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16. Abstract:
A study was carried out of two tests for the prediction of motor-vehicle interference in an on-board radio. The tests were TxDOT Tex-899-B and SAE J551/4, and the vehicles and radios of interest were new TxDOT pickup trucks and TxDOT two-way FM radios. The study involved a vehicle-testing component in which both tests were conducted on eleven trucks and a laboratory component in which TxDOT radios were subjected to simulated vehicle interference. The results show that, unlike Tex-899-B, J551/4 is not well suited to predict the occurrence of interference in the TxDOT radios, but it could be modified to do so. Some questions remain regarding the implementation of the modifications.

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TESTING FOR FM-RADIO INTERFERENCE IN MOTOR VEHICLES FINAL REPORT

FINAL REPORT

by

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Research Report Number 7-2995

conducted for

Texas Department of Transportation

by the

DEPARTMENT OF ELECTRICAL ENGINEERING

TEXAS TECH UNIVERSITY

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IMPLEMENTATION STATEMENT

Included in the results of the present study are some recommended modifications to the TxDOT Tex-899-B test, which serve to simplify and clarify the test procedure, and some recommended modifications to the SAE J551/4 test, which serve to improve the agreement between the two tests. The Tex-899-B modifications are easy to implement and have the effect of making a good test even better; they should be implemented straight away in TxDOT's ongoing new-vehicle testing program. Other state DOTs may also benefit from the use of the Tex-899-B test as modified. The J551/4 modifications are of more relevance to the vehicle manufactures than to TxDOT directly, because the manufactures currently use tests similar to J551/4. Their implementation of these modifications, in whole or in part, is expected to be a subject of continuing discussion.

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

ACKNOWLEDGMENT

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

AUTHOR'S DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view of policies of the Department of Transportation or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

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TRADE NAMES AND MANUFACTURERS' NAMES

The United States Government and the State of Texas do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

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1. INTRODUCTION

Background

This research project was undertaken to expand the in-house program of the Texas Department of Transportation (TxDOT) which addresses the problem of interference in mobile radio receivers. The project was carried out by Texas Tech University, with a subcontract to Southwest Research Institute.

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. 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 project as an independent investigation of the problem, focusing on testing methodologies and on cooperation with the vehicle manufacturers.

Personnel

The research staff for this project consisted of professors, students, engineers, and technicians. The following persons were the main contributors:

At Texas Tech University (TTU), Lubbock

Principal Investigator	T. Trost
Faculty Associate	T. Maxwell
Postdoctoral Assistant	A. Mitra
Graduate Students	Y. Jin, Q. Zhou
Undergraduate Students	M. Gary, H. Hendrickson, G. Kidwell, M. Ouren, R. Wiant
Technician	D. Castro
Bookkeeper	S. Willingham

At Southwest Research Institute (SwRI), San Antonio

W. Cory, I. Martinez, J. Scrivner, D. Smith

At Professional Testing (EMI), Inc. (PT), Round Rock

B. Rehm

Equipment Support

Major test equipment was provided to TTU by G. Sonnde from Rohde & Schwarz GmbH & Co. This support included the loan of an R&S model ESS receiver and the donation of an R&S model CMS54 radio-communication service monitor. These instruments proved invaluable in carrying out the measurements required for the project. The TTU Electrical Engineering Department also supplied several important test instruments, and a few were obtained through short-term rental. An annotated list of the equipment used for the project is contained in Appendix A of this report.

Technical Advice

Many valuable suggestions came to this project from a group of advisors, or TEAM (Technical Expert Advisory Members), who formed a loose-knit Advisory Board. Formal briefings on recent accomplishments were given by the project PI (Principal Investigator) to the Advisory Board at intervals throughout the course of the project. The advisors constituted a blue-ribbon panel whose members included electromagnetic-compatibility engineers from the Big Three automakers and other vehicle manufacturers, as well as engineers from test-equipment and two-way-radio companies, and consultants. The briefings were held on Nov. 21, 1996, Feb. 28, 1997, Aug. 21, 1997, April 17, 1998, and Oct. 30, 1998.

Valuable assistance throughout the project was also supplied by two TxDOT radio technicians, G. Morgan and L. Bryan.

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 by different agencies over the years. Two EMC test standards were of primary interest in this project, the TxDOT test referred to above, Tex-899-B [1], and a Society of Automotive Engineers test, SAE J551/4 [2]. 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 (akin to a signal-to-noise ratio test) [3]. The vehicle, emissions, antenna, and radio are shown in a simplified sketch in Fig. 1-1.

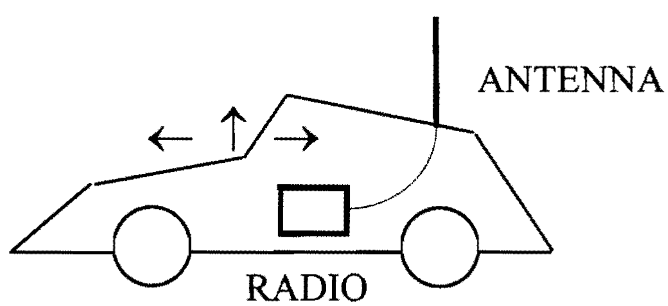


Fig. 1-1. Diagram of vehicle, emissions, antenna, and radio.

Actually, while the intent of Tex-899-B is to determine the effect on a radio "in the vehicle," for convenience in testing new vehicles, the radio is not installed but is located externally and connected to the antenna on the vehicle by a coaxial cable.

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. On the other hand, J551/4 is a more general industry standard, the applicability of which to the TxDOT problem was, a priori, not known.

Objectives and Methods

Concisely stated, our objectives were to evaluate and compare the two tests for TxDOT vehicles, to assess the degree of correlation between them, to look for ways to improve them, 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 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. A list of the TxDOT frequencies is given in Appendix B.

Our approach involved a two-pronged attack on the problem. First, we performed outdoor whole-vehicle tests on TxDOT trucks. The testing was done at three different sites, PT, SwRI, and TTU; and thirteen trucks were tested. This work allowed us to gain insight into the nature of the emissions produced by the vehicles and to become familiar with the practicalities of carrying out the two tests, J551/4 and Tex-899-B. Second, we performed bench-top tests related to J551/4 and Tex-899-B on TxDOT radios. The testing was done in a laboratory at TTU. A variety of noise sources was employed, and ten radios were tested. This work gave us a chance to apply different noise sources, individually and in combination, to the radios and to vary the noise amplitudes, in order to examine the effects on the radios. Finally, we applied all of the information gained to arrive at conclusions and make recommendations.

Because a large amount of data was collected during this project, the list of results is rather lengthy. As an aid to the reader, the major results are given separately in Chapter 4, with the complete list in Chapter 5.

2. OUTDOOR WHOLE-VEHICLE TESTS

Our whole-vehicle test campaign involved a total of thirteen vehicles, one 1996-model and twelve 1997's. A list of the vehicles and the tests performed is shown in TABLE 2-1. The vehicles labelled "Chevy" are Chevrolet S10 V-6 gasoline-powered pickup trucks, those labelled "Dodge" are Dodge RAM 1500 V-8 gasoline pickups, and those labelled "Ford" are Ford F-150 V-8 gasoline pickups. All the vehicles are owned by TxDOT except "Chevy TTU," which is owned by Texas Tech. Vehicles carrying the suffix "propane" had been converted to run on propane as well as gasoline before being tested; the rest were converted after testing.

TABLE 2-1. LIST OF WHOLE-VEHICLE TESTS PERFORMED

Truck	Testing Agency		
	SwRI	PT	TTU
'97 Chevy 1	SAE,TX(m)	TX(m)	
'97 Chevy 2	SAE,TX(m)		
'97 Chevy 3	SAE,TX(m)		
'97 Dodge 1	SAE,TX(m)	TX(m)	
'97 Dodge 2	SAE,TX(m)		
'97 Dodge 3	SAE,TX(m)		
'97 Ford 1	SAE,TX(m)	TX(m)	FS,TX(m)
'97 Ford 2	SAE,TX(m)		
'97 Ford 3	SAE,TX(m)		
'97 Chevy TTU			FS
'97 Dodge propane 1			SAE,FS,TX(b)
'97 Dodge propane 2			TX(b)
'96 Dodge propane	SAE,TX(r)		SAE,TX(r)

Notes: (1) "SAE" = SAE J551/4 test
"TX(m)" = Tex-899-B test with Motorola *MaraTrac* radio
"TX(r)" = Tex-899-B test with GE RANGR™ radio
"TX(b)" = Tex-899-B test with both radios
Frequencies– 47.02 MHz and 47.18 MHz
(2) "FS" = narrow-band frequency scan
Frequency range– 47.00 MHz to 48.60 MHz

The TxDOT vehicles were loaned to the project by the district offices in Beaumont, Ft. Worth, Lubbock, and Yoakum. The whole-hearted support of the project shown by these districts in making their trucks available was much appreciated.

The SAE J551/4 test employed an EMI receiver meeting standard specifications [4], while the Tex-899-B test required the use of a radio from the TxDOT fleet. For the latter, we chose the two most popular TxDOT radios, the Motorola *Mara Trac* and the GE RANGR™.

A detailed presentation of test data and discussion of results for the SwRI tests are presented in two SwRI subcontractor reports [5,6]. An overall presentation of the whole-vehicle data and results is contained in a TTU master's thesis by Q. Zhou [7]. We include in Chapter 5 of the present report a summary of the results given in these three references. We also include in Appendix C a copy of the thesis.

To give an idea of the type of data recorded, we now show some examples from the SwRI tests in the form of two bar graphs: In Figure 2-1 results are given for the Tex-899-B test, and in Figure 2-2 the results for J551/4. Two radio frequencies were used for the measurements, as indicated in the Notes of TABLE 2-1 above, however the data in the figures is for only one frequency, 47.02 MHz. In each figure the test results from the three trucks of each brand are averaged together. The various vehicle test configurations are specified at the bottom of the bars; those with the engine turned off are toward the left; those with the engine running are toward the right. "HVAC" means heating, ventilation, and air conditioning. The engine-off configurations allowed us to isolate DC-motor noise from spark-ignition noise. DC motors are used in the fuel pump, windshield wipers, and HVAC fan. The configuration of engine ***off*** and fuel pump ***on*** is the only one not to be expected during normal operation of the vehicles; we jumpered the fuel pump relay to achieve it.

In the Tex-899-B test (Fig. 2-1), the height of the bars indicates the signal amplitude needed to achieve a 12 dB SINAD reading at the output of the radio. The test limit is 0 dBμV, so all the vehicles passed. In the J551/4 test (Fig. 2-2), the height of the bars gives the peak amplitude of the broad-band RF noise at the radio antenna port. The test limit is 28 dBμV, so the vehicles failed the test for many configurations.

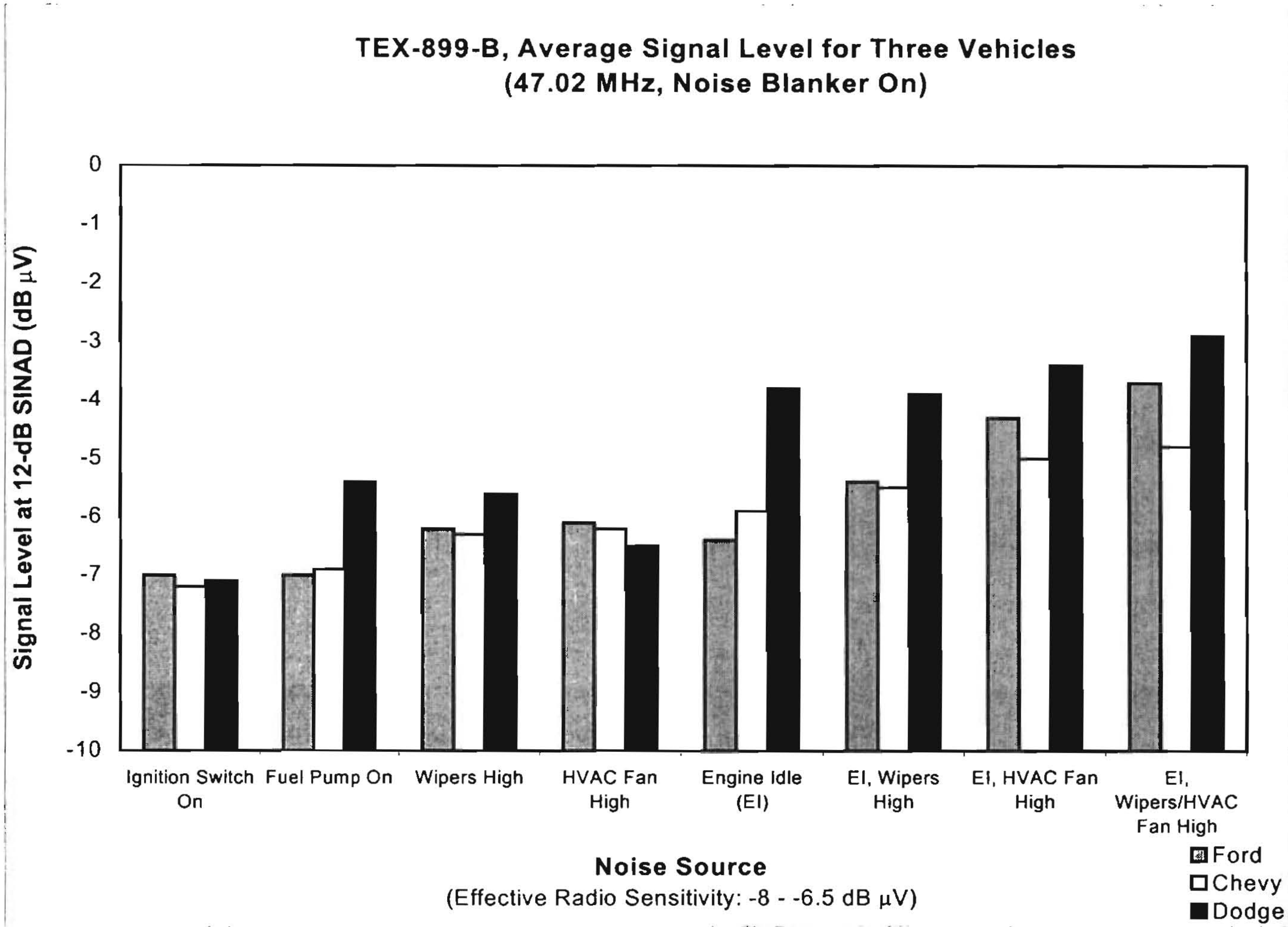


Fig. 2-1. Example of data recorded in TxDOT Tex-899-B test.

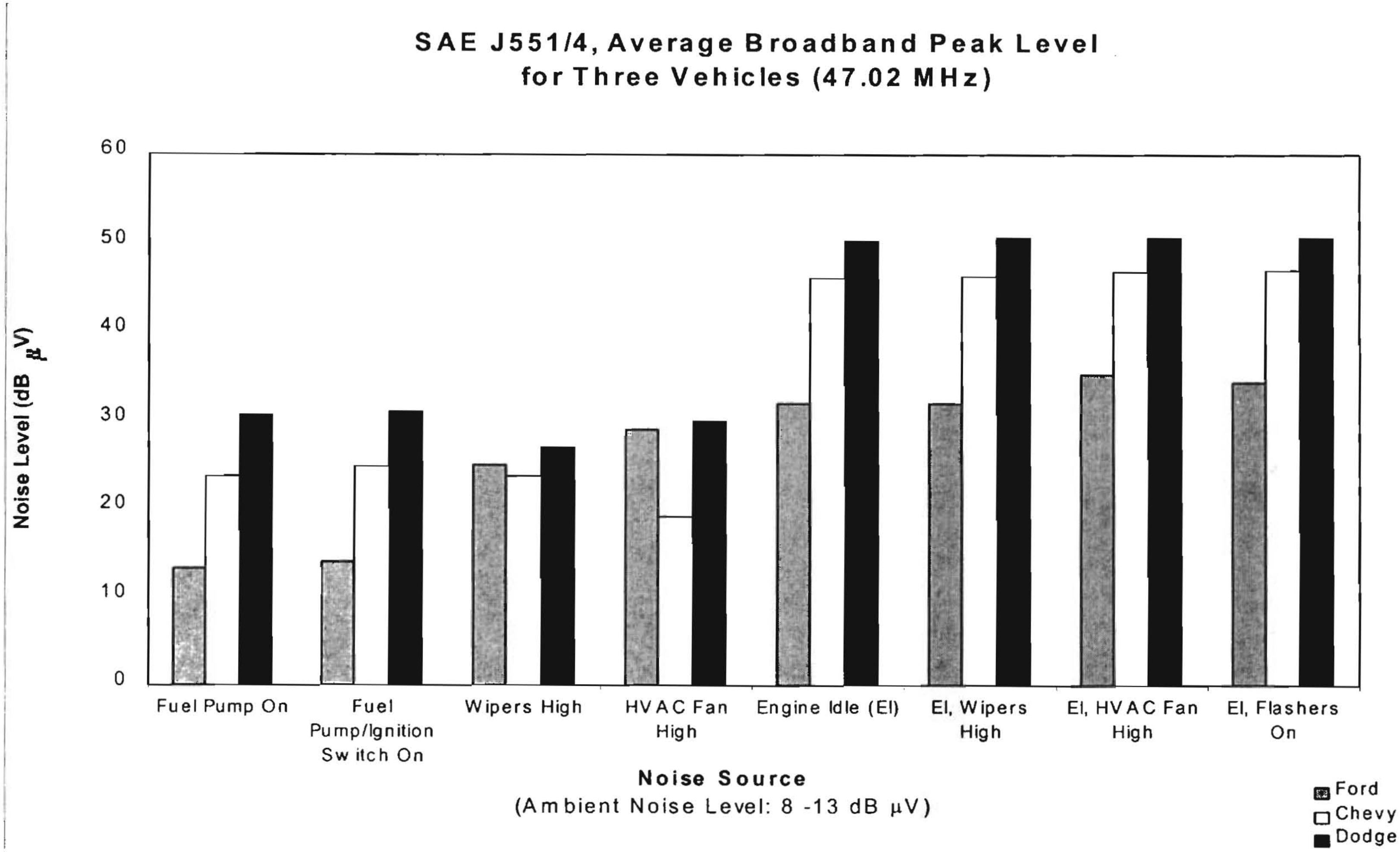


Fig. 2-2. Example of data recorded in SAE J551/4 test.

The largest values recorded in the whole-vehicle tests are of special interest; they are listed in TABLE 2-2. The values are slightly higher than those indicated by the tallest bars in the figures because of the averaging used for the bars. J551/4 distinguishes between two kinds of noise, broad-band (BB) and narrow-band (NB). Only broad-band was observed in the tests at the TxDOT frequencies.

