vehicle (6 in.) off floor.
4	Verify that magnetic mount antenna is mounted in center of vehicle roof.
5	Key microphone on test radio.
6	Record nominal forward RF power to the antenna.
7	Record rectified RF power from the antenna.
8	Adjust length of antenna, if needed, and repeat steps 5 through 7 until nominal forward power is 100 watts ± 10 watt and reflected power is less than 10 % of the forward power.

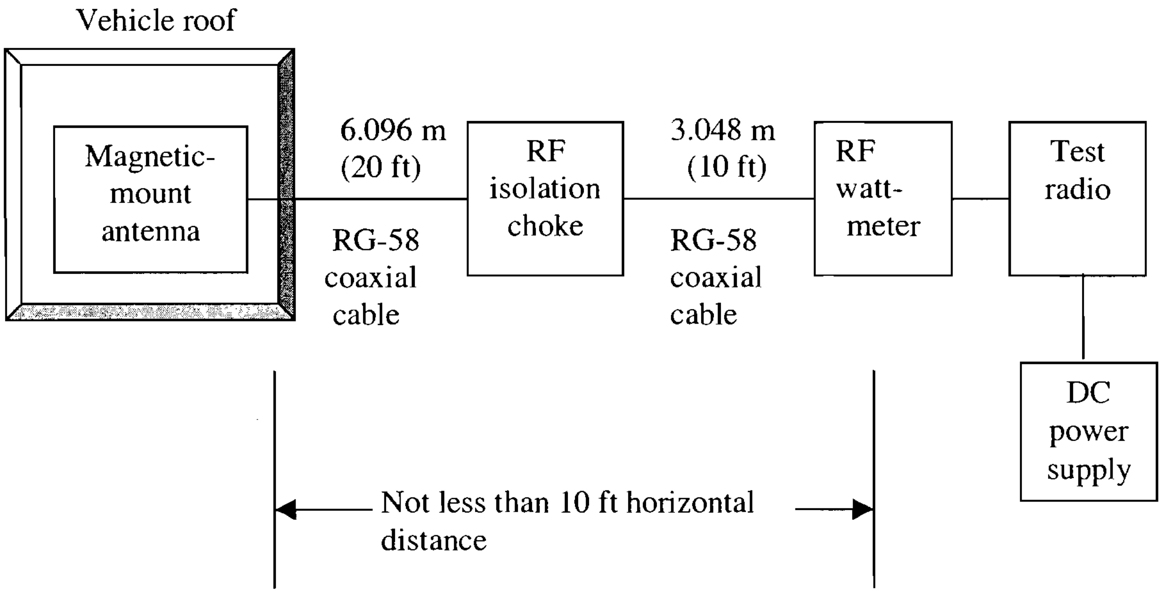

Figure A.3.Vehicle Qualification for Acceptance

Step	Action
1	Start vehicle.
2	Put vehicle in gear and rotate tires at a moderate speed.
3	Activate one vehicle system or accessory. Be certain to check the braking operation.
4	Activate the radio transmitter for approximately five seconds.
5	Record results as one of the following: 1. No adverse reaction 2. Reaction resulting in safety hazard 3. Reaction resulting in a nuisance operation.
6	Repeat steps 3 through 5 until all vehicle systems and accessories are activated.
7	Repeat vehicle qualification for all test radio channels/frequencies to be used.
8	Stop wheels of vehicle and turn off engine.

Vehicle Qualification Results

Safety Hazard – No vehicle system and/or accessory shall operate and/or fail to operate as a result of the activation of the VHF FM radio transmitter in a manner which constitutes a safety hazard.

Nuisance operation – correct nuisance operations of any vehicle system and/or accessory.

Failure to meet the criteria of this test method will result in rejection of the vehicle.

APPENDIX B

SAE J551/4 TEST

Test limit and methods of measurement of radio disturbance characteristics of vehicles and devices, broadband and narrowband, 150 kHz to 1000 MHz

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Forward – This SAE standard is based on CISPR 25, which has been developed by CISPR Subcommittee D and has been approved to be published. The SAE Electromagnetic Radiation Committee has been an active participant in Subcommittee D and in the development of CISPR 25.

This document provide test limits and procedures for the " protection of vehicle receiver from radio frequency (RF) emission caused by on-board vehicle components."

NOTE – Appendix II provides helpful methodology for resolution of interference problems.

Table of Contents

1. Scope – This SAE Standard contains test limits[1] and procedures for the measurement of radio disturbances in the frequency range of 150 kHz to 1000 MHz. The document applies to any electronic/electrical component intended for use in vehicles. Refer to International Telecommunication Union (ITU) Publications for details of frequency allocations. The tests are intended to provide protection for receivers installed in a vehicle from disturbances produced by components/modules in the same vehicle[2].

   The receiver types to be protected are: broadcast radio and TV[3], land-mobile radio, radio telephone, amateur and citizens' radio.

   The limits in this document are recommended and subject to modification as agreed between the vehicle manufacturer and the component supplier. This document shall also be applied by manufacturers and suppliers of components and equipment, which are to be added and connected to the vehicle harness or to an on-board power connector after delivery of the vehicle.

   This document does not include protection of electronic control systems from RF emissions, or from transient or pulse type voltage fluctuations. These subjects are covered in other sections of SAE J551 and in SAE J1113.

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[1] .only a vehicle can be used to determine the component compatibility to a vehicle limit.

[2] adjacent vehicle can be expected to be protected in most situations.

[3] adequate TV protection will result from compliance with the levels at the mobile service frequencies.

The Word Administrative Radiocommunications conference (WARC) lower frequency limit in region 1 was reduced to 148.5 kHz in 1979. For vehicular purposes, test at 150kHz are considered adequate. For the purpose of this document, test frequency ranges have been generalized to cover radio services in various parts of the world. Protection of radio reception at adjacent frequencies can be expected in most cases.