TABLE 2-2. WORST-CASE RF NOISE IN WHOLE-VEHICLE TESTS

	Tex-899-B (FM signal)	J551/4 (BB peak noise)
Engine ***off*** Fuel pump ***on***	– 4 dBμV	37 dBμV
Engine ***running*** Fuel pump ***on*** HVAC fan ***on***	– 3 dBμV	56 dBμV

3. LABORATORY BENCH-TOP TESTS

Measurements and Data

Our bench-top tests were conducted on ten radios in the Electrical Engineering Department at Texas Tech. Nine radios were supplied for the project by the TxDOT radio shops in Austin and Lubbock as follows: GE RANGR™ (3 ea.), Ericsson ORION™ (2 ea.), Motorola *MaraTrac* (2 ea.), and Motorola *SYNTOR X* (2 ea.). A single Kenwood TK-630H was provided by a Lubbock radio retailer. A block diagram of the test-equipment setup is shown in Figure 3-1. The hybrid junction sends the combined noise and FM signal to the FM radio and to the EMI receiver. Most of the noise sources employed with the setup were intended to simulate those in the actual vehicles; others were more generic; still others were deliberately chosen for their interference potential. Our noise-source repertory is listed in TABLE 3-1.

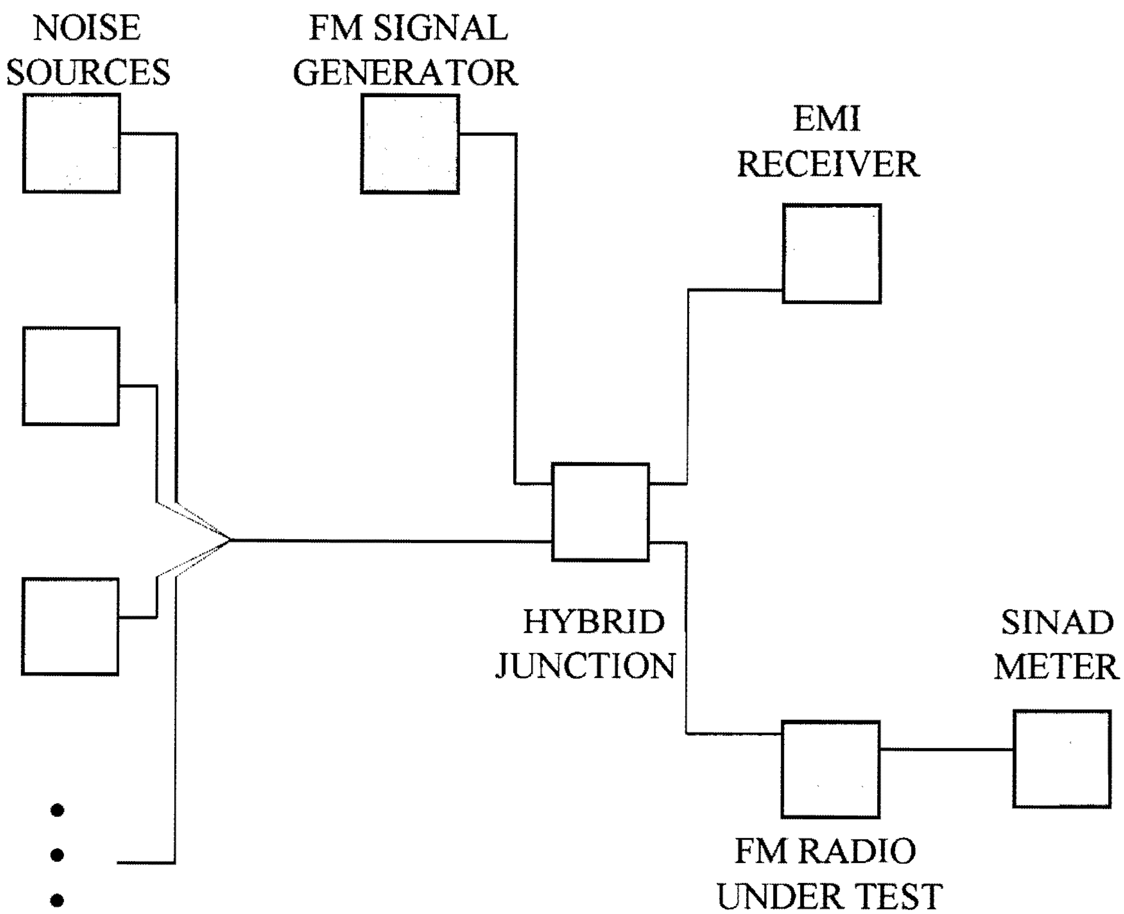


Fig. 3-1. Block Diagram of Bench-Top Test System.

TABLE 3-1. LIST OF BENCH-TOP NOISE SOURCES USED

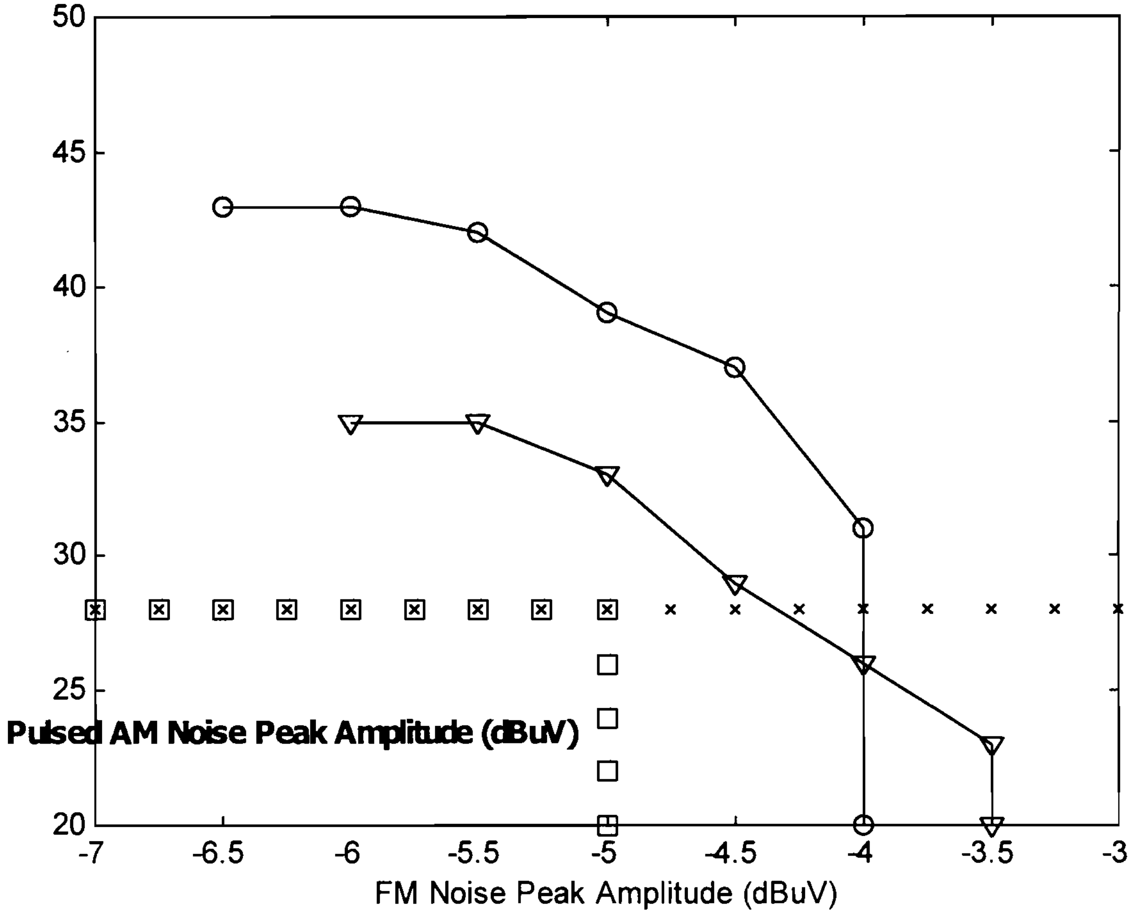
Narrow-Band	
	CW
	AM, sinusoidal (400 Hz and 1500 Hz)
	AM, pulsed (1500 pps; duty cycle = 3 % to 70 %)
	FM, sinusoidal (400 Hz and 1500 Hz; deviation = 3 kHz to 6 kHz)
	Microcontroller
	Thermal
Broad-Band	
	Spark Ignition
	Fuel pump (with Stoddard solvent)
	HVAC Motor
	AM, pulsed (1500 pps; duty cycle = 0.03 % to 1.0 %)

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 1.0 μV amplitude, the highest allowed by Tex-899-B.
2. With a particular noise source connected, the noise amplitude was adjusted to produce a SINAD reading equal to 12 dB, the value always 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.

A detailed presentation of test data and results from the bench-top tests is contained in a TTU master's thesis by Y. Jin [8]. We include in Chapter 5 a summary of the results. We also include in Appendix C a copy of the thesis.

One type of test not included in the thesis, however, is that in which two noise sources were used simultaneously. An example of this type is shown in Figure 3-2, where the worst-case narrow-band noise was combined with the worst-case broad-band noise. The narrow-band noise consisted of an FM signal which had been selected for maximum interference effect, with 1.5 kHz modulation frequency and 6.0 kHz frequency deviation; and the broad-band noise consisted of a radar-like pulse train, pulsed AM with 1500 pps and 1 % duty cycle. The noise sources were combined with a directional coupler, not shown in Fig. 3-1, then sent to the hybrid junction.



Notes: o = *MaraTrac* radio
∇ = RANGR™ radio
Pulsed AM noise has 1500 pps and
1 % duty cycle (broad-band noise)
FM noise has 1500 Hz modulation frequency and
6.0 kHz frequency deviation (narrow-band noise)
Radio frequency = 47.02 MHz
x = current J551/4 limit
□ = suggested new J551/4 limit

Fig. 3-2. Amplitudes of Two Simultaneous Noise Sources for 12 dB SINAD in Two Radios.

The data points in Figure 3-2 were measured while recording a 12 dB SINAD reading with a 1.0 μV FM signal– the Tex-899-B limit– and using different relative amplitudes for the two noise sources. Each curve represents a different TxDOT radio. The horizontal portions of the curves at the upper left correspond to the case where the radio response is dominated by strong pulsed AM noise, the FM noise being weak and inconsequential. The vertical portions at the lower right correspond to the opposite case where the FM noise dominates. Between these extremes both noise sources affect the radio, and the curves are sloping.

Considering now J551/4 instead of Tex-899-B, we could draw two limit lines on Fig. 3-2— a horizontal one for broad-band noise and a vertical one for narrow-band noise. In order to be able to substitute J551/4 for Tex-899-B, these limit lines would need to approximate the measured curves.

Shown in the figure by the row of x's is the current J551/4 broad-band limit at 28 dBμV. The current narrow-band limit lies off-scale to the right at 0 dBμV. Clearly the 0 dBμV value is too high to make a good approximation of the curves; and a new, better value is shown by the column of squares at –5 dBμV. A very conservative way to choose a new broad-band limit would be just to leave it at the current 28 dBμV value, as indicated by the row of squares. However a closer approximation to the curves would be obtained by raising the broad-band value to, say, 32 dBμV, thus bringing the corner of the limiting rectangle up close to the lower of the two measured curves.

Of course the validity of these new J551/4 limits depends on the two noise sources being realistic worst-case motor vehicle threats. When Figure 3-2 was presented by the PI at the Oct. 30, 1998, meeting of the Advisory Board, some board members suggested that these sources are probably not realistic, not likely to be encountered in a vehicle; and so the new narrow-band limit at - 5 dBμV is excessively low. One combination that certainly would be considered realistic is that of DC-motor noise, (e.g. HVAC fan) and CW noise (e.g. microcontroller clock harmonic). Our bench-test data for this case suggests new limits of 35 dBμV and - 4 dBμV.

The two-noise-source simulation, employing HVAC fan and CW, would be applicable to a vehicle with the engine off. For the case of the engine running, a third source, spark ignition, would have to be added. We have not studied this case, and so it is left as a task for the future.

<u>Broad-Band versus Narrow-Band Noise</u>

For our noise sources, the TxDOT radios are much more sensitive to narrow-band noise than to broad-band. This type of behavior in a victim device is accommodated in J551/4 through the use of a higher limit for broad-band than for narrow-band noise. However we have found that, for application of J551/4 to TxDOT radios, the boundary between broad-band and narrow-band noise should be moved to a larger bandwidth. For example, the radios are very sensitive to the pulsed AM noise suggested by D. Hibbard [9], but J551/4 would classify this as broad-band and apply an erroneously high limit.

To investigate this problem, we chose pulsed AM (1500 pps) as a single representative noise waveform, and varied its bandwidth by changing the duty cycle. The J551/4 test for broad-band vs. narrow-band noise instructs us to measure the peak-to-average ratio of the noise at 9 kHz bandwidth. If the result is over 6 dB, it's broad-band. Application of this 6 dB test to the pulsed AM waveform places the broad-band/narrow-band boundary at 3.6 kHz bandwidth (50 % duty cycle). However, as far as the radio response is concerned, the boundary lies at about 180 kHz bandwidth (1.0 % duty cycle); that is, if the bandwidth of the noise is more than 180 kHz (less than 1.0 % duty cycle), the radio is much less sensitive to it.

Based on laboratory experimentation with the pulsed AM source as well as other noise sources, we have devised what we feel is a practical method for characterizing unidentified noise with respect to the new 180 kHz boundary. We measure the peak value of the noise at two different bandwidths, 10 kHz and 120 kHz; if the difference is 17 dB or greater, it's broad-band noise, otherwise narrow-band.

4. PRINCIPAL RESULTS AND RECOMMENDATIONS

Regarding TxDOT Tex-899-B

The noise blanker circuit in the TxDOT radios is very effective in reducing spark-ignition noise and somewhat effective against noise from DC-motors such as fuel pumps and HVAC fans. It is always switched on when the radios are in use in the fleet. We urge that it be switched on when the Tex-899-B tests are conducted. This can make the difference between passing and failing, and it has not been the practice in the past.

Two limits are specified in Tex-899-B as follows: The FM signal level needed for a 12 dB SINAD reading can be no more than 1.0 μV or no more than 6.0 dB above the level needed with just ambient noise present, whichever is lower. We recommend using only the 1.0 μV limit, which is sufficiently stringent and is less complicated to implement than the 6.0-dB-increase limit.

When the two recommendations above were followed during the Tex-899-B testing in this project, all three brands of 1997-model trucks passed the test (cf. Fig. 2-1) and the 1996 truck narrowly missed passing. Thus the pass/fail record for the trucks was good.

Regarding SAE J551/4

All the trucks failed the test with engine running due to high spark-ignition noise, although the Fords came to within a few dB of passing (from Fig. 2-2). With engine switched off, all the trucks passed, or came within 2 dB, when the HVAC fan or the windshield wipers were set to high (from Fig. 2-2). Thus the pass/fail record for the trucks was mixed.

Based on our whole-vehicle and bench-top studies, it appears that J551/4 can be substituted for Tex-899-B if the following modifications are made to J551/4:

1. The limit on narrow-band peak noise must be lowered from 0 dBμV to - 4 dBμV (from discussion following Fig. 3-2). The TxDOT radios, when receiving an FM signal at the Tex-899-B limit of 0 dBμV, cannot tolerate narrowband noise at this same level; it must be a few dB lower.

2. The current 28 dBμV limit for broad-band noise may be raised because of the effectiveness of the TxDOT radio noise blankers. For DC-motor noise only, the broad-band limit can be raised to 35 dBμV and, for spark-ignition plus DC motor, to 50 dBμV (from TABLE 2-2, allowing a few-dB margin). And these limits ought to be good if some narrow-band noise is present in combination with the broad-band.

3. Instead of defining broad-band noise as that which causes greater than 6 dB difference between peak and average amplitude readings at 9 kHz bandwidth, we suggest broad-band noise should be defined as that which causes 17 dB or more increase in peak amplitude when bandwidth is increased from 10 kHz (or 9 kHz) to 120 kHz.

5. DETAILED RESULTS

From Whole-Vehicle Tests

Pass/Fail Outcomes for Tex-899-B

Eleven '97-model trucks were tested according to Tex-899-B at two frequencies. One frequency, 47.18 MHz, lies in the center of the TxDOT range, and the other frequency, 47.02 MHz, is the major state-wide frequency for TxDOT vehicles. All the vehicles passed the test when the radio noise blanker was turned on (cf. Fig. 2-1). In fact, the radio was so quiet that the testing proved somewhat frustrating to the Texas Tech personnel who were hoping to study motor vehicle noise.

In order to insure that no narrow-band vehicle emissions within the TxDOT range were missed by performng Tex-899-B at only two frequencies, a frequency scan covering all 14 TxDOT frequencies was run on three of the '97-model trucks (one of each brand). All of them passed.

Both '97-model propane-converted Dodge trucks passed the Tex-899-B test at TTU when running on propane and when running on gasoline, so that the installation of the propane fuel system did not adversely affect the noise emission of the trucks. The propane conversion was done by Northwest Butane Gas Co., Dallas, TX.

The only '96-model truck tested, a propane-converted Dodge, failed Tex-899-B by about 1 dB, but only under the condition of the engine running at cruising speed (1500 rpm) on gasoline and the air conditioning turned on. The propane conversion might have adversely affected the noise emission. It was done by R & W Supply Co., Littlefield, TX.

Pass/Fail Outcomes for J551/4

All the trucks failed the test with engine running due to high spark-ignition noise, although the Fords came to within a few dB of passing (from Fig. 2-2).

With engine switched off, all the trucks passed, or came within 2 dB, when the HVAC fan or the windshield wipers were set to high (from Fig. 2-2).

Noise Sources/Coupling

Spark-ignition noise has the highest peak value of any vehicle emission but does not appear in the output of the TxDOT radios because of the effectiveness of the radio noise blankers.

In Tex-899-B tests on three '97-model trucks (one of each brand), noise with the engine at idle (750 rpm) was about the same as with the engine at cruising speed (1500 rpm) except for the case of the Dodge with the radio noise blanker off, which showed a 3 dB to 6 dB increase.

There is no need to use the PT-designed fuel pump and HVAC noise-reducing filters on the '97-model Dodge trucks in order to improve the Tex-899-B test results, since they all passed without filters; although the filters do reduce the noise measured in the J551/4 test.

Vehicle Comparisons

The Dodge trucks were noisier than the Ford and Chevrolet trucks.

From one vehicle to another of the same brand, the level of spark-ignition noise was the same, while noise from DC motors (i.e. fuel pump and HVAC fan) changed 3 to 7 dB in the J551/4 test. This variation in DC-motor noise may be another aspect of the motor aging that we observed in the bench-top tests. (See *Noise Sources/Coupling.*)

Radios

The performance of the Motorola *MaraTrac* radio is a little better than that of the GE RANGR™ in the sense of rejecting broad-band vehicle noise. (A similar result is evident for the pulsed AM noise in the bench test data in Figure 3-2.)

Test-Site Comparisons

Three trucks were tested according to Tex-899-B at SwRI and PT and one of these was also tested at TTU. The same radio was used throughout. Test readings were generally highest at PT, lower at SwRI, and lowest at TTU, with a spread of up to 4 dB with the noise blanker on and 9 dB with the noise blanker off. The reasons for this may be that (1) the ambient noise level was lowest at TTU, thus reducing all measured levels, (2) at PT a different magnetic-mount antenna, with less capacitance to the vehicle body, was employed, thus increasing the likelyhood of noise pickup by the antenna cable, and (3) there were some differences in make and model of test equipment among the three sites.

For the '96-model vehicle the SwRI and TTU results for the Tex-899-B test were in good agreement, with TTU noise readings about 1 dB higher, but in the J551/4 test there was a systematic difference of about 5 dB, TTU values being higher. This difference may have been due to the very long (30 s) measurement time which was used at TTU to obtain very stable readings but which could not be matched by the older EMI receiver (1 s) at SwRI. The measurement time is an important parameter whenever one measures the peak value of spark-ignition and DC-motor noise. Because of the random nature of the noise, longer measurement times catch the occasional higher peaks and give higher readings.

Tex-899-B Methods

The radio noise blanker should be switched on during the Tex-899-B test because it is on when the radio is in service at TxDOT. The noise blanker can improve the test results by 4 to 12 dB.

There should be no 6-dB-increase (or degradation) limit in Tex-899-B because the 1 μV amplitude limit, while less stringent than the 6 dB, is nevertheless adequate, and the 6 dB requirement represents an added complication in the testing.

When the Tex-899-B test is applied to a new vehicle, there is no installed two-way radio or antenna, so the test procedure calls for the placement of a magnetic-mount antenna on the vehicle, with a coaxial cable running to the radio several meters away. In our tests, the positioning of the cable and the application of ferrite chokes to the cable were not found to be important (TTU, noise blanker on and off). This is the desired result since one would have to question the validity of the test if the cable played a major role.

There was little or no difference in Tex-899-B results (at SwRI) when the radio was installed in the vehicle and used with an installed antenna instead of being operated outside with a magnetic-mount antenna in the usual way, provided the radio noise blanker was switched on. However, about 2 dB higher noise was measured for the installed radio and antenna when the noise blanker was off. This is again a desired result, because the occurrence of a large difference here would have suggested that the external radio did not adequately represent the installed one.

J551/4 Methods

A rather long, one second, measurement time is needed to get an accurate peak level in the J551/4 test when exercising the windshield wipers since they exhibit a periodic fluctuation. In fact, a one second measurement time is recommended for all broad-band peak measurements in order to get a sufficient sample of the random waveform of the noise.

Quasi-peak [10] data were recorded along with peak data, but showed no unique patterns.

Relationship of J551/4 to Tex-899-B

If substituting J551/4 for Tex-899-B, the broad-band peak limit can be raised from 28 dBμV to 35 dBμV for DC-motor noise and to 50 dBμV for spark-ignition noise.

<u>From Bench-Top Tests</u>

Radios

Performance varies somewhat from one brand of radio to another (cf. Fig. 3-2), and this creates an undesirable uncertainty in the application of Tex-899-B and in the correlation between Tex-899-B and J551/4. However, all ten radios are really quite similar, and we judge the variability to be not too great to prevent a reasonable level of correlation between the tests.

For the different types of noise we employed, the TxDOT radios are much more sensitive to the narrow-band noise than to the broad-band.

Among the different types of narrow-band noise, the FM noise is the greatest threat to the TxDOT radios. This is probably not surprising since they're FM radios. The worst case occurs when the frequency deviation is 6 kHz.

The radio noise blankers have no effect on narrow-band noise but they improve the test results by about 8 dB for DC-motor noise and by more than 25 dB for spark-ignition noise (exact value not known because of limited ignition noise simulator power).

The current J551/4 definition of broad-band vs. narrow-band noise greatly restricts the narrow-band region and does not suit the TxDOT radios. For noise in the form of pulsed CW, for example, the current definition places the boundary between broad-band and narrow-band at 3.6 kHz bandwidth (6 dB points), whereas the response of the radios requires the boundary at about 180 kHz bandwidth.

When delivering a 1.0 kHz tone at 12 dB SINAD, the TxDOT radios produce a noisy sound containing about 50 clicks per second (ckps), and they are operating in the region of strong SINAD variation, with about 3 dB of SINAD change for 1 dB of noise change. (SINAD is measured at the audio output of the radios, noise at the RF input.) This is the well-known "threshold" effect in FM detectors [11]. As a related point of interest, note that the FM detectors in all the TxDOT radios are quadrature detectors [12].

Tests of so-called back-door penetrations of the radios, not covered by either J551/4 or Tex-899-B, found some susceptibility of the radios to CW RF noise induced by a small loop into their DC-power, control-head, and audio-output cables. No susceptibility was found for HVAC fan noise. It is not known whether back-door penetrations are a problem in the TxDOT vehicles.

A test was conducted employing simultaneously the most severe narrow-band threat, FM noise, and the most severe broad-band threat, pulsed AM noise (see Fig. 3-2). Results showed that the radios are more sensitive to the combination of noise sources than to either one by itself. The effect can be taken into account by a slight lowering of the J551/4 broad-band and narrow-band noise limits. Extending this work to the case of three simultaneous sources seems warranted.

Noise Sources/Coupling

The occurrence of several cycles of ringing of the vehicle whip antenna is an interesting feature of the radio input voltage in response to vehicle spark-ignition noise, and it was included in the spark-ignition noise simulation in the laboratory by use of a series-RL network at the output of an impulse generator.

Some aging of our new Dodge HVAC fan motor was observed; after running for 25 hours, the peak value of the noise output required for a 12 dB SINAD had risen by 5 dB, from about 42 dBμV to about 47 dBμV, for a *MaraTrac* radio. We speculate that the brushes had become better seated on the commutator so as to change the characteristics of the sparking. Component aging had been suggested by P. Andersen [13] as a source of variability in RF emissions data. It would be interesting to see if the fuel pumps experience the same type of aging.

The exact form of the transfer function, or coupling, between vehicle DC-motor current and TxDOT radio input noise, while not known, may not be important because our tests showed similar radio response when using two different coupling mechanisms– a current transformer attached to the motor leads and a monopole antenna located near the leads. Both common-mode and differential-mode connections [14] were used with the current transformer.

SINAD Meter

A psophometric (CCITT) filter [15] is built into the SINAD meter to emulate the response of the human ear. Our measurements show that switching on this filter allows the noise source amplitudes to be increased by 1 to 13 dB, depending on the source, for the standard 12 dB SINAD reading. This filter is not called for in the Tex-899-B test; perhaps it should be, in order to increase the correlation with human hearing.

Another improvement to the SINAD meter that might be worth considering is to change its detector response from RMS to something else– for example quasi-peak, which is designed to allow for the human annoyance factor when listening to pulsed noise. Quasi-peak detection in the SINAD meter was tried but not studied in detail in the present project.

Relationship of J551/4 to Tex-899-B

If substituting J551/4 for Tex-899-B, the narrow-band peak limit must be lowered from 0 dBµV to - 5 dBµV to protect against our worst-case narrow-band noise.

If substituting J551/4 for Tex-899-B, the broad-band peak limit can be raised from 28 dBµV to 35 dBµV for DC-motor noise and to 66 dBµV for spark-ignition noise. (But ignition noise without motor noise (electric fuel pump) occurs only when a vehicle is running on propane.) The limit should remain at or near 28 dBµV for the worst-case noise combination we used in the lab.

If substituting J551/4 for Tex-899-B, the J551/4 boundary between broad-band and narrow-band noise must be moved as stated above in Chapter 3. A suggested new test method for use with unidentified noise, which properly locates the boundary, is to measure the noise peak value at 10 kHz and 120 kHz bandwidths; if the difference is 17 dB or greater, it's broad-band noise, otherwise narrow-band.

<u>Supplied in Report by Subcontractor, SwRI</u>

The following results apply to the nine 1997-model vehicles tested by SwRI [6].

1. More vehicle test failures occurred for J551/4 than for Tex-899-B with the radio noise blanker switched off– 76 % versus 50 %.

2. There was little test-result variability among vehicles of the same manufacturer.

3. There was little test-result variability between two test sites, SwRI and PT.

4. (a) The RF noise amplitude ranking, from highest to lowest, was Dodge, Chevrolet, Ford.
   (b) The type of noise with highest-amplitude was spark ignition.

5. For both J551/4 and Tex-899-B, the fuel pump and HVAC fan filters designed by PT were generally ineffective.

6. On Dodge 1, the radio was installed in the vehicle and used with an installed antenna in addition to being operated outside with a magnetic-mount antenna in the usual way. Two small differences were found with the installed setup, when the noise blanker was switched off: although the filters were more effective than usual, the tendency for vehicle test failure was actually greater.

7. Switching on the radio noise blanker eliminated all vehicle failures to Tex-899-B.

8. On Dodge 3, Tex-899-B tests for wet soil and dry soil conditions showed little difference.

9. On Ford 3, the Tex-899-B test was run using a quasi-peak detector and an average detector in the SINAD meter in addition to the usual RMS detector. With the average detector, no difference greater than 2 dB was observed; but with the quasi-peak detector, significantly higher readings were seen, making the test more stringent.

6. CONCLUSIONS AND FUTURE RESEARCH DIRECTIONS

Conclusions

A number of interesting results have been obtained and some unanswered questions have arisen (Chapter 5) during the course of the project. Although the degree of correlation between the tests Tex-899-B and J551/4, as they currently stand, is very poor, a series of recommended changes in the tests (Chapter 4) would improve the correlation and allow J551/4 to be substituted for Tex-899-B. There remain some questions of implementation, however, which are discussed below.

The recommendations contained in Chapter 4 regarding the Tex-899-B test will be easy to implement and will make a good test even better.

The recommendations in regard to J551/4 are that the narrow-band limit be lowered, the broad-band limit be raised, and the narrow-band/broad-band boundary be adjusted. Applying these recommendations, along with those for Tex-899-B, will bring the limits of the two tests into general agreement, that is, will force a degree of correlation between the tests.

Actually implementing the recommendations regarding J551/4 may prove difficult for the following reasons:

If the measurements are done outdoors, it may be unrealistic to expect to measure accurately down to the new - 4 dBμV narrow-band peak limit because of the ambient noise level. The ambient level for tests like this we have done in the past has been - 6 dBμV. Doing the measurements in a chamber would be much preferred, where the EMI receiver would provide a noise floor of perhaps - 10 dBμV.

Another problem with the measurement of narrow-band peak noise, whether measured indoors or out, is that, with the vehicle engine running, spark-ignition noise will obscure any narrow-band noise near the limit. It might be necessary to resort to a very narrow bandwidth [16] or to an average detector rather than a peak.

Broad-band peak noise near the new 35 dBμV and 50 dBμV limits can be measured outdoors, where we have found the ambient noise to be around 12 dBμV. But with two limits specified where before there was only one, a longer test time will result because of the need for two frequency scans. The two limits arise because of the presence of two different noise sources.

The practical difficulties involved in performing the J551/4 measurements need to be resolved. It may turn out that, with all its modifications, the J551/4 test will be more troublesome and time-consuming to carry out than the Tex-899-B test it was intended to replace.

Future Directions

This project could be continued in the future with the addition of the following tasks:

1. Carry out both J551/4 and Tex-899-B tests, with recommended modifications, on new TxDOT vehicles.

(a) Verify the validity and practicality of the suggested new limits and the suggested new broad-band/narrow-band definition for J551/4.

(b) Provide feedback to vehicle manufacturers regarding test results.

2. Carry out additional bench testing at TTU.

(a) Investigate new test-equipment possibilities, such as a custom-designed detector weighting function tailored to motor vehicle emissions and FM radio receivers. This has been suggested by R. Kautz [17] and others and was a point of discussion at the Oct. 30, 1998, meeting of the Advisory Board. It has the potential of simplifying J551/4 testing. It is a lofty goal, one that may be unattainable.

(b) Perform tests as in the past but employing up to three simultaneous noise sources so as to assess their additive effect, as discussed in Chapter 3 following Fig. 3-2.

(c) Provide laboratory support to investigate questions arising during the whole-vehicle testing in task 1 above.

3. Investigate the impact of future trends.

(a) The use of more complex electrical environments (digital and analog) in vehicles.

(b) The change-over to higher radio frequencies and more sophisticated radio systems, such as trunking.

(c) The change-over to narrow-band FM radios.

4. Exchange information.

(a) Contact other state DOTs for possible technology transfer based on our research results.

(b) Continue the use of the existing Advisory Board.

(c) Present research results at a national EMC symposium to reach a larger audience.

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APPENDIX A: BRAND AND MODEL OF PRINCIPAL TEST EQUIPMENT

(Noted in parentheses below is the use to which each item of equipment was put.)

RF Sources

Fluke 6060B Signal Generator (FM signal)
R&S CMS54 Radiocommunication Service Monitor (CW, AM, and FM noise)
E-H Research Labs 139B Pulse Generator (spark ignition noise)
Dodge, Ford, AutoZone Fuel Pumps (fuel pump noise)
Dodge HVAC Fan (fan noise)
Motorola 68HC11 Microcontroller on Circuit Board (microcontroller noise)
Mini-Circuits ZFL-500HLN RF Amplifier (thermal noise)

Spectrum Analyzers

HP 8592L Spectrum Analyzer (RF spectrum)
HP 3580A Spectrum Analyzer (AF spectrum)

EMI Receiver

R&S ESS EMI Receiver (RF noise amplitude)

SINAD Meters

HP 8903A Audio Analyzer, RMS detector, readings/second = 2 (RMS voltage and SINAD)

R&S CMS54 Radiocommunication Service Monitor, RMS detector, readings/second = 1 to 4 (RMS voltage and SINAD)

Oscilloscopes

HP 54616B, 2 GSa/s, 500 MHz (RF waveforms)
Fluke PM3370A, 1 MSa/s, 60 MHz (AF waveforms)

Network Analyzer

HP 8753C (S-parameters of truck antenna, hybrid junction, etc.)

Other Devices

Synergy Microwave KDK-702 20-dB Directional Coupler (used in Tex-899-B whole-vehicle testing)

Synergy Microwave DJK-702 0°-180° Hybrid Junction (used in bench-top testing)

Weinschel 3200T-1 Programmable Attenuator (used with all noise sources except CMS54)

Mini-Circuits ZFSWHA-1-20, RF Switch (used with CMS54 for pulsed AM noise)

Fischer F-33-1 current transformer (used to sample RF current in fuel pump and HVAC fan)

APPENDIX B: LIST OF TXDOT LOW-BAND VHF RADIO FREQUENCIES

The following are the 18 low-band frequencies assigned to TxDOT. Values are in MHz. Frequencies marked with an asterisk (*) are used only for mobile-radio transmission to a repeater and not for mobile-radio reception; as such, they were not of interest in this project.

45.680 *	47.120
45.720 *	47.140
45.800 *	47.160
45.840 *	47.180
47.020	47.200
47.040	47.220
47.060	47.240
47.080	47.260
47.100	47.340

APPENDIX C: MASTER'S THESES

Two master's theses are reproduced in this appendix:

1. "Testing Motor Vehicles for Radio Interference," Q. Zhou, MSEE Thesis, Texas Tech University, Aug. 1998.

2. "Laboratory Simulation of Motor Vehicle Radio Interference," Y. Jin, MSEE Thesis, Texas Tech University, Dec. 1998

LABORATORY SIMULATION OF MOTOR VEHICLE RADIO INTERFERENCE

by

YE JIN, B.S.

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

Osama Ishihara

[illegible]

Accepted

Dean of the Graduate School

December, 1998

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CHAPTER I

INTRODUCTION - THE TxDOT PROJECT

As more microprocessor-based electronics are used in modern motor vehicles, the compatibility between vehicle electronic systems and after-market electronic equipment has become increasingly important. Radio frequency interference (RFI) between these systems, which causes compatibility problems, can produce random failure of both original equipment manufacturer (OEM) and after-market components. Failure of critical vehicle systems can pose grave safety problems and adversely affect the operation of the vehicles.

Recognizing the significance of RF emissions in modern vehicles, the Society of Automotive Engineers (SAE) has been involved in writing electromagnetic compatibility (EMC) standards since 1957. These standards are continually examined and updated to keep pace with technology. The SAE J551/4 test,[1] a standard vehicle EMC test, is being used by the three major US vehicle manufacturers. Comparable European standards also exist, and there are other more specialized standards and specifications that are related to automotive RFI issues, such as TxDOT Test Method Tex-899-B.[2]

Extensive RFI testing by vehicle manufacturers typically provides adequate protection for OEM-installed electronics. Great efforts are made to assure all of the subsystems in a vehicle work correctly and are not affected by any electrical noise generated within the vehicle. And to some extent, the vehicle is also assured to work properly in the presence of external interference signals.

However, the manufacturer cannot test the vehicle under all conditions for after-market subsystems. There is evidence of after-market compatibility problems with two-way mobile radios, cellular phones, alternative fuel conversion systems and personal computers. So if one of these electronic subsystems is added to the vehicle, it may produce or receive interference with the existing vehicle electronic systems.

The Texas Department of Transportation (TxDOT) is experiencing compatibility problems between its vehicles and after-market two-way communication systems. TxDOT depends heavily on the reliable use of two-way FM (Frequency Modulation) radios to conduct daily business. Reliable radio communication is critical to the successful fulfillment of TxDOT operations. But the interference with TxDOT two-way communication systems reduces the range which users can expect from tens of miles to, in some cases, less than one mile. Thus, there exists a requirement to develop new guidelines for control of RF emissions from the vehicles.

The current TxDOT project conducted at Texas Tech University is divided into two test activities: whole-vehicle tests and laboratory bench-top simulation tests. The overall objective is to develop and validate effective RFI test procedures that will allow vehicle manufacturers to identify RFI problems related to the use of after-market two-way radios in their vehicles. The project results include specific RFI limits for the vehicles. These results will be forwarded to vehicle manufacturers for consideration in future vehicle design and to SAE.

This thesis covers the laboratory bench-top test part of the project. It is organized into five chapters: chapter 2 is entitled, 'Laboratory Test System for FM Radios' and covers the description of the bench-top test setup for measurement of FM radio input noise voltage and SINAD (Signal, Noise, and Distortion) value for different noise sources. Chapter 3 is entitled, 'Results for Narrow-Band Sources' and covers the examination of all types of narrow-band vehicle emissions. All the bench test results are provided. Chapter 4 is entitled, 'Results for Broad-Band Sources' and covers the radio tests on two types of broad-band vehicle noise sources, and also the test data are listed in this chapter. Chapter 5 is entitled, 'Data Interpretation and Conclusions' and includes the summary of radio bench test results, the determination of the relationship between the limits imposed by SAE J551/4 and TxDOT Tex-899-B, and finally, the conclusion on how SAE J551/4 might be substituted for TxDOT Tex-889-B. Also covered in this chapter are back-door penetration observations on the TxDOT FM radios and a new working definition for narrow-band versus broad-band noise for use with SAE J551/4.