2. References

2.1 Applicable Documents – the following publications contain provisions which, through reference in this text, constitute provisions of this document. At the time of publication, the editions indicated were valid. All documents are subject to revision, and parties to agreements based on this document are encouraged to investigate the possibility of applying the most recent editions of the documents indicated. Members of IEC and ISO maintain registers of currently valid International standards.

2.2.1 SAE Publication – Available from SAE, 400 Commonwealth Drive, Warrendale, PA 15096-0001:
SAE J551/1 MAR94 – Performance Level and Method of Measurement of Electromagnetic Compatibility of Vehicle and Devices (60 Hz to 18 GHz)

2.1.2 CISPR Publication – Available from ANSI 11 West 42 Street, NY, NY 10036-8002:
CISPR16-1:1993-08–Specification for Radio Disturbance and Immunity Measuring Apparatus and Methods. Part 1: Radio disturbance and immunity measuring apparatus

2. Definitions – See SAE J551/1.

4. Requirements common to vehicle and component/module emissions measurement

4.1 General Test Requirements and Test Plan

4.1.1 Test Plan Notes – A test plan should be established for each item to be tested. The test plan should specified the frequency range to be tested, the emission limits, the disturbance classification [Broad Band (long or short duration) Narrow Band], antenna types and locations, test report requirements, supply voltage, and other relevant parameters.

4.1.2 Determination of Conformation with Limits – If the type of disturbance is unknown, test should be made to determine whether measured emissions are narrow band and/or broad band to apply limits properly as specified in the test plan. Figure 1 outlines the procedure to be followed in determining conformance with limits.

4.1.3 Categories of Disturbance Sources (as applied in the test plan) – Electromagnetic disturbance sources can be divided into three types:[4]

a. Continuous/long duration broadband and automatically actuated short duration devices
b. Manually actuated short duration broadband
c. Narrowband

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[4] For example see 4.1.4 and 4.1.5 and Table 1.

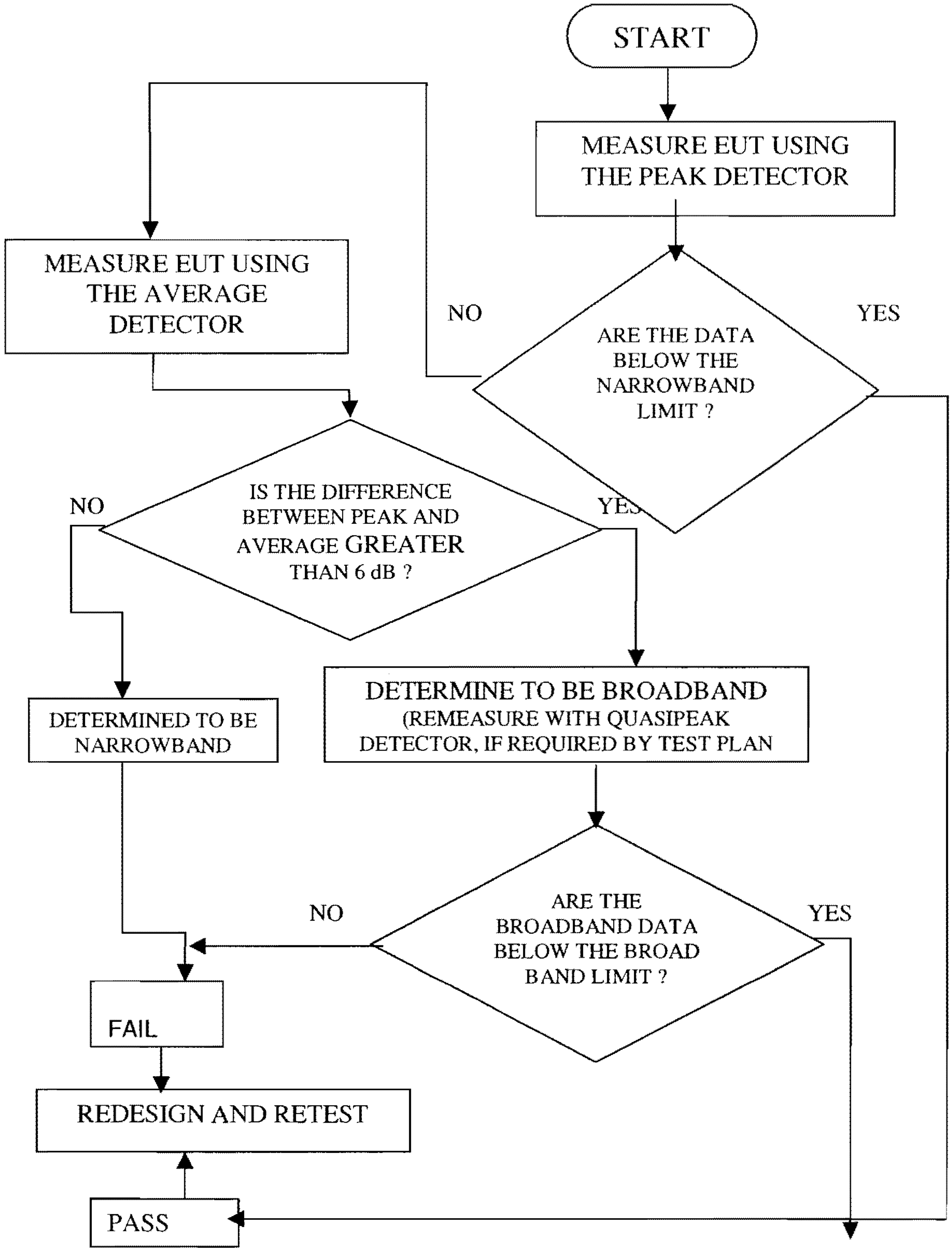

FIGURE B.1 – METHOD OF DETERMINATION OF CONFORMANCE OF RADIATED/CONDUCTED DISTURBANCE

4.1.4 Example of Broadband Disturbance sources

Note – The Examples in table 1 are intended as a guide to assist in determining which test limits to use in the test plan.

Table B.1- Example of Broadband Disturbance Sources by Duration.