CHAPTER II

LABORATORY TEST SYSTEM FOR FM RADIOS

RF Noise Sources in Vehicles

TxDOT basic service trucks are similar to consumer market vehicles with the exception of state-required propane conversion systems. Propane conversion systems allow the vehicles to run on gaseous propane as well as on gasoline.

In general, modern motor vehicles have three major RFI noise sources that can significantly effect the performance of the two-way FM radios. The first noise source is the spark ignition system for the internal combustion engine, a well-known noise source in vehicles. The second one is DC (Direct Current) motor noise. For example, both fuel pump and HVAC (Heater Ventilation Air Conditioner) fan provide significant amounts of noise. The third noise source is associated with the microprocessor-based systems, which are used more and more in modern motor vehicles. They communicate with a variety of sensors and actuators throughout the vehicle. These microprocessor systems are primarily digital systems operating at relatively high frequencies. The switching of the digital circuits generates even higher frequencies over a broad frequency range, including the TxDOT two-way FM radio band. RF emissions from the microprocessor-based systems can form different types of spectra when the microprocessor runs on different instructions or programs.

Vehicle EMC Test Methods of Interest

There are two vehicle EMC test methods which were used and investigated in this TxDOT project. They are the SAE Standard J551/4 and the TxDOT Test Method Tex-899-B.

The current SAE J551/4 version was updated and issued in 1994. This standard contains test limits and procedures for the measurement of radio disturbances in the frequency range of 150 kHz to 1000 MHz. There are three types of limits in this standard: narrow-band peak, broad-band peak and broad-band quasi-peak. The last one, being mainly used in Europe, was omitted in this thesis.

The TxDOT Test Method Tex-899-B, which involves a SINAD test, provides test limits and methods to assure the compatibility of TxDOT fleet vehicles and VHF (Very High Frequency) radio equipment operating in the frequency ranges of 30 to 50 MHz and 150 to 174 MHz. The SINAD, normally expressed in dB, is defined as a ratio as follows:

$$\mathrm{SINAD} = 20\log_{10}\left(\frac{\text{rms value of signal, noise, and distortion}}{\text{rms value of noise and distortion}}\right).$$

There exists one important difference between these two test methods. The SAE J551/4 test measures the RF emissions received by an antenna on the vehicle. On the contrary, the TxDOT Tex-899-B test measures the effect on a radio of emissions received by an antenna on the vehicle.

TxDOT Two-Way FM Communication Radios

TxDOT has several different models of two-way FM radios in use in their vehicle fleet. Every model has its own features, but all TxDOT two-way FM radios have the same basic characteristics: First, they all operate in the frequency range of 47-48 MHz, which is the TxDOT low-band VHF frequency range. Second, their receiver sensitivity to a standard FM signal is better than –115 dBm for a 12 dB SINAD. Third, the receiver bandwidth is between 13 kHz and 16 kHz. Fourth, the audio bandwidth of these radios extends from 300 to 3000 Hz. Fifth, the receiver includes a noise blanker circuit.

Bench-Top Test System

The objective of this bench-top simulation test was to determine the correlation between the limits imposed by the two test methods, SAE J551/4 and TxDOT Tex-899-B, including the dependence on individual radio and different type of noise. Figure 1 shows the general bench-top test setup. It was used to simulate the vehicle RF emissions, and to measure the FM radio input noise voltage for the SAE J551/4 test and the SINAD value for the TxDOT Tex-899-B test.

In order to simulate the real-world RF emissions from the vehicles, several different types of simulation noise sources are used in this laboratory test system. Two fuel pumps and one HVAC fan are used for the broad-band motor noise sources. The ignition noise is also simulated in the tests. An IC (Integrated Circuit) board was used for measuring the RF emissions from a microcontroller. For other narrow-band noise from a microcontroller-based system, a CW (Continuous Wave) signal and an HMCW (Heavily

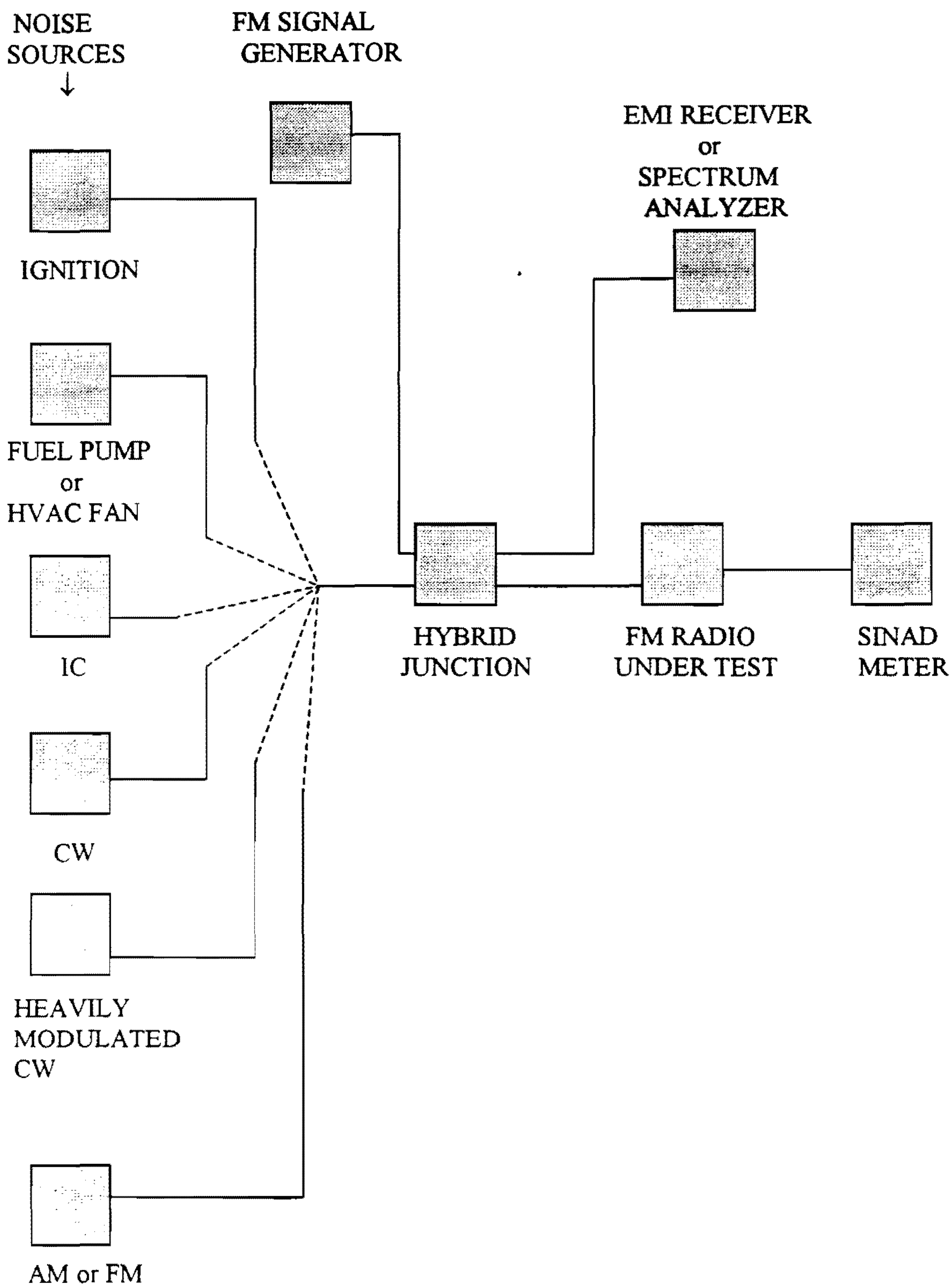


Figure 1. Block Diagram of Bench Test Setup

Modulated Continuous Wave) signal are generated for simulation purposes. We use the terminology HMCW to mean 100% amplitude modulation (AM) with rectangular pulses. In addition, for the sake of completeness, sinusoidal AM and FM signals are also used as noise sources for this bench-top test.

A 1.0 μV FM signal is generated to simulate the communication signal voltage delivered by an antenna on the vehicle. It is combined with one of the noise sources by a hybrid junction. This four-port hybrid junction is shown in Figure 2. There is no coupling between ports 1 and 3, nor between ports 2 and 4. Signals entering ports 2 and 4 are coupled as indicated by the arrows in the figure. The combined signals come out from ports 1 and 3. There is a 3.6 dB attenuation from port 2 or 4 to port 1, and a 3.2 dB attenuation from port 2 or 4 to port 3.

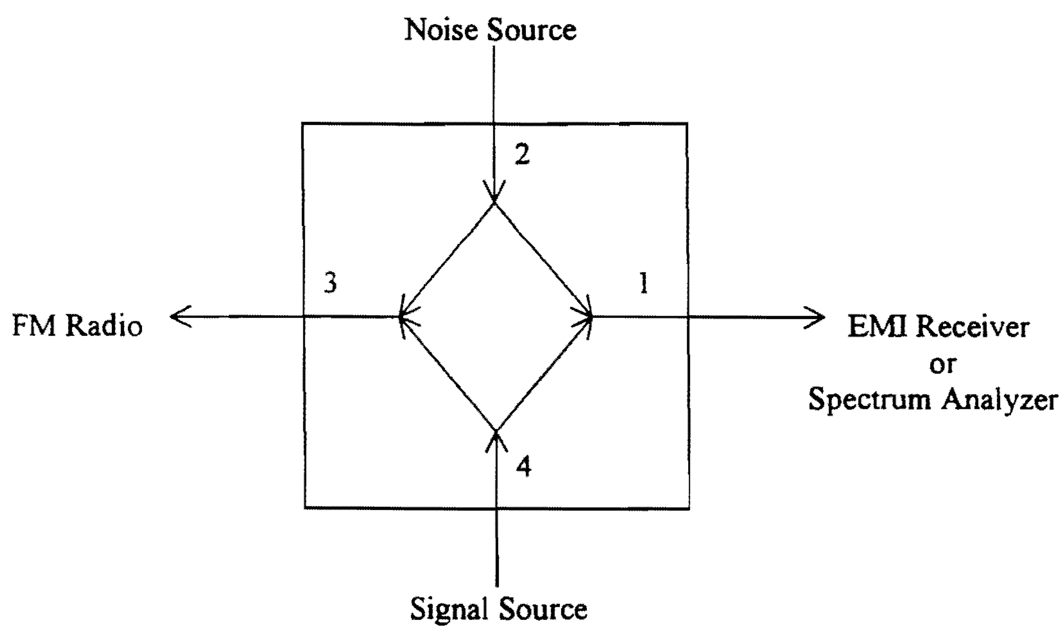


Figure 2. A 4-port Hybrid Junction

The noise source and signal source are connected to port 2 and port 4 respectively. Port 1 is connected to an EMI (Electromagnetic Interference) receiver to measure the FM radio input noise voltage for SAE J551/4 test, or to a spectrum analyzer for spectrum checks. Port 3 is connected to a TxDOT two-way FM radio. Ten radios of five different models are used in this TxDOT project. They are three GE RANGR's, two Ericsson ORION's, two Motorola MaraTrac's, two Motorola SYNTOR X's, and one Kenwood TK-630H. Three frequencies, 47.00 MHz, 47.02 MHz, and 47.18 MHz, were chosen for the tests. The audio output from the radio is put into a SINAD meter to get the SINAD reading for the TxDOT Tex-899-B test.

We used two different amplitude units, dBμV and dBm, in this TxDOT project. The amplitude, expressed in dB relative to 1 μV, is referred to as dBμV, that is,

$$\mathrm{dB\mu V} \equiv 20\log_{10}\left(\frac{\mathrm{volts}}{1\,\mu\mathrm{V}}\right).$$

And the amplitude unit, dBm, is expressed in dB above 1 mW, that is,

$$\begin{aligned}\mathrm{dBm} &\equiv \mathrm{dBmW} \\ &\equiv 10\log_{10}\left(\frac{\mathrm{watts}}{1\,\mathrm{mW}}\right).\end{aligned}$$

For a 50 Ω system, the conversion between μV, dBμV and dBm is as follows:

$$\begin{aligned}1\ \mu\mathrm{V} &= 0\ \mathrm{dB\mu V} \\ &= -107\ \mathrm{dBm}.\end{aligned}$$

Principle Test Equipment

According to their usage, the various items of test equipment are divided into different categories: RF sources, RF receiving equipment, SINAD meter, oscilloscopes, network analyzer, and passive devices. Table 1 gives the brand and model of the equipment, along with its usage.

Table 1. Brand and Model of Principle Test Equipment

Category	Brand and Model	Usage
RF Sources	Fluke 6060B Signal Generator	FM Signal
	R&S CMS54 Radiocommunication Service Monitor	CW Noise, AM Noise, FM Noise, and HMCW Noise
	E-H Research Labs 139B Pulse Generator	Ignition Noise and HMCW Noise
RF Receiving Equipment	HP 8592L Spectrum Analyzer	Spectrum Checks
	R&S ESS EMI Receiver	All Noise Measurements
SINAD Meter	HP 8903A Audio Analyzer, readings/second = 2	12 dB Reading
Oscilloscopes	HP 54616B, 2 GSa/s, 500 MHz	RF Waveforms
	Fluke PM3370A, 1 MSa/s, 60 MHz	AF (Audio Frequency) Waveforms
Network Analyzer	HP 8753C	S-parameters of Hybrid Junction
Passive Devices	Synergy Microwave DJK-702 0°-180° Hybrid Junction	Couple Together Multiple Devices
	Weinschel 3200T-1 Programmable Attenuator	Ignition, Fuel Pump, and HVAC Fan Noise Sources

General Test Procedure

The general test procedure for this bench-top test is as follows:

First, choose one frequency for the radio under test.

Second, use the signal generator to get an FM signal with the same frequency as the radio, and with 1.0 kHz modulation frequency and 3.3 kHz frequency deviation. And adjust the radio volume control for 1.0 W audio output power.

Third, with the FM signal only, do a sensitivity test on the radio.

Fourth, switch on a noise source in addition to a 1.0 μV FM signal, and adjust the noise voltage level to get a 12 dB reading on the SINAD meter. This 12 dB SINAD value is the test limit for the radios to pass the TxDOT Tex-899-B.

Fifth, turn off the signal generator, and use the EMI receiver to measure the noise voltage with a 10 kHz or 120 kHz bandwidth, depending on whether the noise is narrow-band or broad-band. This step provides the SAE J551/4 test value corresponding to the above Tex-899-B limit.

The Automatic Testing Program

The test equipment is also connected to a computer via GPIB (General Purpose Interface Bus) cables. A programmable attenuator is attached to the computer as well. The computer is used for automatic control of the test equipment and data acquisition in some tests. Automatic testing programs were written using LabVIEW, which is a graphical programming language. The advantages of the automatic measurement are that more data and a greater variety of data can be obtained and fewer operator errors can be expected.

In an automatic test, the computer adjusts the amount of attenuation provided by the programmable attenuator to control the noise level entering the radio under test. Once the 12 dB SINAD value is achieved, the computer will record the noise voltage level and save the data to a text file. Figure 3 is a screen shot of a program when it ran a test using the fuel pump as a noise source.

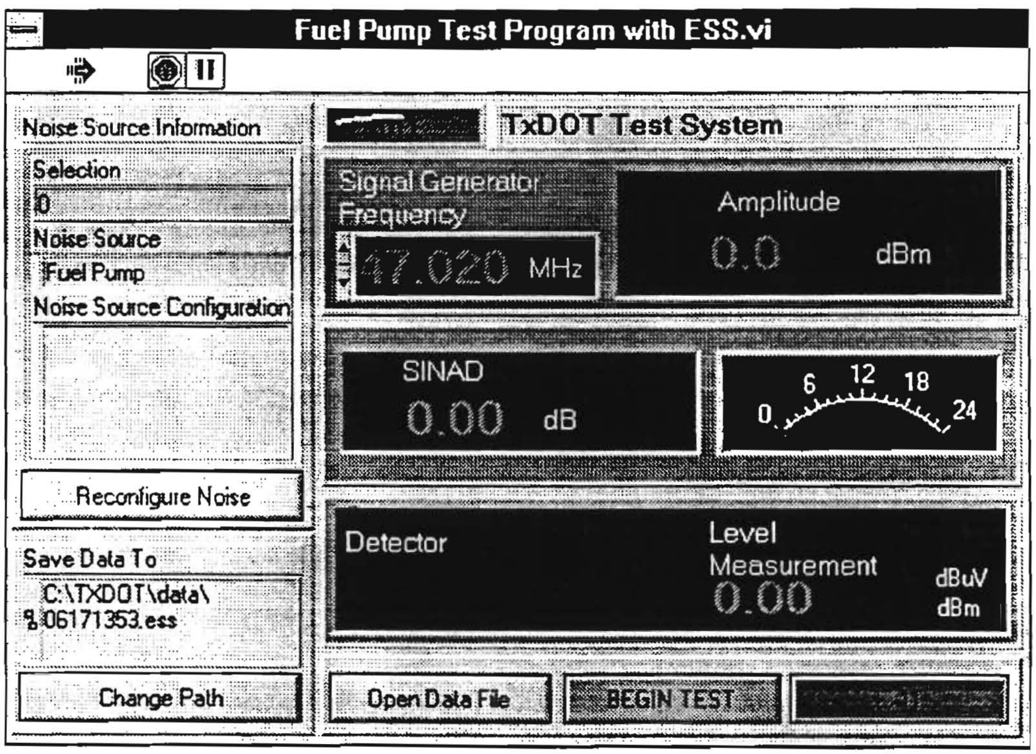


Figure 3. A Run-Time Screen Shot of the Automatic Testing Program

CHAPTER III

RESULTS FOR NARROW-BAND SOURCES

In this chapter, the results from all the narrow-band noise sources are presented. According to their modulation characteristics, these simulated narrow-band vehicle emissions are divided into four categories: CW noise, AM noise (rectangular pulse and sinusoidal), FM noise and AM/FM noise. Since these sources are narrow-band, a 10 kHz measurement bandwidth was used on the R&S ESS EMI receiver for measuring the RF noise voltage according to SAE Standard J551/4. The spectra and RF waveforms shown in this chapter are printouts from the HP 8592L spectrum analyzer and the HP 54616B oscilloscope.

Radio Noise Blankers

Besides the frequency-domain filters, every TxDOT two-way FM radio has a noise blanker circuit, which can be turned manually on or off. The noise blanker is devised to reduce noise on a time-domain basis because in some situations frequency-domain filtering is not adequate due to the magnitude of the disturbance.[3] The noise blanker is triggered by the interfering signals or noise and renders the system inoperative for the duration of the interference.

Although the exact working mechanism of the noise blanker is unknown for the TxDOT radios, the observation on the bench shows that it is not effective against the narrow-band noise so that either noise blanker on or off can be used in the narrow-band noise tests. Therefore, for the sake of consistency, the radio noise blanker was switched on in the tests with the narrow-band sources.

FM Signal

The FM signal is obtained by using the Fluke 6060B signal generator. It was set to the same frequency as the radio under test, with 1.0 kHz modulation frequency and 3.3 kHz frequency deviation as specified in TxDOT Tex-889-B. This FM signal was used in all the bench-top simulation tests, and its voltage level was set to 1.0 μV because this value is the maximum allowed in the Tex-899-B test. Figure 4 shows the spectrum of this FM signal at 47.02 MHz with a 200 μV voltage level.

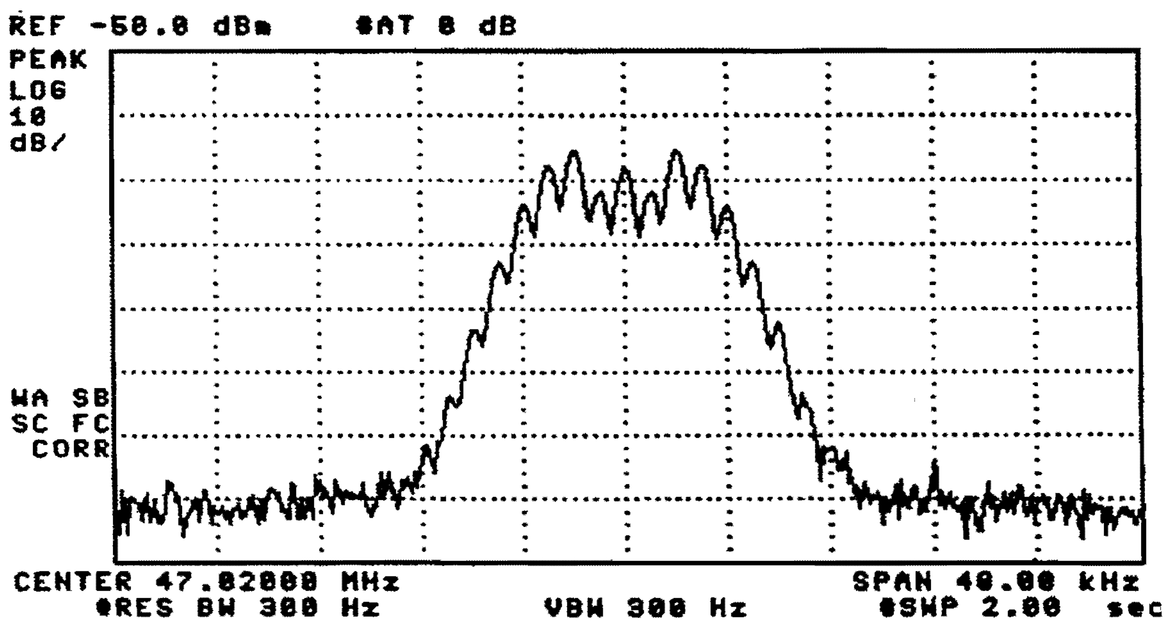


Figure 4. The Spectrum of a 47.02 MHz FM Signal with 1.0 kHz Modulation Frequency and 3.3 kHz Frequency Deviation

CW Noise Simulation and Test

CW noise comes from microcontroller-based systems in vehicles. It is a harmonic of the microcontroller clock. On the bench, the R&S CMS54 radiocommunication service monitor is used to simulate this type of noise. It is set to the same frequency as the radio under test. And there is no modulation on the signal. The spectrum of a 47.02 MHz CW signal is shown in Figure 5.

For a CW signal, both theory and measurement using the R&S ESS EMI receiver show that its peak (PK) value is equal to its average (AV) value, that is,

PK = AV.

Two frequencies, 47.02 MHz and 47.18 MHz, and all the ten radios with noise blankers turned on were used in the test. Table 2 lists the bench test results for the 12 dB SINAD with a 1.0 μV FM signal. From the test data, the average value and the standard deviation can be calculated using the following statistical methods:

$$\text{Average} = \overline{X} = \frac{\sum X}{n},$$

and

$$\text{Standard Deviation} = S = \sqrt{\frac{\sum (X - \overline{X})^2}{n - 1}},$$

where X is the test data value and n is the number of test data. For the CW noise, these values are

Average = -2.5 dBμV,

and

Standard Deviation = 0.8 dB.

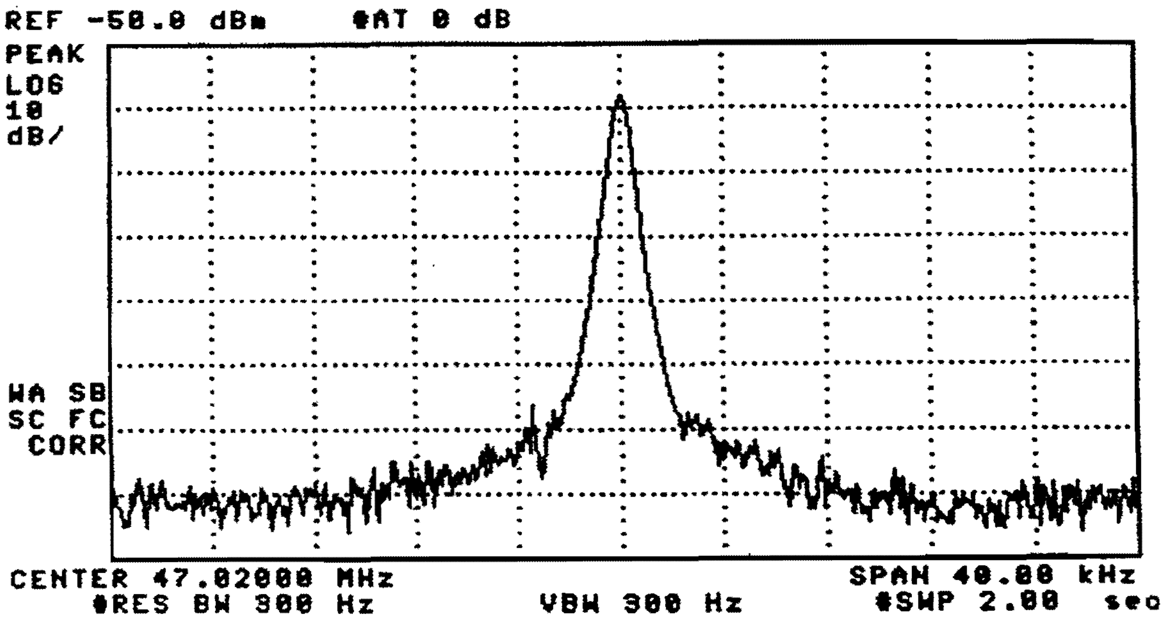


Figure 5. The Spectrum of 47.02 MHz CW Noise

Table 2. Bench Test Data for CW Noise

Radio Brand & Model	Peak Level of CW Noise (dBμV) at Two Frequencies for 12 dB SINAD with 1.0 μV FM Signal	
	47.02 MHz	47.18 MHz
GE RANGR (No. 1)	-3	-3
GE RANGR (No. 2)	-3	-3
GE RANGR (No. 3)	-3	-3
Ericsson ORION (No. 1)	-1	-1
Ericsson ORION (No. 2)	-3	-3
Motorola MaraTrac (No. 1)	-2	-2
Motorola MaraTrac (No. 2)	-2	-2
Motorola SYNTOR X (No. 1)	-2	-2
Motorola SYNTOR X (No. 2)	-2	-2
Kenwood TK-630H	-4	-4

AM Noise Simulation and Test

AM signals with two different types of modulation, square wave and sine wave, were used to simulate the AM noise sources that might be present in a vehicle. For all the tests in this section, the R&S CMS54 radiocommunication service monitor produced the AM signals and used the same frequency as the FM radio under test.

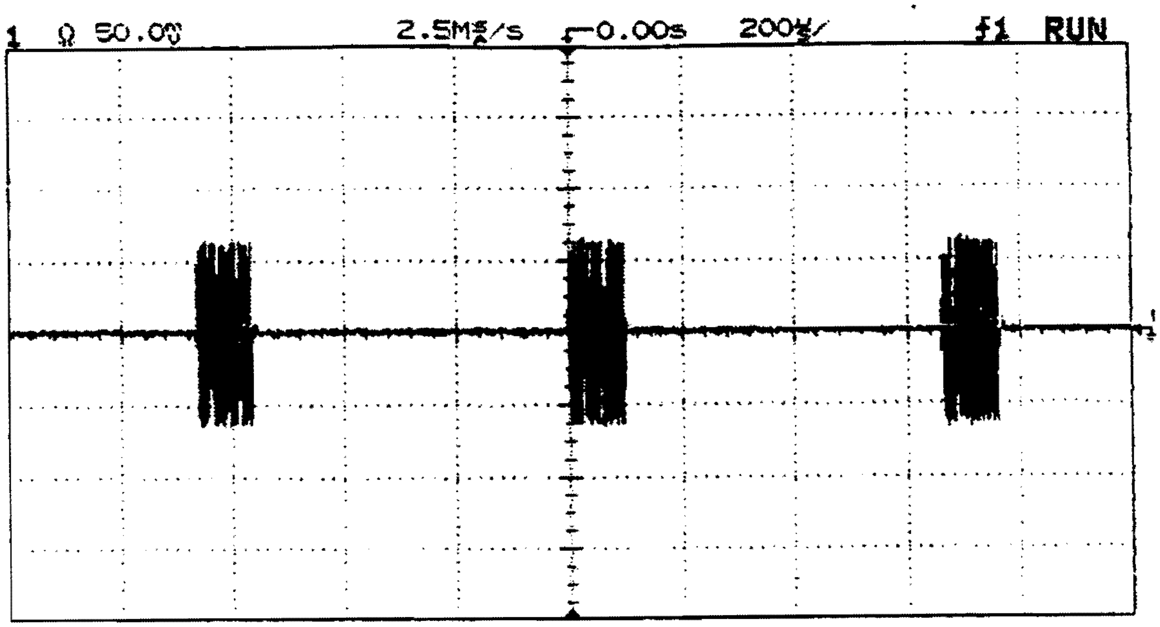
HMCW noise can originate from microcontroller-based systems. On the bench, it is simulated by 100% externally amplitude modulating the R&S CMS54 radiocommunication service monitor with a 15% or 50 % duty cycle square wave. The repetition rate in this test is 1.5 kHz. The 1.5 kHz rectangular pulse train is generated using the E-H Research Labs 139B Pulse Generator. This method was suggested by Don Hibbard and Daren Shanholtzer at the General Motors EMC Lab. The spectrum and RF waveform of a 47.02 MHz HMCW signal with a 15% duty cycle are shown in Figure 6. Figure 7 gives the same for a 50% duty cycle.

For an HMCW signal with a 15% duty cycle, its average level is theoretically 16 dB less than its peak level, that is,

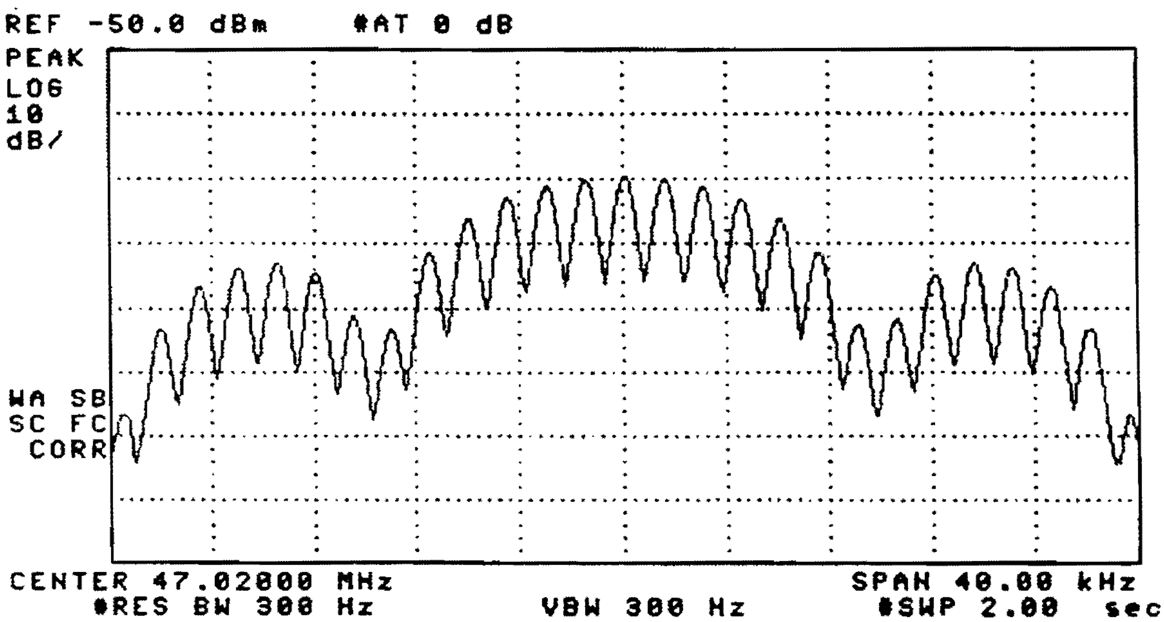
$$PK = AV + 16 \text{ dB}.$$

But this is different from the measured result using the R&S ESS EMI receiver, which showed a 13.8 dB difference between these two levels. The reason for this is that the 10 kHz measurement bandwidth was used on the EMI receiver and this narrow bandwidth lowered the measured peak value of the signal.

For the HMCW signal with a 50% duty cycle, the measurement gave the average level as 6.2 dB less than the peak level, that is,

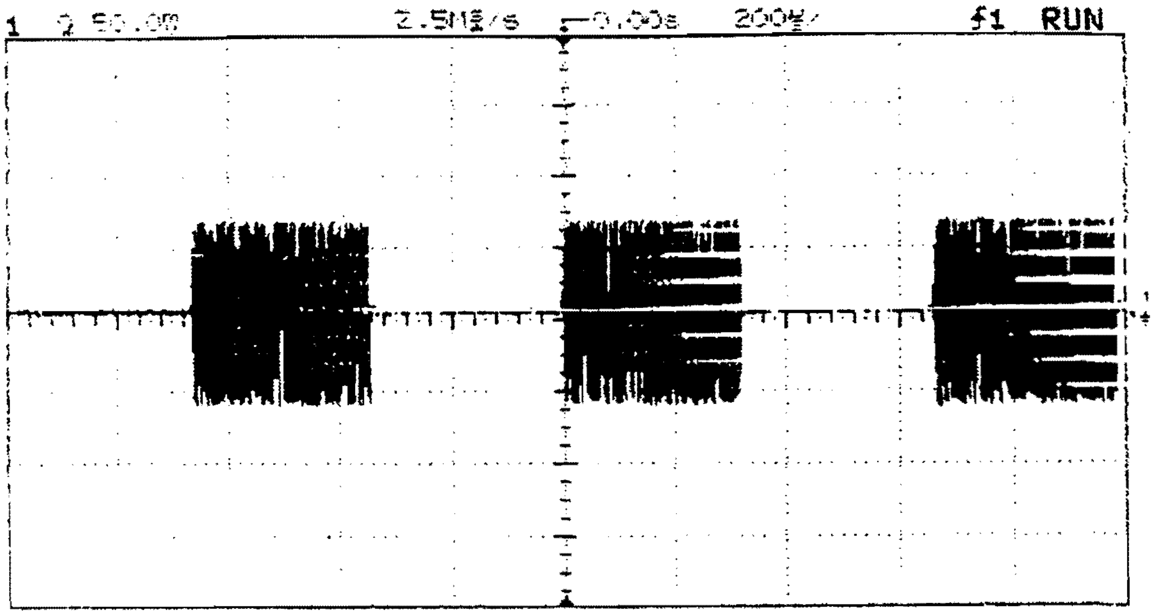


(a)

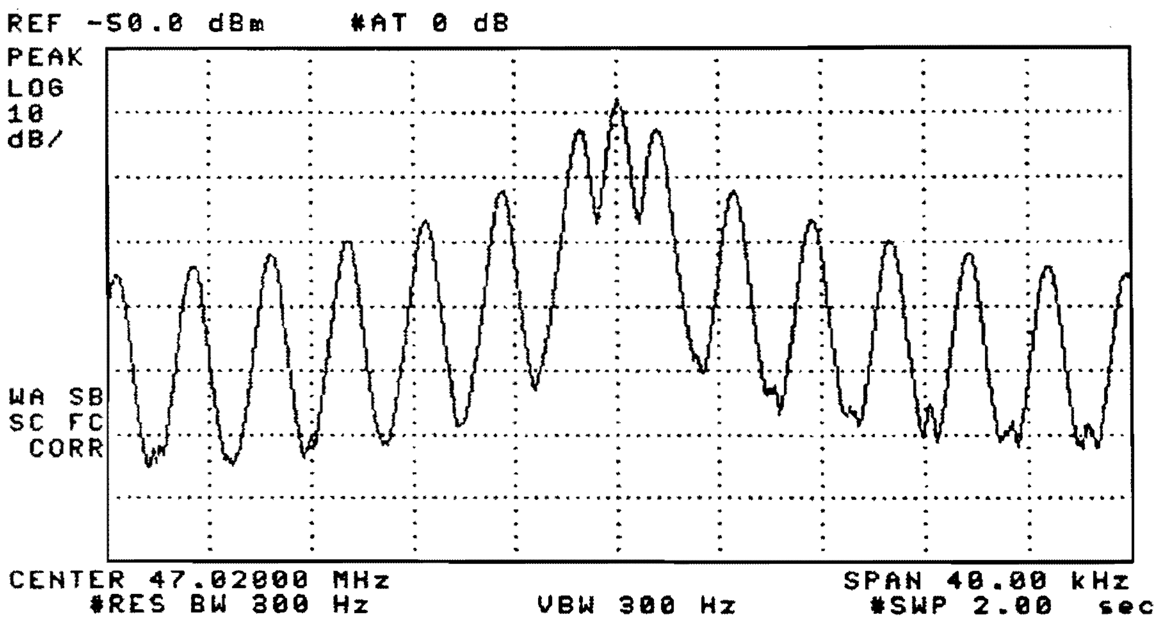


(b)

Figure 6. (a) RF Waveform and (b) Spectrum of a 47.02 MHz HMCW Noise with a 15% Duty Cycle



(a)



(b)

Figure 7. (a) RF Waveform and (b) Spectrum of a 47.02 MHz HMCW Noise with a 50% Duty Cycle

$$PK = AV + 6.2 \text{ dB},$$

which is slightly different from the theoretical value, 6 dB.

The test results corresponding to the HMCW noise with two different duty cycles are listed in Table 3 and Table 4, respectively. Two frequencies, 47.02 MHz and 47.18 MHz, were used in these tests, and five radios, three GE RANGR's and two Motorola MaraTrac's, were selected because these two models are the most used in the TxDOT vehicle fleet. From Table 3, the average and standard deviation values were calculated as

$$\text{Average} = -1.1 \text{ dB}\mu\text{V},$$

and

$$\text{Standard Deviation} = 0.2 \text{ dB}.$$

And from Table 4, the same calculation was also done to get the results:

$$\text{Average} = -1.8 \text{ dB}\mu\text{V},$$

and

$$\text{Standard Deviation} = 0.2 \text{ dB}.$$

Two other AM signals employing sinusoidal modulation were also used in the simulation tests. Whether such signals are produced in motor vehicles is unknown, but they are so easy to produce in the laboratory that they are included in this thesis. One of them was generated using the R&S CMS54 radiocommunication service monitor with 90% modulation and 400 Hz modulation frequency. The spectrum of this signal at 47.02 MHz is shown in Figure 8. Figure 9 gives the spectral display of the other AM signal at 47.02 MHz. It was obtained with 100% modulation and 1.5 kHz modulation frequency on the R&S CMS54.