Continuous	Long Duration[1]	Short Duration[1]
Ignition system	Wiper motor	Power antenna
Active ride control	Heater blower motor	Washer pump motor
Fuel injection	Rear wiper motor	Door mirror motor
Instrument regulator	Air conditioning compressor	Central door lock
Alternator	Engine cooling	Power seat

[1] As defined in the test plan

4.1.5 Narrowband Disturbance Sources – Disturbances from sources employing micro processors, digital logic, oscillators or clock generators, etc., cause narrowband emissions.

4.1.6 Operating Conditions – All continuous and long duration system shall be operated at their maximum RF noise creating conditions. All intermittently operating systems (i.e., thermostatically controlled) that can operate continuously, safely, shall be caused to operate continuously.

When performing the narrowband test , Broadband sources (i.e., ignition system, in particular) may create noise of higher amplitude. In this situation, it will be necessary to test for narrowband noise with ignition switch ON, but the engine not running

4.1.7. Test Report – The report shall contain the information agreed upon by the customer and the supplier

4.2. Measuring Equipment Requirements- All equipment shall be calibrated on a regular basis to assure continued conformance of equipment to required characteristics. The measuring equipment noise floor shall be at least 6 dB less than limit specified in the test plan

4.3 Shielded Enclosure – The ambient electromagnetic noise levels shall be at least 6 dB below the test limits specified in the test plan for each test to be performed. The shielding effectiveness of the shielded enclosure shall be sufficient to assure that the required ambient electromagnetic noise level requirement is met.

The shielded enclosure shall be of sufficient size to ensure that neither the vehicle/EUT nor the test antenna shall be closer than (a) 2 m from the walls or ceiling, and (b) 1 m to the nearest surface of the absorber material used.

4.4. Absorber-Lined Shielded Enclosure (ALSE) – For radiated emission measurements, however, the reflected energy can cause errors of such as 20 dB. Therefore, it is necessary to apply RF absorber material to the walls and ceiling of a shielded enclosure that is to be used for radiated emission measurements. No absorber material is required for the floor. The following ALSE requirement shall also be met for performing radiated RF emission measurements:

4.4.1 Reflection Characteristics – The reflection characteristic of the ALSE shall be such that the maximum error caused by reflected energy from the wall and ceiling is less than 6 dB in the frequency range of 70 to 1000 MHz.

4.4.2 Objects in ALSE – In particular, for radiated emission measurements the ALSE shall be cleared of all items not pertinent to the tests. This is required in order to reduce any effect they may have on the measurement. Included are unnecessary equipment, cable racks, storage cabinets, desks, etc. Personnel not actively involved in the test shall be excluded from the ALSE.

4.5 Receiver – Scanning receivers which meet the requirements of CISPR 16 are satisfactory for measurements. Manual or automatic frequency scanning may be used. Spectrum analyzer and scanning receivers are particularly useful for interference measurements. Special consideration shall be given overload linearity, selectivity, and the normal response for pulses. The peak detection made by spectrum analyzer and scanning receiver provides a display indication which is never less than the quasi-peak indication for the same bandwidth. It may be convenient to measure emissions using peak detection because of the faster scan possible than with quasi-peak detection. When quasi peak limits are being used, any peak measurements close to the limit shall be measured using the quasi-peak detector.

4.5.1 Minimum Scan Time – the scan rate of a spectrum analyzer or scanning receiver shall be adjusted for the CISPR frequency band and detection mode used. The minimum sweep time/frequency (i.e., most rapid scan rate) is listed in table2:

TABLE B.2 – MINIMUM SCAN TIME

	Band	Peak Detection	Quasi-Peak Detection
A	9 to 150 kHz	Does not apply	Does not apply
B	0.15 to 30 MHz	100 ms / MHz	200 s / MHz
C,D	30 to 1000 MHz	1 ms /100 ms / MHz[1]	20 s / MHz

Band definition from CISPR 16 part 1

[1] When 9 kHz bandwidth is used, the 100 ms / MHz value shall be used

Certain signals (e.g., low repetition rate or intermittent signal) may require slow scan rates or multiple scans to insure that the maximum amplitude has been measured.

4.5.2 Measuring Instrument Bandwidth – The bandwidth of the measuring instrument shall be chosen such that the noise floor is at least 6 dB lower than the limit curve. The bandwidths in table 3 are recommended.

Note – When the bandwidth of the measuring instrument exceeds the bandwidth of a narrowband signal, the measured signal amplitude will not be affected. The indicated value of impulsive broadband noise will be lower when the measuring instrument bandwidth is reduced.

TABLE B.3 – MEASURING INSTRUMENT BANDWIDTH (6 dB)

Frequency Band MHz		Broadband Peak	Broadband q-Peak	Narrowband Peak	Narrowband Average
0.15 – 30		9 kHz	9 kHz	9 kHz	9 kHz
30 – 1000	FM broadcast	120 kHz	120 kHz	120 kHz	120 kHz
	Mobile service	120 kHz	120 kHz	9 kHz	9 kHz

If a spectrum analyzer is used for peak measurements, the video bandwidth shall be at least three times the resolution bandwidth.

For the narrow band/broadband discrimination according to figure1, both bandwidths (with peak and average detectors) shall be identical.

5. Antenna and Impedance Matching Requirements – Vehicle Test

5.1 Type of Antenna – An antenna of the type to be supplied with the vehicle shall be used as the measurement antenna. Its location and attitude are determined according to the production specifications.

If no antenna is to be furnished with the vehicle (as is often the case with a mobile radio system), the antenna types in table 4 shall be used for the test. The antenna type and location shall be included in the test plan.

TABLE B.4 – ANTENNA TYPES

Band		Antenna Type
Broadcast		
LW	AM	1 m monopole
MW	AM	1 m monopole
SW	AM	1 m monopole
VHF	FM	1 m monopole
Mobile Services		
30 – 54		loaded quarter wave monopole
70 – 87		quarter wave monopole
144 – 172		quarter wave monopole
420 – 512		quarter wave monopole
800 – 1000		quarter wave monopole

5.2 Measurement System Requirements

5.2.1 Broadcasting Bands – For each band, the measurement shall be made with instrumentation which has the specified characteristics.