Table 3. Bench Test Data for HMCW Noise
with a 15% Duty Cycle

Radio Brand & Model	Peak Level of HMCW Noise (dBμV) at Two Frequencies for 12 dB SINAD with 1.0 μV FM Signal	
	47.02 MHz	47.18 MHz
GE RANGR (No. 1)	-1.2	-1.2
GE RANGR (No. 2)	-1.1	-1.1
GE RANGR (No. 3)	-1.4	-1.4
Motorola MaraTrac (No. 1)	-1.1	-1.1
Motorola MaraTrac (No. 2)	-0.9	-0.9

Table 4. Bench Test Data for HMCW Noise
with a 50% Duty Cycle

Radio Brand & Model	Peak Level of HMCW Noise (dBμV) at Two Frequencies for 12 dB SINAD with 1.0 μV FM Signal	
	47.02 MHz	47.18 MHz
GE RANGR (No. 1)	-2.0	-2.0
GE RANGR (No. 2)	-1.9	-1.9
GE RANGR (No. 3)	-1.8	-1.8
Motorola MaraTrac (No. 1)	-1.6	-1.6
Motorola MaraTrac (No. 2)	-2.0	-2.0

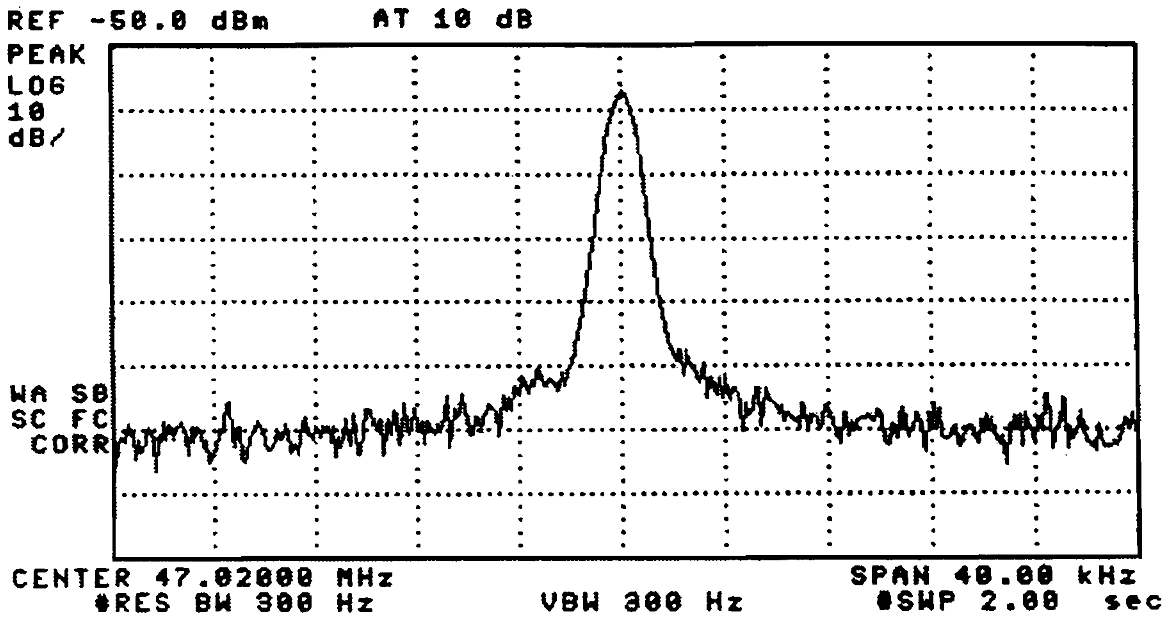


Figure 8. The Spectrum of 47.02 MHz AM Noise with 90% Modulation and 400 Hz Modulation Frequency

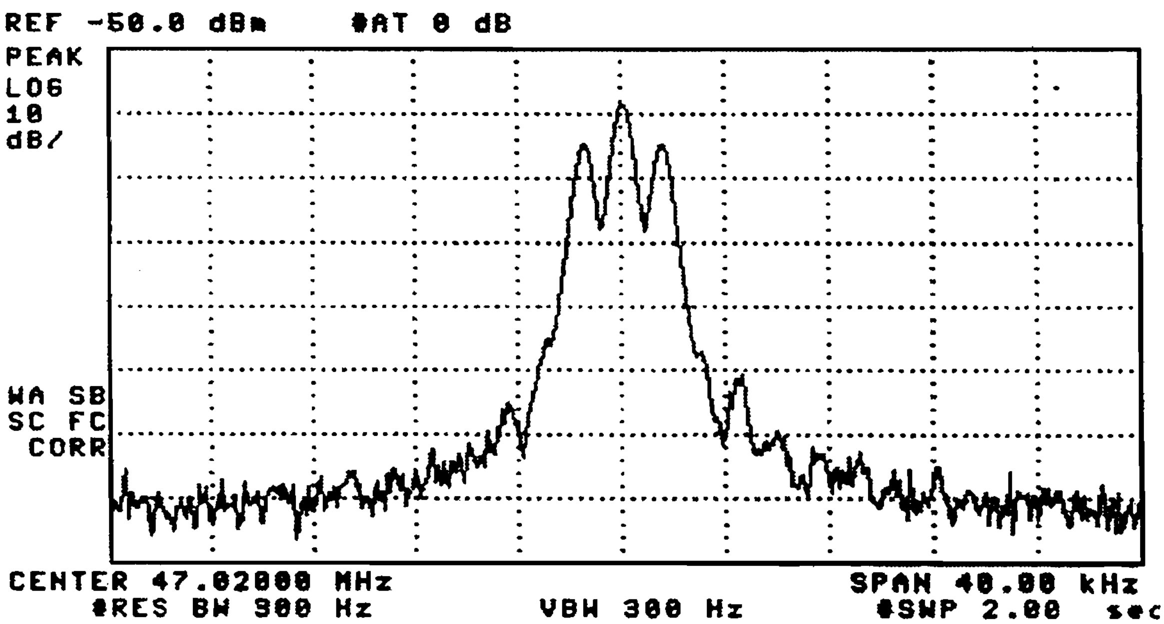


Figure 9. The Spectrum of 47.02 MHz AM Noise with 100% Modulation and 1.5 kHz Modulation Frequency

For these two AM signals, the measurement using R&S ESS EMI receiver showed that the average level is 6 dB less than the peak level, that is,

PK = AV + 6 dB,

which agrees very well with the theoretical result.

Two frequencies, 47.02 MHz and 47.18 MHz, were used in the tests. For the 400 Hz AM noise, all ten radios were used, but only five radios, as above, were used for the 1.5 kHz AM noise, for the same reason. Table 5 and Table 6 give the test results for the 12 dB SINAD with a 1.0 μV FM signal. From the bench test data, for the 400 Hz AM noise, the statistics give

Average = -0.7 dBμV,

and

Standard Deviation = 0.3 dB.

And for the 1.5 kHz AM noise, these values are

Average = -1.9 dBμV,

and

Standard Deviation = 0.2 dB.

FM Noise Simulation and Test

In this bench-top test, two FM signals were used to simulate the FM noise that might be present in a vehicle. The production of such noise by microcontrollers was suggested by Gus Morgan at the Texas Department of Transportation, and such noise also appears in PWM (Pulse Width Modulation) power supplies.[4] The FM signals were

Table 5. Bench Test Data for 400 Hz AM Noise

Radio Brand & Model	Peak Level of 400 Hz AM Noise (dBμV) at Two Frequencies for 12 SINAD with 1.0 μV FM Signal	
	47.02 MHz	47.18 MHz
GE RANGR (No. 1)	-1	-1
GE RANGR (No. 2)	-1	-1
GE RANGR (No. 3)	-1	-1
Ericsson ORION (No. 1)	0	0
Ericsson ORION (No. 2)	-1	-1
Motorola MaraTrac (No. 1)	0	0
Motorola MaraTrac (No. 2)	-1	-1
Motorola SYNTOR X (No. 1)	0	0
Motorola SYNTOR X (No. 2)	0	0
Kenwood TK-630H	-2	-2

Table 6. Bench Test Data for 1.5 kHz AM Noise

Radio Brand & Model	Peak Level of 1.5 kHz AM Noise (dBμV) at Two Frequencies for 12 dB SINAD with 1.0 μV FM Signal	
	47.02 MHz	47.18 MHz
GE RANGR (No. 1)	-1.6	-1.6
GE RANGR (No. 2)	-1.5	-1.5
GE RANGR (No. 3)	-1.5	-1.5
Motorola MaraTrac (No. 1)	-0.8	-0.8
Motorola MaraTrac (No. 2)	-1.2	-1.2

generated using the R&S CMS54 radiocommunication service monitor with 400 Hz and 1.5 kHz modulation frequencies and 3.0 kHz frequency deviation. Their spectra at 47.02 MHz are given in Figure 10 and Figure 11, respectively.

For such FM signals, the average level is 1.2 dB less than the peak level, that is,

PK = AV + 1.2 dB,

which was measured using the R&S ESS EMI receiver. Theoretically, the peak value of an FM signal is equal to its average value.

Two frequencies, 47.02 MHz and 47.18 MHz, and nine of the ten radios were used in the tests for the 400 Hz FM noise because one of the Motorola SYNTOR X's had become inoperative. The same five radios as in the HMCW noise tests were chosen for the 1.5 kHz FM noise test. The bench test results are included in Table 7 and Table 8 for the 12 dB SINAD with a 1.0 μV FM signal. By comparing these two tables, it is obvious that both FM waveforms have almost the same effects on the radios. From Table 7, the average value for the peak level and the standard deviation are:

Average = -2.6 dBμV,

and

Standard Deviation = 0.8 dB.

And from Table 8, these values are:

Average = -2.6 dBμV,

and

Standard Deviation = 0.4 dB.

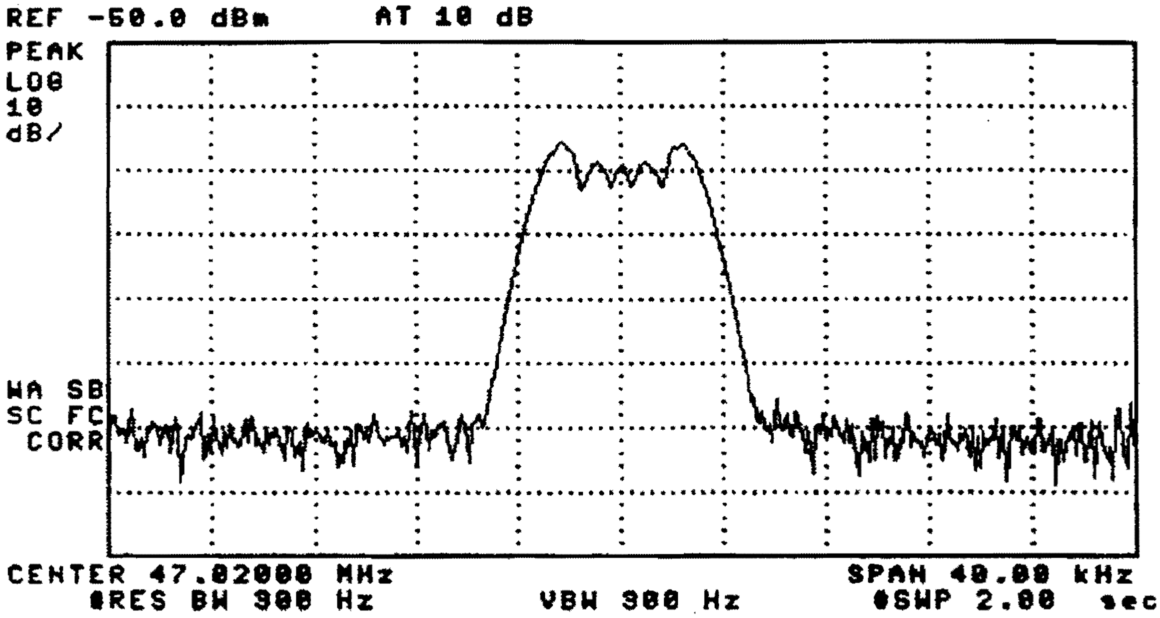


Figure 10. The Spectrum of 47.02 MHz FM Noise with 400 Hz Modulation Frequency and 3.0 kHz Frequency Deviation

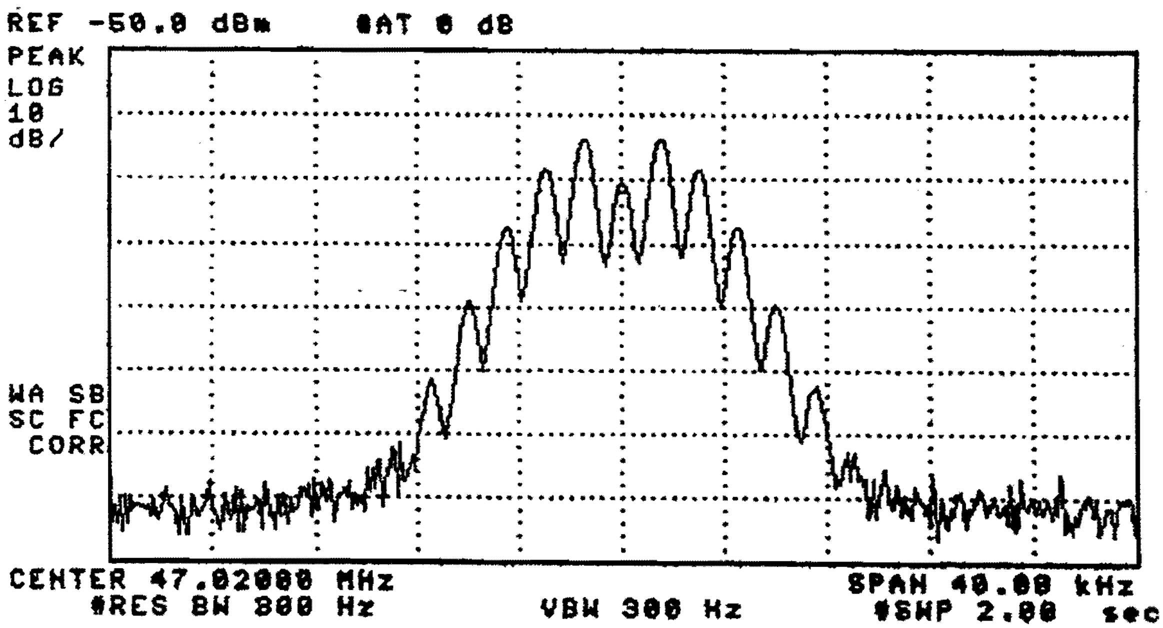


Figure 11. The Spectrum of 47.02 MHz FM Noise with 1.5 kHz Modulation Frequency and 3.0 kHz Frequency Deviation

Table 7. Bench Test Data for 400 Hz FM Noise

Radio Brand & Model	Peak Level of 400 Hz FM Noise (dBμV) at Two Frequencies for 12 dB SINAD with 1.0 μV FM Signal	
	47.02 MHz	47.18 MHz
GE RANGR (No. 1)	-3	-3
GE RANGR (No. 2)	-3	-3
GE RANGR (No. 3)	-3	-3
Ericsson ORION (No. 1)	-1	-1
Ericsson ORION (No. 2)	-2	-2
Motorola MaraTrac (No. 1)	-2	-2
Motorola MaraTrac (No. 2)	-3	-3
Motorola SYNTOR X (No. 2)	-2	-2
Kenwood TK-630H	-4	-4

Table 8. Bench Test Data for 1.5 kHz FM Noise
(with 3.0 kHz Frequency Deviation)

Radio Brand & Model	Peak Level of 1.5 kHz FM Noise (dBμV) at Two Frequencies for 12 dB SINAD with 1.0 μV FM Signal	
	47.02 MHz	47.18 MHz
GE RANGR (No. 1)	-3.0	-3.0
GE RANGR (No. 2)	-2.7	-2.7
GE RANGR (No. 3)	-2.6	-2.6
Motorola MaraTrac (No. 1)	-1.8	-1.8
Motorola MaraTrac (No. 2)	-2.8	-2.8

However, it is obvious that the above FM waveforms do not fill out the bandwidth of the TxDOT FM radios, which is a little less than 16 kHz. Thus we decided to increase the frequency deviation of the FM noise simulated with 1.5 kHz modulation frequency so that its spectrum can spread out over the radio's bandwidth. A test done on Motorola MaraTrac No. 2 at 47.02 MHz found that for the 12 dB SINAD with a 1.0 μV FM signal, the worst peak noise level was –4.5 dBμV when the frequency deviation reached 6.0 kHz and larger. Therefore, the FM waveform with 1.5 kHz modulation frequency and 6.0 kHz frequency deviation was chosen for further measurements, which were carried out on three GE RANGR's and two Motorola MaraTrac's at two radio frequencies, 47.02 MHz and 47.18 MHz. The test results are included in Table 9. From the table, the average value and the standard deviation for this worst case are:

Average = -4.1 dBμV,

and

Standard Deviation = 0.2 dB.

Table 9. Bench Test Data for 1.5 kHz FM Noise
(with 6.0 kHz Frequency Deviation)

Radio Brand & Model	Peak Level of 1.5 kHz FM Noise (dBμV) at Two Frequencies for 12 dB SINAD with 1.0 μV FM Signal	
	47.02 MHz	47.18 MHz
GE RANGR (No. 1)	-4.2	-4.2
GE RANGR (No. 2)	-4.0	-4.0
GE RANGR (No. 3)	-4.0	-4.0
Motorola MaraTrac (No. 1)	-3.8	-3.8
Motorola MaraTrac (No. 2)	-4.3	-4.3

The Measurement of IC Emissions

The RF emission from a microcontroller was studied briefly and used as a noise source in the laboratory test system. A test board was built using the 68HC11 'Quick Setup' board with the Motorola MC68HC11E1 microcontroller installed on it.

A program was written using Motorola 68HC11 assembly language. The program has seven different modes provided by subroutines which send different pulses to the pins on the microcontroller at different frequencies. And it flows in a continuous loop to assure that measurements are repeatable.

The board and its power supply, which consists of four D-size 1.5 V alkaline batteries in series with a 5 V voltage regulator, are contained in a small aluminum box. Inside the box, a short wire is placed as a small antenna to receive the RF emissions from the microcontroller. One end of this wire is a 50 Ω feed-through termination, which is connected to a coaxial cable outside.