5.2.1.1 AM Broadcast

a. Long Wave (150 to 300 kHz)

b. Medium Wave (0.53 to 2.0 MHz)
c. Short Wave (5.9 to 6.2 MHz)[5]

The measuring system shall have the following characteristics:

a. Output Impedance of Impedance Matching Device: 50 Ω resistive.
b. Gain: the gain (or attenuation) of the measuring equipment shall be known with an accuracy of ±0.5 dB. The gain of the equipment shall remain within a 6 dB envelop for each frequency band as shown in figure 2. Calibration shall be performed in accordance with Appendix I.
c. Compression Point: The 1 dB compression point shall occur at a sine wave voltage level greater than 60 dB(μV)
d. Measurement System Noise Floor: The noise floor of the combined equipment including measuring instrument, matching amplifier and preamplifier (if used) shall be at least 6 dB lower than the limit level.
e. Dynamic Range: From the noise floor to the 1 dB compression point.
f. Input Impedance: the impedance of the measuring system at the input of the matching network shall be at least 10 times the open circuit impedance of the artificial antenna network in Appendix I.

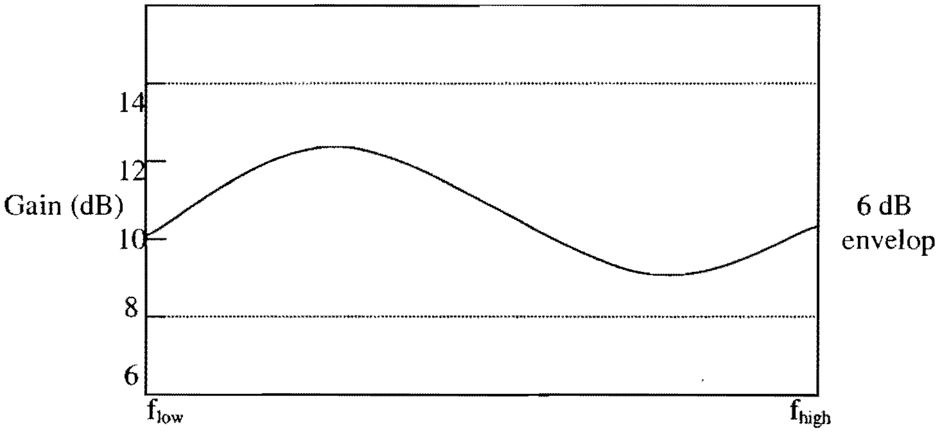

FIGURE B.2 – EXAMPLE GAIN CURVE

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[5] Although there are several other short wave broadcast bands, this particular band has been chosen because it is most commonly used in vehicles. It is expected that other short wave bands will be protected by conformance to the limits in this band.

5.2.1.2 FM Broadcast (87 to 108 MHz) – Measurements shall be taken with a measuring instrument which has an input impedance of 50 Ω. If the standing wave ratio (SWR) is greater than 2:1, an input matching network shall be used. Appropriate correction shall be made for any attenuation/gain of the matching unit.

5.2.2 Communication Bands (30 to 1000 MHz) – The test procedure assumes a 50 Ω measuring

instrument and a 50 Ω antenna in the frequency range 30 to 1000 MHz. If a measuring instrument and an antenna with differing impedances are used, an appropriate network and correction shall be used.

6. Method of Measurement – As a general principle, the disturbance voltage shall be measured at the terminal of the radio receiving antenna placed at the correct vehicle location(s).

To determine the disturbance characteristics of individual disturbance sources or disturbance systems, all sources shall be forced to operate independently across their range of normal operating conditions (transient effects to be determined)

The disturbance voltage shall be measured at the receiver end of the antenna coaxial cable using the ground contact of the connector as reference. The antenna connector shall be grounded to the housing of the on – board radio (center conductor of the antenna coax is not connected to the on-board radio). The radio housing shall be grounded to the vehicle body using the production harness. The use of a high quality double shielded cable for connection to the measuring receiver is required.