In order to look at the IC noise spectrum, the output from the box was directly connected to the HP 8592L spectrum analyzer. All the modes were checked and only two characteristic spectra were found for the RF emissions at TxDOT radio frequencies. These two spectra are identified as a CW spectrum and an AM/FM spectrum. The AM/FM spectrum is shown in Figure 12. The reason for using the designation AM/FM spectrum is that the IC noise at this center frequency generated similar sounds while we used the demodulation function keys, 'F3' and 'A3', on the R&S ESS EMI receiver. The result from the spectrum analyzer shows that the IC emission from modes 5, 6, and 7 has the CW spectrum, and that of modes 1, 2, 3, and 4 has the AM/FM spectrum. For the

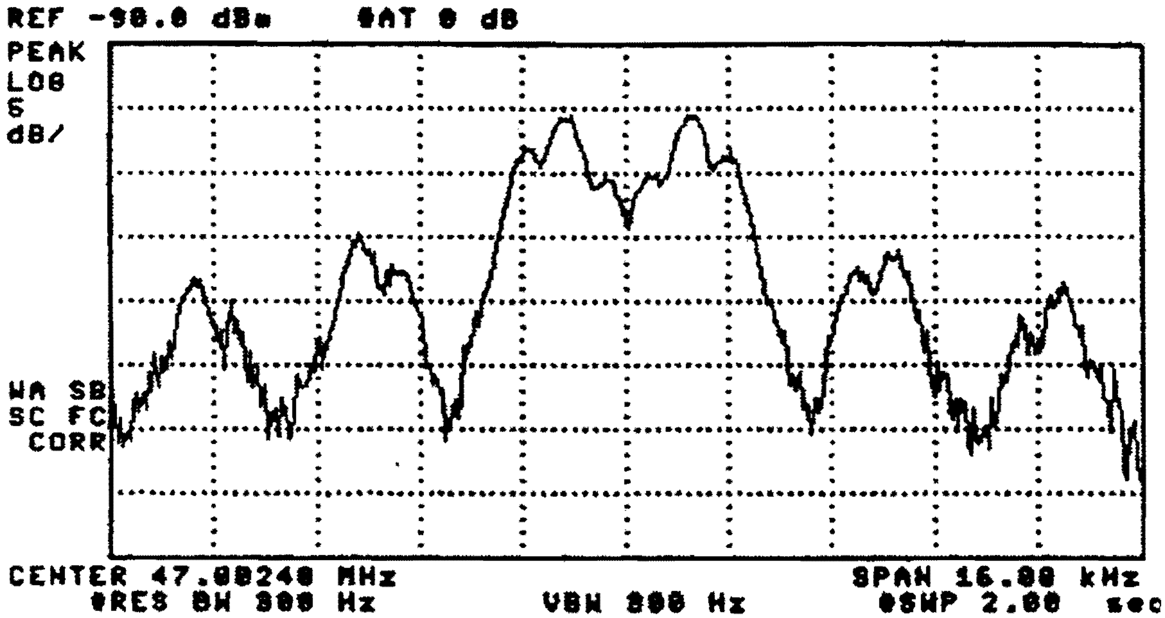


Figure 12. The AM/FM Spectrum of IC Emissions from Motorola MC68HC11E1 Microcontroller

noise from this AM/FM spectrum, the ratio of peak to average is 2 dB, which was measured using the EMI receiver.

On the bench, the frequency of 47.00 MHz was chosen on Motorola MaraTrac No. 1 and GE RANGR No. 1. The modes 1 and 3 of the microcontroller were used, and the box was connected as the noise source to the bench-top test system with the Weischel 3200T-1 programmable attenuator in cascade. In the tests, both the radio noise blanker on and off were used. The measurement was done using the automatic testing program as mentioned in Chapter 2. The test results are shown in Table 10 for the 12 dB SINAD with a 1.0 μV FM signal. The statistics for modes 1 and 3 were calculated together because they have a similar AM/FM spectrum. The average and the standard deviation of the peak level of the noise are

Average = -2.0 dBμV,

and

Standard Deviation = 0.1 dB.

Table 10. Bench Test Data for IC Noise

Radio Brand & Model	Peak Level of IC Noise (dBμV) for Two Modes at 47.00 MHz for 12 dB SINAD with 1.0 μV FM Signal	
	1	3
GE RANGR (No. 1) with Noise Blanker On	-1.9	-1.9
GE RANGR (No. 1) with Noise Blanker Off	-1.9	-2.2
Motorola MaraTrac (No. 1) with Noise Blanker On	-2.1	-1.9
Motorola MaraTrac (No. 1) with Noise Blanker Off	-2.0	-2.1

CHAPTER IV

RESULTS FOR BROAD-BAND SOURCES

Two types of broad-band noise sources were investigated and simulated in the bench-top test system. They are the ignition noise from the spark ignition system of an internal combustion engine, and the DC motor noise coming from the commutators of the various electric motors in the vehicle. For the electric motor noise, two actual fuel pumps and one HVAC fan were used in the tests. Following SAE Standard J551/4, a 120 kHz measurement bandwidth was used on the R&S ESS EMI receiver for measuring the noise voltage. The Weinschel 3200T-1 programmable attenuator, which was connected to the noise source in cascade, and the automatic testing program were used for all the measurements in this chapter.

Ignition Noise Simulation and Test

Two test activities were conducted, one on a truck and one in the laboratory. The first one was carried out on a 1996 Dodge truck from the TxDOT vehicle fleet. The HP 5416B oscilloscope was connected directly to the antenna on the truck. The waveform of the ignition noise at the antenna was recorded at various sweep speeds, and a fast-sweep example is shown in Figure 13. From the observation, the following characteristics were noticed:

First, the ignition noise has pairs of pulses occurring with the steep rises of the spark current. These rises are evidently due to spark initiation in the distributor rotor and

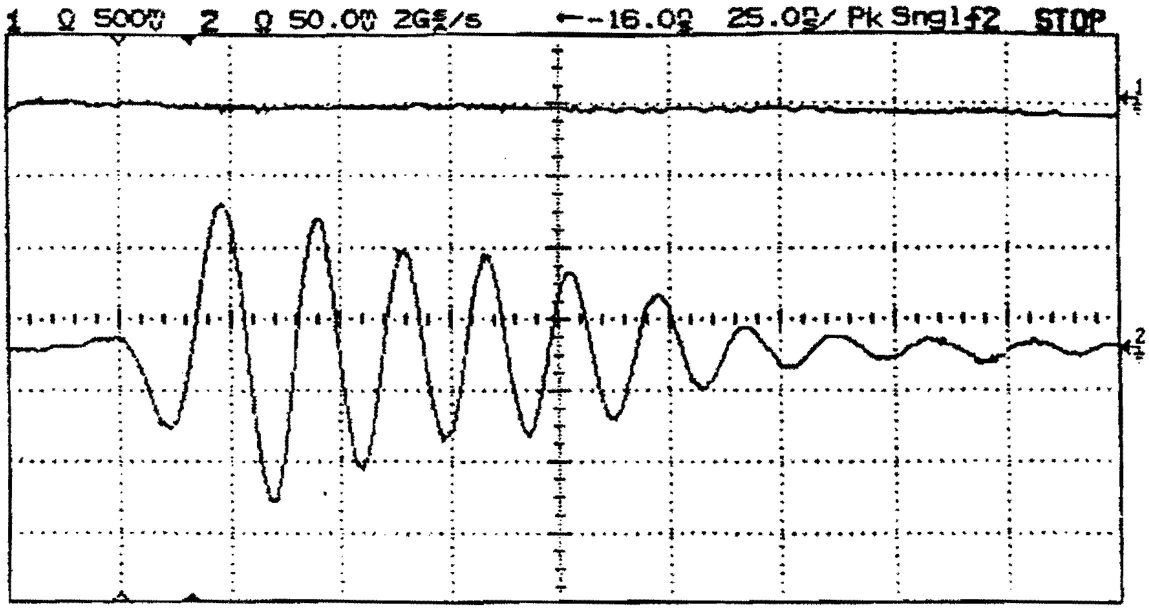


Figure 13. The Waveform of Ignition Noise at the Antenna on a Dodge Truck

in the spark plug.

Second, each pulse shows the ringing of the VHF low-band antenna. This is illustrated in Figure 13.

Third, a large amplitude of about 200 mV peak-to-peak is shown by each pulse.

On the bench, this ignition noise was simulated using the E-H Research Labs 139B pulse generator. It was set to the 'Double Pulse' mode, 10 ns pulse width, 10 ms pulse period, 10 μs second-pulse delay, and 1.5 V peak-to-peak. A band-pass filter was connected to the output of the pulse generator to simulate the antenna ringing. Figure 14 shows the simulation result, which is a printout from the HP 5416B oscilloscope. By comparing Figure 13 and Figure 14, it is clear that this is a good simulation.

Bench tests were run on all ten radios at 47.02 MHz and 47.18 MHz using the ignition simulator as the noise source. The noise blankers were switched on for the first tests. But it turned out that under such a condition, the noise level was insufficient to reduce the SINAD reading to 12 dB, even with the maximum noise amplitude, that is, 66 dBμV. The actual SINAD value from the HP 8903A audio analyzer was between 27 and 31 dB.

In the next tests, the noise blankers of these ten radios were turned off. In this case, the 12 dB SINAD was achieved. The test data are listed in Table 11. From the test results, the average value of the noise peak level is

Average = 40.7 dBμV,

and the standard deviation is

Standard Deviation = 3.4 dB.

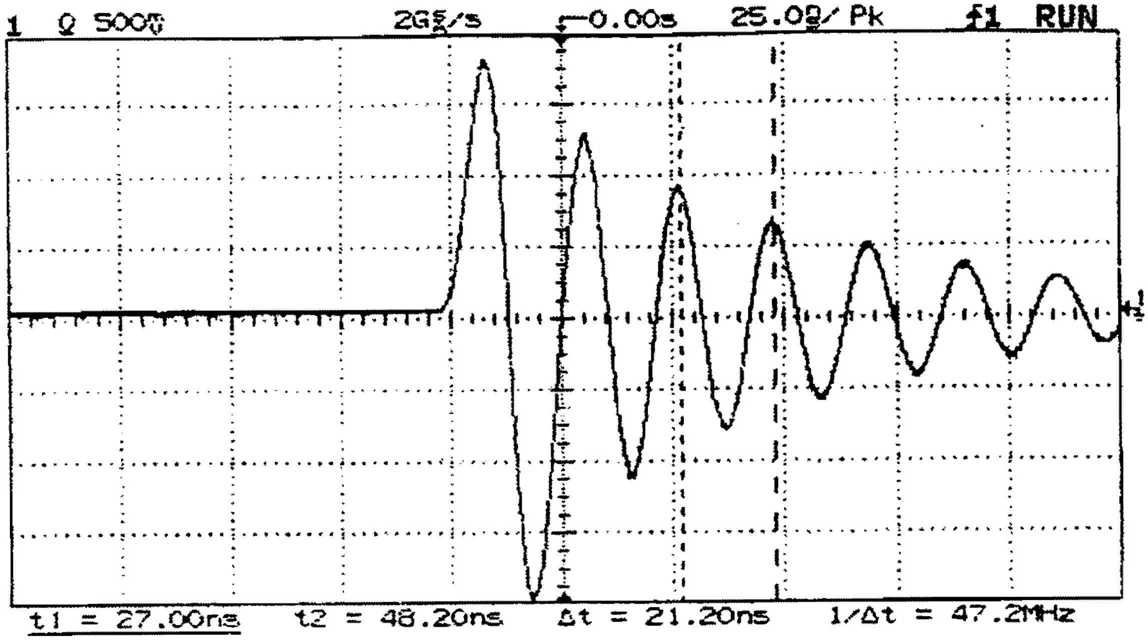


Figure 14. The Waveform of Simulated Ignition Noise

Table 11. Bench Test Data for Ignition Noise

Radio Brand & Model (with Noise Blanker Off)	Peak Level of Ignition Noise (dBμV) at Two Frequencies for 12 dB SINAD with 1.0 μV FM Signal	
	47.02 MHz	47.18 MHz
GE RANGR (No. 1)	40	42
GE RANGR (No. 2)	36	43
GE RANGR (No. 3)	41	39
Ericsson ORION (No. 1)	38	40
Ericsson ORION (No. 2)	45	39
Motorola MaraTrac (No. 1)	38	34
Motorola MaraTrac (No. 2)	39	39
Motorola SYNTOR X (No. 1)	44	43
Motorola SYNTOR X (No. 2)	49	44
Kenwood TK-630H	39	41

Differential-Mode versus Common-Mode Currents

In general, there are three conductors connecting with a DC motor system in a vehicle. Two of them are the wires between the DC motor and the battery. The third one is the chassis of the vehicle, which is connected to the battery and either connected or capacitively coupled to the motor. Currents flow in these three conductors when the motor runs.

These currents are composed of two different modes of currents: the differential mode (DM) and the common mode (CM).[5] The differential-mode currents are equal in magnitude and oppositely directed in the two wires. But the common-mode currents are equal in magnitude and flow in the same direction, returning on the chassis. These definitions apply to both the fuel pump motor and the HVAC fan motor.

A Fischer F-33-1 clamp-on current probe with a frequency range from 10 kHz to 250 MHz was used to detect the currents flowing in the two wires. When the current probe is placed around one individual wire, it measures the differential-mode currents; and when the probe is clamped around both wires, it measures the common-mode currents.

Fuel Pump Noise Test

An observation was made of fuel pump noise on an AutoZone MASTER E3902 fuel pump with distilled water. The fuel pump and its power supply, which is a 12 V battery, were put inside a screened enclosure 20 inches high, 39 inches wide and 28 inches deep. The output from the current probe was connected to the HP 5416B oscilloscope. The printout is shown in Figure 15. Some features of the fuel pump noise from the differential-mode currents were identified:

First, it is a group of bursts of ringing pulses.

Second, the amplitude is about 100 mV from peak to peak.

Third, the burst period and length are about 1.0 ms and 0.3 ms respectively.

Fourth, the pulse spacing within the burst is at least about 150 ns.

Fifth, the pulse ringing frequency is about 50 MHz.

On the bench, the first test was done on this fuel pump with distilled water. The output from the current probe was connected to the bench-top test system. But only the noise from differential-mode currents was measured. All ten radios with the noise blanker on and off were used in the test. The test results are given in Table 12 for the 12 dB SINAD with a 1.0 μV FM signal. The test data show that the noise blanker was ineffective against the fuel pump noise in this setup. The result for calculation of average value and standard deviation of all the data is:

Average = 28.3 dBμV,

and

Standard Deviation = 3.4 dB.

The same measurement was repeated on this AutoZone fuel pump but with stoddard solvent (Tri-methyl-benzene) in order to see the difference between water and stoddard solvent with the same pump. It turned out that in this case, the noise from both differential-mode and common-mode currents was insufficient to reduce the SINAD

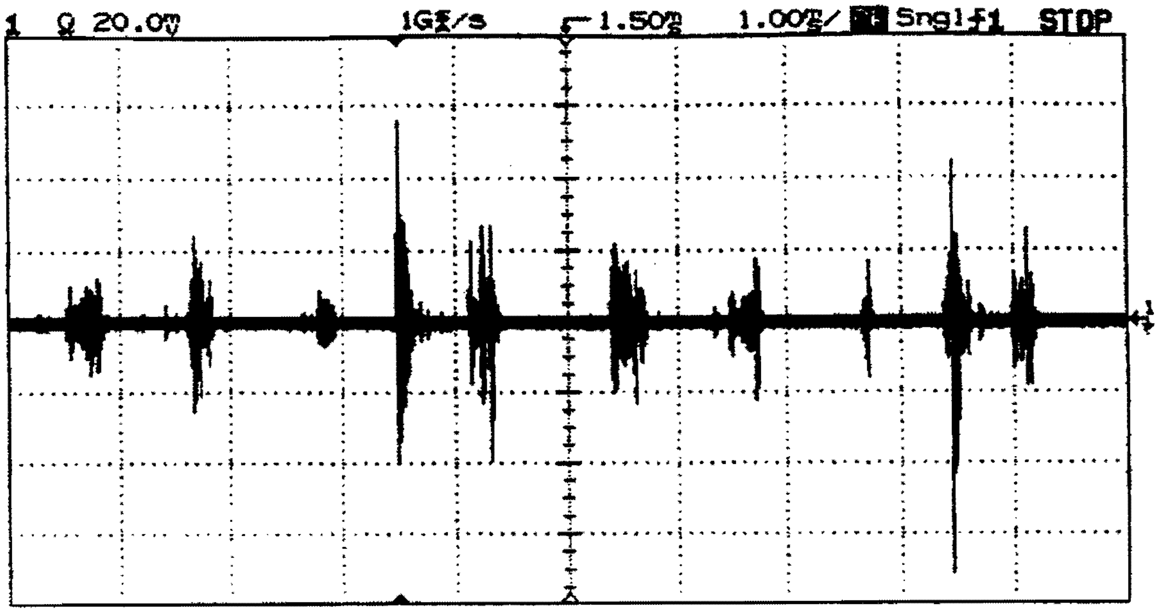


Figure 15. Fuel Pump Noise Observed on an AutoZone Pump

Table 12. Bench Test Data for AutoZone Fuel Pump Noise
(with Distilled Water)

Radio Brand & Model	Peak Level of Fuel Pump Noise (dBμV) at Two Frequencies: 47.02 MHz and 47.18 MHz for 12 dB SINAD with 1.0 μV FM Signal	
	Noise Blanker On	Noise Blanker Off
GE RANGR (No. 1)	22, 23	28, 33
GE RANGR (No. 2)	26, 28	28. 33
GE RANGR (No. 3)	25, 26	30, 28
Ericsson ORION (No. 1)	34, 29	33,30
Ericsson ORION (No. 2)	27, 25	30, 28
Motorola MaraTrac (No. 1)	29, 34	31, 30
Motorola MaraTrac (No. 2)	33, 33	25, 30
Motorola SYNTOR X (No. 1)	30, 28	28, 31
Motorola SYNTOR X (No. 2)	29, 26	30, 32
Kenwood TK-630H	29, 30	32, 33

reading to 12 dB whether the radio noise blanker was on or off. The actual SINAD value from the HP 8903A audio analyzer was around 29 dB.

Another test was set up using a Dodge fuel pump with stoddard solvent. In this test, the RF emissions from both differential-mode currents and common-mode currents were measured. Two radios, GE RANGR No. 1 and Motorola MaraTrac No. 2, were put under test at two frequencies, 47.02 MHz and 47.18 MHz. Table 13 gives the test results with the radio noise blanker on and off. From the table, it is clear that the noise blanker has an effect against the fuel pump noise in this setup. It also shows that the RF noise from these two modes has a different effect on the radios when the noise blanker is on. But when the noise blanker is off, the effects are almost the same. For the 12 dB SINAD with a 1.0 μV FM signal, the worst case is a 30.4 dBμV peak noise level.