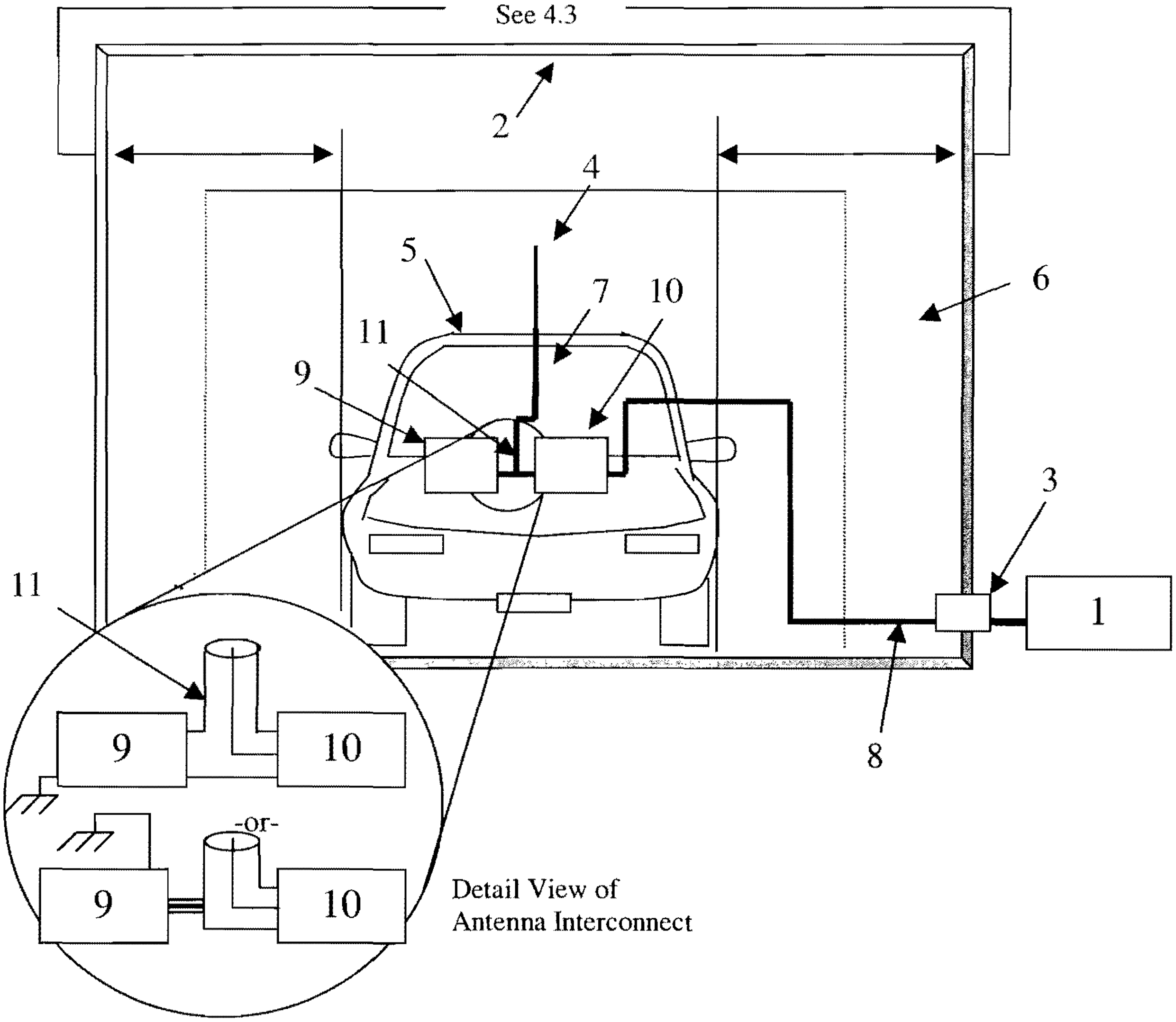
NOTE – The use of ferrite or other suppression material on the coax is recommended, particularly below 2 MHz, for suppression of surface current.

A coaxial bulkhead connector shall be used for connection to the measuring receiver outside the shielded room. See Figure 3.

Some vehicles may allow a receiver to be mounted in several locations (e.g., under the dash, under the seat, etc.). In these cases a test shall be carried out as specified in the test plan for each receiver location.

7. Limit for Vehicle Radiated Disturbances – The limits of disturbance may be different for each disturbance source. Long duration disturbance sources such as a heater blower motor must meet a more stringent requirement than short duration disturbance sources. Short duration disturbance may be decided upon by the vehicle manufacturer. For example, door mirror operation may be allowed at a high level of disturbance, as it is operated for only 1 or 2 s at a time. Coherent energy from microprocessors is more objectionable because it resembles desired signal and is continuous.

For acceptable radio reception in a vehicle, the disturbance voltage at the end of the antenna cable shall not exceed the values shown in table 5.



1.	Measuring instrument
2.	ALSE
3.	Bulkhead connector
4.	Antenna (see 5.1)
5.	EUT
6.	Typical absorber material
7.	Antenna coaxial cable
8.	High quality double shielded coaxial cable
9.	Housing of on-board radio
10.	Impedance matching unit (when required)
11.	Optional tee connector with one leg removed

FIGURE B.3. – VEHICLE RADIATED EMISSIONS – EXAMPLE FOR TEST LAYOUT (END VIEW WITH MONOPOLE ANTENNA)

TABLE 5. – LIMITS OF DISTURBANCE – COMPLETE VEHICLE

Band	Frequency (MHz)	Terminal noise Voltage at Receiver Antenna Terminal dB(μV) Broadband Continuous QP	Terminal noise Voltage at Receiver Antenna Terminal dB(μV) Broadband Continuous P	Terminal noise Voltage at Receiver Antenna Terminal dB(μV) Broadband Short Duration QP	Terminal noise Voltage at Receiver Antenna Terminal dB(μV) Broadband Short Duration P	Terminal noise Voltage at Receiver Antenna Terminal dB(μV) Narrowband P
LW	0.15 – 0.3	9	22	15	28	6
MW	0.53 – 2	6	19	15	28	0
SW	5.9 – 6.2	6	19	6	19	0
VHF	30 – 54	6(15[1])	28	15	28	0
VHF	70 – 87	6(15[1])	28	15	28	0
VHF	87 – 108	6(15[1])	28	15	28	6
VHF	144 – 172	6(15[1])	28	15	28	0
UHF	420 – 512	6(15[1])	28	15	28	0
UHF	800–1000	6(15[1])	28	15	28	0

All broadband values listed in this table are valid for the bandwidth specified in Table 3.

Stereo signals may be more susceptible to interference than monaural signals in the FM – broadcast band. This phenomenon has been factored into the VHF (87 to 108 MHz) limit.

It is assumed that protection of services operating on frequencies immediately below 30 MHz will most likely be provided if the limits for services above 30 MHz are observed.

[1] Limit for ignition system only

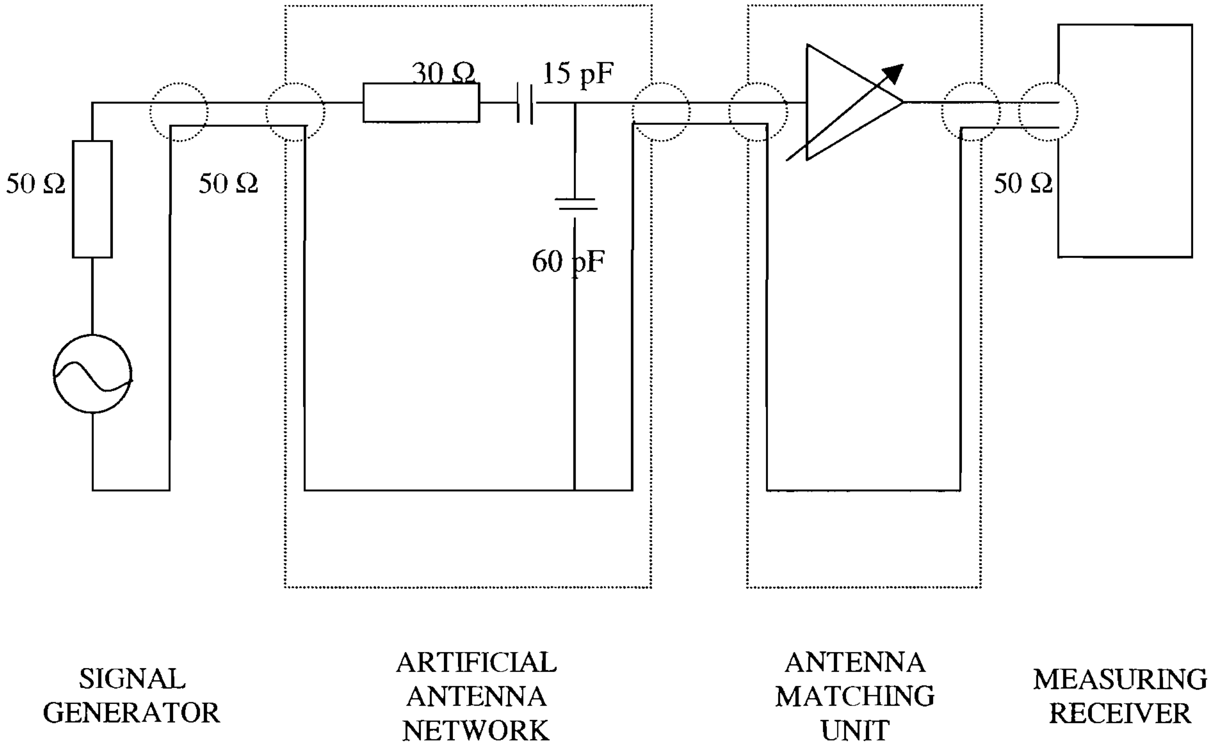
APPENDIX I

(Normative)

ANTENNA MATCHING UNIT - VEHICLE TEST

I.1 Antenna Matching Unit Parameters (150 kHz to 6.2 MHz) – The requirements for the measurement equipment are defined in 5.2.1.

I.2. Antenna Matching Unit – calibration – the artificial antenna network of Figure A1 is used to represent the antenna including the coaxial cable. The 60 pF capacitor represents the capacitance of the coaxial cable between the car antenna and the input of the radio.



I.2.1 Gain Measurement – The antenna matching unit shall be measured to determine whether its gain meets the requirements of 5.2.1.1 using the test arrangement shown in Figure A.1

I.2.2 Test Procedure

a. Set the signal generator to the starting carrier frequency with 1000 Hz, 30 % amplitude modulation and 40 dB(μV)output level.
b. Plot the gain curve for each frequency segment.

I.3 Impedance Measurement – Measurement of the output impedance of the antenna and antenna matching unit shall be made with a vector impedance meter (or equivalent test equipment). The output impedance shall be within a circle on a Smith chart crossing 100 + j0 Ω, having its center at 50 + j0 Ω (e.g., SWR less than 2 to 1).

APPENDIX II

(Informative)

NOTES ON THE SUPRESSION OF INTERFERENCE

II.1 Introduction – Success in providing radio disturbance suppression for a vehicle requires a systematic investigation to identify sources of interference which can be heard in the loudspeaker. This interference may reach the receiver and loudspeaker in various ways:

a. Disturbance coupled to the antenna
b. Disturbance coupled to the antenna cable
c. Penetration into the receiver enclosure via the power supply cables
d. Direct radiation into the receiver (immunity of an automobile radio to radiated interference)
e. Disturbance coupled to all other cables connected to the automobile receiver

Before the start of the investigation, the receiver housing, the antenna base, and each end of the shield of the antenna cable must be correctly grounded.

II.2 Disturbance Coupled to the Antenna – Most types of disturbances reach the receiver via the antenna. Suppressors can be fitted to the sources of disturbances to reduce these effects.

II.3 Coupling to the Antenna Cable – To minimize coupling, the antenna cable should not be routed parallel to the wiring harness or other electrical cables, and should be placed as remotely as possible from them.

II.4 Clock Oscillators – Radiation/conduction from on-board electronic modules may affect other components on the vehicle. Significant harmonics of the execution clock("E-Clock") must not coincide with duplex transceiver spacings, nor with receiver channel frequencies. The fundamental frequency of oscillator used in automotive modules/components shall not be an integer fraction of the duplex frequency of any mobile transceiver system in operation in the country in which the vehicle will be used

II.5. Other Sources of Information – Corrective measures for penetration by receiver wiring and by direct radiation are covered in other publications. Similarly, tests to evaluate the immunity of a receiver to conducted and direct radiated disturbances are also covered in other publications.

APPENDIX C

MATLAB PROGRAM FOR CALCULATION OF THEORETICAL PEAK-TO - AVERAGE (Written by Prof. T.F. Krile)

```
%tpi=2*pi.
%tau=half-width of trapezoidal input pulse.
%tp=period of pulse train. 20 ms for the 50 hz pulse
%bw=bandwidth in rad/sec for 6 db point to be at 120 KHz
%for the fifth-order Butterworth filter.
%wo=center frequency of equivalent first-order filter.
%wu=upper cutoff and wl=lower cutoff frequencies.
%amp is an arbitrary amplitude scaling factor.
%dt is the time resolution of the output pulse,
%which is 500 samples long.
%nmax is the number of discrete spectral lines to
%be used in finding the output pulse.
%pre() is the Fourier transform of the input pulse,which
% is a trapezoidal pulse with a width of 10ns at half
%maximum.
%gain() is the transfer function of the bandpass filter.
%coef() is the spectrum of the output.
%peak is the peak value of the output pulse.
%aver is the average value of the output pulse.
%ratio is the peak/average ratio in db.
tpi=2*3.14159;
tau=10e-9;
tp=1/500;
bw=tpi*107.5e3;
delbw=bw/2;
wo=tpi*47.18e6;
wu=wo+delbw;
wl=wo-delbw;
amp=.6/4;
dt=tp/(1*500);
nmax=round(12*bw/(tpi/tp))
for n=1:nmax
   nn=n-(nmax)/2;
   w=wo+nn*tpi/tp;
   p1=w*tau/2;
   pre(n)=(tpi/tp)*(amp*tau*sin(p1)/p1)*(sin(p1/2)/(p1/2));
   gain(n)=(1/(1+(((w*w-wu*wl)/(w*(wu-wl)))^5)*i));
   coef(n)=gain(n)*pre(n);
end
c=abs(coef);
%plot(c)
%This section computes the output pulse.
for l=1:500
   ti=(l-250)*dt;
```

```
   out=0;
   for n=1:nmax
      nn=n-(nmax)/2;
      w=wo+nn*tpi/tp;
      out=out+abs(coef(n))*cos((w-wo)*ti+angle(coef(n)));
   end
   pulse(l)=out;
   %This subsection full-wave rectifies the pulse.
   if pulse(l)<0
     pulse(l)=-pulse(l);
   end
end
%This section computes the peak value of the output.
   pk=0;
   for n=1:500
      if pulse(n)>=  pk
         pk=pulse(n);
      end
   end
   peak=pk
   %This section computes the average value.
   ave=0;
   for n=1:500
      ave=ave+pulse(n)*dt;
   end
   aver=(ave/tp)
   ratio=20*log10(peak/aver)
plot(pulse)
```

Appendix E: Survey of State DOTs

STATE DOT SURVEY SUMMARY

(COMPILED BY D.J. MEHRL, AUGUST, 2000)

Note: Our first survey mailing was based on a list of lowband users supplied to us by TxDOT and included 23 states. Form this mailing we received 10 responses. A second mailing was based on an FCC list of lowband mobile licenses and included 16 states not in the first mailing. We subsequently received 3 additional responses. The remaining 11 states were not contacted.

RESPONSE TO SURVEY QUESTION #1:

"What percentage of your mobile radios currently operate in the VHF low band? Can you estimate (even roughly) how many low-band mobile radios are currently deployed within your agency?"

State	**No. of Lowband* VHF Radios**	**No. of Highband VHF Radios**	**Total**	**% Lowband**
Arizona	118	2,387	2,505	5
California	2,434	9,376	11,810	21
Georgia	2,500+	???	???	~75
Illinois	~2,200	???	???	~60
Indiana	~2,000	???	???	???
Maine	~2,185	115	2,300	95
Mississippi	~1,250	???	???	???
Nebraska	~2,000	2,000	2,000	100
Ohio	5,247	5,247	5,247	100
Oregon	0	2,100	2,100	0
Texas**	5,350	3,748	9,263	58
Washington	~150	???	???	???
West Virginia	~2,500	0	2,500	100
Total Lowband VHF Radios	27,934			

* Lowband VHF radio count does not include portable (handheld) radios. It is uncertain as to what extent handhelds might be used inside of vehicles, hence subject to radiated emissions.

** TxDOT data dates back to April, 1998.

RESPONSE TO SURVEY QUESTION #2:

2. TxDOT typically encounters certain makes/models of pickup trucks that present RFI problems. In some cases, wide-band noise problems, appearing on all radio channels, have stemmed from, e.g., electric fuel pumps and HVAC fans. Increasingly, more incidents of microcontroller-related narrow-band noise have cropped up. This noise often requires only the key to be switched on, not the engine running, to be detected. With the engine running *and the vehicle warming up, the noise may tend to come and go on one, or a few, radio channels.*

Can you comment on your experiences (and, if available, your fixes) with RFI problems on various makes/models of vehicles? Are there particular makes/models that present common problems? By compiling a central database of reported problems and fixes from DOT agencies across the nation, we may be able to make identification and remediation of RFI problems <u>*easier for all!*</u> *(Please add an extra page if you need more space.)*

Arizona:

We experienced problems with 1996/97 ford Taurus' electric fuel pumps that caused RFI problems. Dealer replaced the fuel pumps and the problem was resolved.

California (CALTRANS):

We have had many RFI problems in the past. Vehicle equipment tends to interfere with our low band radios. 800 MHz radio equipment tends to interfere with microprocessor controlled electronics. We have initiated many fixes including shielding, grounding and clock frequency changes.

Georgia:

We have encountered problems with Motorola low band radios in certain vehicles. Example: Buick Century Sedans and Wagons, Ford Taurus Sedans and Wagons, and Dodge pickup trucks.

<u>Other comments:</u> *Georgia DOT is in the process of converting from traditional low band/high band radios to an 800 MHz Southern Link System.*

Illinois:

1999-2000 Dodge Pickups - Fuel Pumps and something else (probably engine control modules on some trucks, not all).

1999-2000 Navistar Trucks - Engine control modules on DT 466 engines.

Indiana:

A few interference problems from on board computers. No fixes.

Maine:

Most of the past problems were with 1994-95-96 Ford and GMC vehicles. We do not have enough newer vehicles to evaluate. Some sources of receiver RFI are Vehicle computers of which this issue was partly resolved with the purchase of special computer filters from Compatibility Products of Round Rock, Texas. Additionally, we have electric fuel pump noise which was eliminated with the use of filters attached very close to the fuel pump. The same source of filters as above were used. Additional sources of noise to receivers were heater blower motors, windshield wiper motors, electronic odometers, Drab and Drak units (alarm systems for heavy duty vehicles such as GMC TOP Kicks) and AM/FM radios.

Standard filters were used on the blowers and to a less acceptable level on windshield wiper motors. In the AM/FM radio, resonator devices were replaced with crystal filters to eliminate "spike" signals on the radio channels we use. On pickup trucks we mounted the mobile antenna on the extreme rear of the vehicle which did help significantly. It appeared that the GMC pickup trucks, 1995-96 were the worst offenders and caused the most problems. Many of which have not been resolved. The cost of computer filters were high, approximately $500 per truck for the computer, fuel and anti-skid brake systems filters.

It should be noted that Van type vehicles had much less noise generation possibly due to the fact that the antenna was shielded more by the vehicle design. No modifications to the vehicles were required.

GMC was helpful; however, their engineering staff was not able to really identify the problems or offer any solutions although they seemed to be trying to work on fixes that related to more grounding. On the other hand, FORD showed no interest in resolving the problems.

The SAE standard for signal generation by electronic devices in vehicles is NOT acceptable due to the rated sensitivities of receivers in this frequency range. The sensitivity of a modern low band receiver is from 0.2 to 0.3 μV and noise sources are considerably higher from numerous sources. The noise blanker function on the radios has helped ignition noise but the frequency of other sources is well above its operating range. I agree that manufacturers have not done much about this problem, in fact they have acknowledged the problem and reduced the sensitivity of the AM portion of the vehicle radio to reduce noise instead of curing it by proper design and filtering at the source.

Because of the lack of available frequencies in the VHF band, Maine DOT will be on low band for some time to come and needs vehicles which are acceptable for use with two-way radios.

Mississippi:

1.) *On the one-ton Chevrolet trucks we ran into a RFI problem which was caused by the computer. It was causing a problem on 47.24 MHz only. There were no RFI problems on any of the other frequencies. The dealer tried reprogramming the computer, but that did not correct the problem. The computer case in this truck was not grounded to anything. That was the first thing we did. We grounded it to the metal frame. Next we wrapped all computer connections with a metal film tape. The third thing we did, which was suggested by GM, was to place an in line filter in the green wire that goes to the battery on this Maratrac radio. This seems to have taken care of the problem. It has been about three months ago and is still working fine.*

2.) *One-ton 1997 & up Chevrolet dual wheels and dual fuel tanks. See attached from Fleet Operations (Chevrolet/GM) on circuit description. We've found that adding a 5 pF capacitor across x-1 solved it most of the time. With a few we added a 10 pF capacitor instead. The problem was intermittent noise on 47.14, 47.22, 47.24, 47.26 and 47.34 MHz.* [Note: Attachments too lengthy to include in this summary.]

Nebraska:

GM AM-FM broadcast band radio interferes. Per Delco tech support we changed ceramic resonator to 3.58 MHz quartz crystal.

<u>Other comments:</u> *Full size carefully resonated whip helps a lot compared to base load.*

Ohio:

- *Narrow band - 98-99 Dodge RAM pickups: air bag circuit. Module replaced by dealer.*
- *Broad band - Ford F-350 w/ Power Stroke diesel, 1995 to present. The electronic injector module. The factory did not support a fix. Note: the F-350 wiring harness is approximately the same length as our standard 1/4 wave whip. This created a broadly resonant antenna.*
- *Broad band - 1995 GMC pickups w/350 gas engine. Could not determine source of RFI. Had many discussions with Delco, but factory did not support a fix.*
- *Broad band - Various Ford pickups w/ 6 & 8 cylinder gas engines. The factory did not support a fix.*
- *Broad band - International 98-99 466E & 530E engines. RFI from engine control module. The factory did support a fix. Corrected by installing a filter (bypass capacitor) installed between the engine and floating ground case of the injector module.*
- *Broad band - Allison Transmissions. Field replacement of electronic control module. The factory supported the fix.*

<u>Other comments:</u> *We located an aftermarket filter from Spectrum Controls. We did not purchase as the cost was $500-600 per unit with a minimum of 25 units and installation may have compromised warranty and emissions requirements with Ford.*

Oregon:

We currently do not encounter many RFI problems with new vehicles. Those that we do encounter problems with are required to be corrected by the manufacturer. (We have a 3 dB desense requirement in our bid specifications.)

Texas:

Some recent problems and fixes--

Problem: 1997/1998 Ford F150 Central Timing Module (CTM) narrow-band noise. Fix: New CTM installed by Ford.

Problem: 1997 Ford F150 LPG Conversion Processor narrow-band noise and immunity. Fix: New processor by Autotronics.

Problem: 1998 Ford F150 Dual Fuel LPG vehicle HVAC and GFI processor broadband noise. Fix: None from factory. Ford is contracting with Professional Testing, Inc., to develop a filter.

Problem: 1997/1998 6.5L GMC diesel vehicle control module (VCM) narrow-band noise. Fix: GM is recalling ten vehicles at a time and replacing the VCM with an enhanced version.

Problem: 1997 Volvo White / Cummins engine fuel injector controller broadband noise. Fix: Cummins has a filter to be tested.

Problem: 1997 International Navistar / Caterpillar C10 electronic engine controller broadband noise. Fix: A filter is out to dealerships and ready for installation.

Problem: 1998 Dodge BR 1500 air bag controller narrow-band noise. Fix: Solution being developed by Professional Testing, Inc.

Problem: 1996 GMC Etnyre Asphalt Maintenance Unit on-board computer immunity problem. Fix: None from the factory. Third letter sent in December, 1998.

Problem: 1999 Chevrolet C7500 series noise was discovered by district before accepting using Acceptance Check List.

Washington:

Virtually all vehicles with lean burn computers, or computer controlled injection systems produce RFI on some frequency or channel in low band between 40-50 MHz.

Since many/most older PC units radiated signals in multiples of 4.7 MHz, the State of Washington made a decision to move the entire fleet to 800 MHz and abandon low band.

West Virginia:

Have had low band noise from various vehicles' sub-systems such as fuel pumps, electronic RPM gauges, AM-FM radios and vehicle main microprocessor.

RESPONSE TO SURVEY QUESTION #3:

3. Any other comments you wish to offer? Do you want more information about TxDOT's Tex-1160-T or about our modified J551/4?

In response to question #3, all but two survey responses indicated that they would like additional information about TxDOT's Tex-1160-T and our modified J551/4 tests.