Table 13. Bench Test Data for Dodge Fuel Pump Noise
(with Stoddard Solvent)

Radio Brand & Model	Peak Level of Fuel Pump Noise (dBμV) at Two Frequencies: 47.02 MHz and 47.18 MHz for 12 dB SINAD with 1.0 μV FM Signal			
	Noise Blanker On		Noise Blanker Off	
	DM	CM	DM	CM
GE RANGR (No. 1)	48.8, 46.7	43.4, 43.1	34.2, 32.0	35.4, 34.4
Motorola MaraTrac (No. 2)	47.5, 45.8	38.2, 39.4	30.4, 32.6	31.3, 33.8

HVAC Fan Noise Test

In the laboratory, a Dodge HVAC fan system was built and put inside the same screened enclosure as the fuel pump. Examples of the fan noise from the differential-mode and common-mode currents are given in Figure 16. This noise has similar characteristics to the fuel pump noise except a larger amplitude, about 160 mV peak-to-peak. Some differences can be identified from these two waveforms:

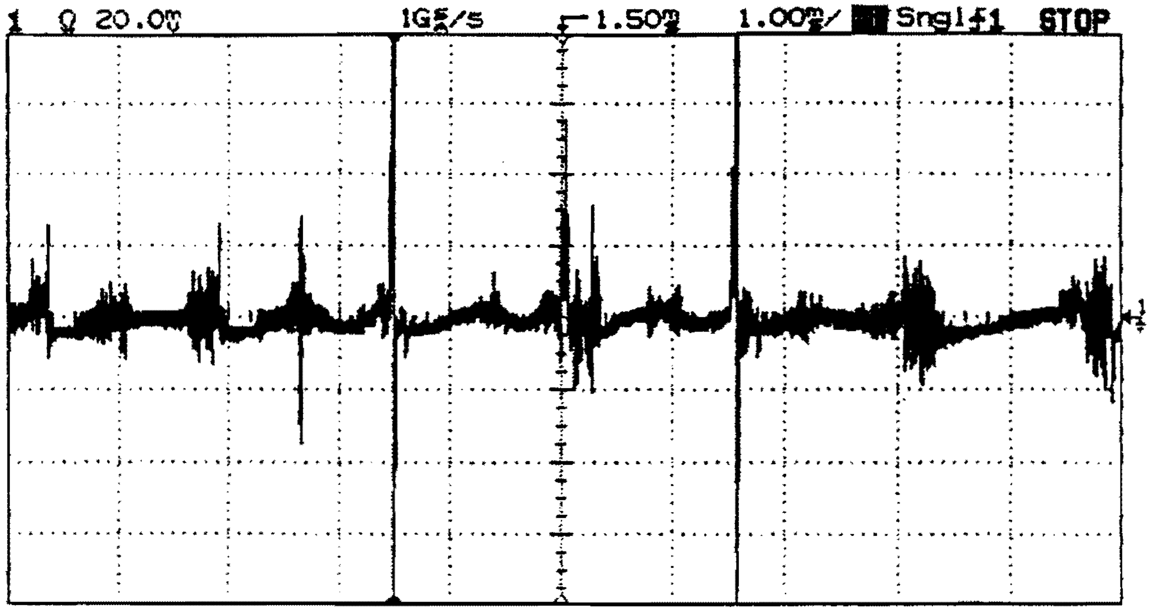
First, there are low frequency oscillations in (a), which are not shown in (b).

Second, it appears that there are longer bursts in (a) than in (b).

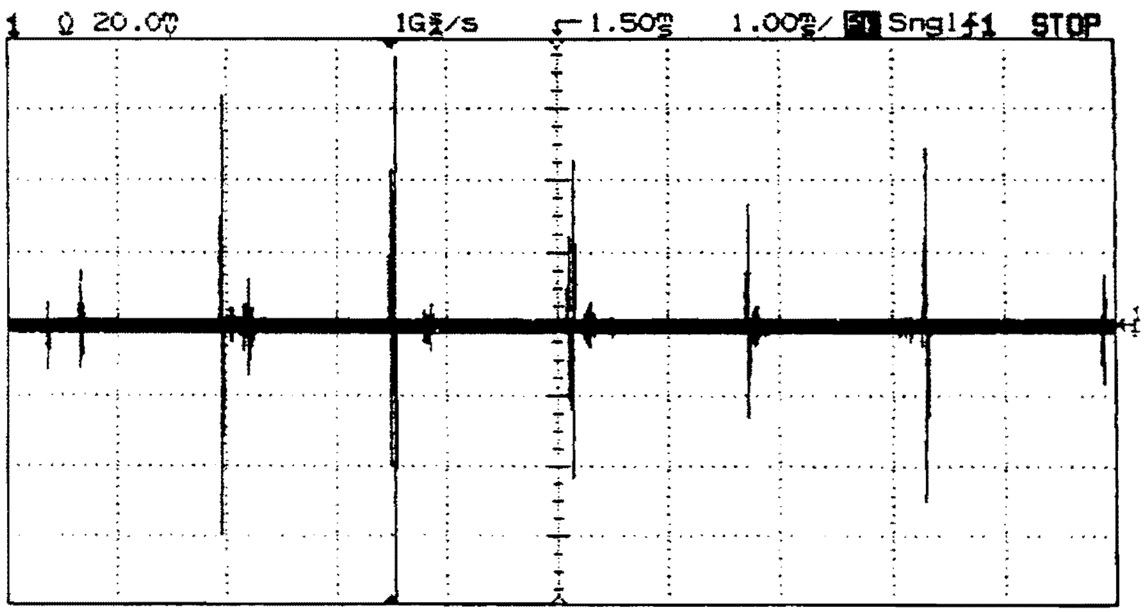
The same type of measurement done with the fuel pumps was repeated. The results are included in Table 14 for the 12 dB SINAD with a 1.0 μV FM signal. It is obvious that the noise blanker is somewhat effective against the HVAC fan noise. The noise from the two modes has almost the same effect on the radios when the noise blanker is on. And this is also true when the radio noise blanker is off. The worst case here shows a 30.0 dBμV peak noise voltage level.

Transfer Function between HVAC Fan Currents and TxDOT Radio Noise Input

The transfer functions, or coupling, in the vehicles between DC motor currents and radio noise are not known. In order to investigate the transfer function between the HVAC fan currents and the TxDOT radio noise input, the above Dodge HVAC fan system was used. But instead of the current probe, a 86 cm long whip antenna was placed



(a)



(b)

Figure 16. HVAC Fan Noise from (a) Differential-Mode Currents, and (b) Common-Mode Currents

Table 14. Bench Test Data for HVAC Fan Noise
(Using Current Probe)

Radio Brand & Model	Peak Level of HVAC Fan Noise (dBμV) at Two Frequencies: 47.02 MHz and 47.18 MHz for 12 dB SINAD with 1.0 μV FM Signal			
	Noise Blanker On		Noise Blanker Off	
	DM	CM	DM	CM
GE RANGR (No. 1)	40.5, 39.7	39.6, 38.4	30.8, 32.3	30.0, 29.4
Motorola MaraTrac (No. 2)	43.2, 43.5	40.9, 43.7	33.0, 30.0	31.4, 33.2

horizontally inside the screened enclosure to measure the RF emissions from the HVAC fan wires. And it was connected to the bench-top test system.

The test was done on the same two radios as above with noise blanker on and off. Table 15 lists the test results for the 12 dB SINAD with a 1.0 μV FM signal. By comparing Table 14 and Table 15, it can be seen that the radio noise input coming from either the current probe or the whip antenna has almost the same effect on the two radios. This suggests that as far as the radio is concerned, the coupling path or the transfer function between the fan currents and the radio noise input is transparent to the radio. Thus, in the laboratory, the current probe can be used to measure the noise from the HVAC fan currents. In addition, the current probe is easy to setup and convenient to use on the bench. Furthermore, this is probably also true for the fuel pump noise.

Table 15. Bench Test Data for HVAC Fan Noise
(Using Whip Antenna)

Radio Brand & Model	Peak Level of HVAC Fan Noise (dBμV) at Two Frequencies: 47.02 MHz and 47.18 MHz for 12 dB SINAD with 1.0 μV FM Signal	
	Noise Blanker On	Noise Blanker Off
GE RANGR (No. 1)	40, 39	31, 33
Motorola MaraTrac (No. 2)	42, 45	32, 30

CHAPTER V

DATA INTERPRETATION AND CONCLUSIONS

Summary of Bench Test Results

Summarized bench-top test results for narrow-band and broad-band noise sources are given in Table 16 and Table 17, respectively. For both narrow-band and broad-band noise sources, the peak voltage levels are listed for comparison with the limits specified by the SAE J551/4. All the data were taken from the tests run at 47.02 MHz and 47.18 MHz, except for the IC noise, which was tested at 47.00 MHz. The radios involved with these tests were mentioned in the previous chapters.

For the narrow-band noise sources, the bench test results show that the FM radios are most sensitive to the presence of FM noise. The average peak levels, –2.6 dBμV and –4.1 dBμV (worst case), using the TxDOT Tex-899-B criterion lie below the SAE J551/4 narrow-band limit of 0 dBμV.

The radios are also sensitive to CW and AM waveforms, which were simulated on the bench. The average peak level of the CW noise, -2.5 dBμV, is lower than the SAE 0 dBμV limit. For the HMCW noise with a 50% duty cycle, the maximum peak level using the Tex-899-B criterion is nearly the same for all ten radios and its average (-1.8 dBμV) is less than the SAE limit. And this is also true for this type of noise with a 15% duty cycle. Even for the AM noise with 400 Hz modulation frequency, to which all radios are least sensitive, the average value of its peak voltage level, that is, -0.7 dBμV, is

Table 16. Summary of Bench Test Results for Narrow-Band Sources

Noise Source (Narrow-Band)	Peak Noise Amplitude (dBμV) at 47.02 MHz and 47.18 MHz for 12 dB SINAD with 1.0 μV FM Signal
CW	-2.5 ± 0.8
AM (400 Hz)	-0.7 ± 0.3
AM (1.5 kHz)	-1.9 ± 0.2
HMCW (1500 Pulses per second) 15% Duty Cycle	-1.1 ± 0.2
HMCW (1500 Pulses per second) 50% Duty Cycle	-1.8 ± 0.2
FM (400 Hz), 3.0 kHz Deviation	-2.6 ± 0.8
FM (1.5 kHz), 3.0 kHz Deviation	-2.6 ± 0.4
FM (1.5 kHz), 6.0 kHz Deviation	-4.1 ± 0.2
Microcontroller (AM/FM Spectrum)	-2.0 ± 0.1

Table 17. Summary of Bench Test Results for Broad-Band Sources

Noise Source (Broad-Band)		Peak Noise Amplitude (dBμV) at 47.02 MHz and 47.18 MHz for 12 dB SINAD with 1.0 μV FM Signal	
		Radio Noise Blanker On	Radio Noise Blanker Off
Ignition		> 66	41.3 ± 3.3
Fuel Pump (with Distilled Water) DM		28.3 ± 3.4	28.3 ± 3.4
Fuel Pump (with Stoddard Solvent)	DM	47.2 ± 1.3	32.3 ± 1.6
	CM	41.0 ± 2.6	33.7 ± 1.7
HVAC Fan	DM	41.7 ± 1.9	31.5 ± 1.4
	CM	40.7 ± 2.3	31.0 ± 1.7

still slightly below SAE 0 dBμV limit. Thus, the TxDOT Tex-899-B limit is more stringent than the SAE in this case.

The ignition noise, which is the strongest type of noise occurring on the Dodge truck, was the least important in causing radio interference in bench tests because of the effectiveness of the radio noise blanker circuits. In fact, the bench-top ignition simulator was unable to reduce the SINAD readings to 12 dB with the radio noise blanker on. However, with the noise blanker turned off, the average peak level (41.3 dBμV) of such noise using the TxDOT Tex-899-B criterion is much higher than the SAE broad-band limit which is 28 dBμV.

In the bench tests, the noise blankers were ineffective against fuel pump noise with distilled water. The maximum peak level of such noise using the TxDOT Tex-899-B criterion varies somewhat from one radio to another, but its average (28.3 dBμV) coincides remarkably with the SAE broad-band limit.

For the fuel pump with Stoddard solvent, the noise blankers were somewhat effective against such noise. The minimum peak level (30.4 dBμV) using the Tex-899-B criterion is above the SAE limit. This is the same with the HVAC fan noise. So for the broad-band noise, the SAE limit is slightly more stringent than the TxDOT.

Back-Door Penetrations

There are various cables connected to a two-way FM radio. The first cable is the power line. The second one is the control line from the radio to the control head. The third cable is the audio line, which connects the control head to a speaker. Thus there exists a chance that the RF emissions from a vehicle may interfere with the performance of the FM radio through these cables. This kind of RFI phenomenon is known as a back-door penetration in electronic warfare in comparison to a front-door penetration, which is the interference through the antenna as studied in the previous chapters. The SAE J551/4 and the TxDOT Tex-899-B ignore back-door penetrations.

A small investigation was done using current TxDOT project equipment. In this setup, the 1.0 μV FM signal generated by the Fluke 6060B signal generator was put directly into the radio's input. The audio output of the radio was connected to the SINAD meter as before. The observations were made on two radios, Motorola MaraTrac No. 2 and GE RANGR No. 2, at 47.02 MHz along with two types of noise, the CW noise and the HVAC fan noise.

Four different frequencies were used on the R&S CMS54 radiocommunication service monitor for the CW noise. The first frequency was 47.02 MHz, which was the same frequency as the radio. The next two were 10.7 MHz and 20.8 MHz, the first IF (Intermediate Frequency) of the radio receiver, for the MaraTrac and the RANGR, respectively. And the last one was 455 kHz, which is the second IF of both models. A small loop antenna was connected to the output of the R&S CMS54 radiocommunication service monitor to produce the CW noise radiation. In the tests, the noise blankers of both radios were turned on. The small loop antenna was put over each of those three connection lines, and the noise voltage level was adjusted in order to get the 12 dB SINAD reading. The test results are recorded in Table 18 and Table 19 for the two

Table 18. Back-Door Penetration Observation on Motorola MaraTrac No. 2 Radio

Position of the Small Loop Antenna	Peak Level of CW Noise (dBμV) at Three Frequencies for 12 dB SINAD with 1.0 μV FM Signal		
	47.02 MHz	10.7 MHz	455 kHz
On Power Line	88.6	No Interference Found	No Interference Found
On Control Line	94.3		
On Audio Line	91.0		

Table 19. Back-Door Penetration Observation on GE RANGR No. 2 Radio

Position of the Small Loop Antenna	Peak Level of CW Noise (dBμV) at Three Frequencies for 12 dB SINAD with 1.0 μV FM Signal		
	47.02 MHz	20.8 MHz	455 kHz
On Power Line	90.0	No Interference Found	No Interference Found
On Control Line	92.3		
On Audio Line	92.1		

radios, respectively. It is evident that only the 47.02 MHz CW noise has a successful back-door penetration while the others have no effect on the radios.

For the fan noise, the same Dodge HVAC fan as in the HVAC fan noise test was used in this observation. Both the radio and the fan were connected to the same 12 V battery, as they are in a vehicle. The power line of the fan was turned into a circle to produce more radiation. This circle was placed over those connection lines but no interference was found for either radio. Even after their noise blankers were switched off and the FM signal voltage level was reduced to –3.0 dBμV, the actual SINAD reading was still above 28 dB for these two radios. So the RF emissions from the HVAC fan are not strong enough to affect the radios through the connection cables.

Narrow-Band versus Broad-Band

The terms narrow-band and broad-band are the relative measures of bandwidth. With the exception of a pure sinusoidal continuous wave (narrow-band) and an ideal delta function (broad-band), no signal or noise may be intrinsically defined as narrow-band or broad-band. In fact, the meanings of 'narrow' or 'broad' can be related to the bandwidth of the instrument used to measure the corresponding signal or noise. In terms of the bandwidth of a given measuring instrument, a narrow-band signal or noise is one whose spectral components lie within the measurement bandwidth at the tuned frequency. On the other hand, a broad-band signal or noise may be defined as having spectral components falling outside the bandwidth of the measuring device.

There are several practical methods for the narrow-band or broad-band determination.[6] One of these methods is to increase the measurement bandwidth. If the peak level of a signal or noise does not change, this signal or noise is narrow-band, otherwise it is determined to be broad-band. Another practical method is to tune off the frequency of maximum amplitude by two impulse bandwidths, a change in amplitude of 3 dB or more implies a narrow-band signal or noise, otherwise it is classified to be broad-band.

For RF emissions from modern motor vehicles, SAE J551/4 gives a test procedure to determine whether the measured emissions are narrow-band or broad-band. This is an important distinction on which the measurement bandwidth and the required limit both depend. The test can be summarized as follows: with a narrow measurement bandwidth on the EMI receiver, if the difference between the peak value and the average value is greater than 6 dB for a noise source, it is classified as broad-band, otherwise it is determined to be narrow-band. The 6 dB limit also appears in a European EMI standard, CISPR 25. CISPR, the French translation meaning International Special Committee on Radio Interference, is a committee of the International Electrotechnical Commission.

For example, following this SAE test procedure, the HVAC fan noise is determined to be broad-band because the measurement using the R&S ESS EMI receiver with a 10 kHz measurement bandwidth showed that the difference between its peak and average values is greater than 30 dB. Also when this 10 kHz bandwidth was increased to 120 kHz, the peak level increased 24 dB. Thus, the measurement-bandwidth-increasing method confirms that this is broad-band noise.

However, the SAE working definition of narrow-band versus broad-band cannot apply to all noise sources such as the HMCW noise with a 15% duty cycle. For this noise, the difference between its peak value and average value is greater than 6 dB, but it is determined to be narrow-band because it affects the TxDOT radios strongly like other narrow-band noise not weakly like broad-band noise. Furthermore, it can be verified to be narrow-band using the measurement-bandwidth-increasing method.

A further study was therefore carried out in the laboratory to develop a new narrow-band/broad-band definition. The same setup as in the HMCW noise tests was used but with various additional duty cycles – the smaller the duty cycle, the greater the bandwidth. The tests were done on Motorola MaraTrac No. 2 and GE RANGR No. 2 at 47.02 MHz and the noise blankers were turned on. The same 1.5 kHz repetition rate was used in the tests. Because the internal modulator of the R&S CMS54 radiocommunication service monitor cannot generate the required square waveforms for duty cycles below 10%, this setup was used only for the HMCW noise with the duty cycle from 70% to 10%. For the duty cycles below 10%, a Mini-Circuits ZYSWA-2-50DR coaxial switch with TTL (Transistor Transistor Logic) driver was used. The 47.02 kHz CW signal and the 1.5 kHz rectangular pulse train were connected to its 'RFIN' and 'TTL' ports, respectively. And its 'RF1' port was terminated with a 50 Ω resistor. The output from the 'RF2' port, which was the desired HMCW noise, was put into the bench-top test system.

The test results are included in Table 20. The difference between the peak and the average values was measured using the R&S ESS EMI receiver with a 10 kHz

Table 20. Bench Test Data for Further Study on HMCW Noise with Two Radios

Duty Cycle (%)	Difference (dB) between Peak and Average for Ideal Rectangular Pulses	Difference (dB) betweeen Peak and Average for 10 kHz Measurement Bandwidth	Difference (dB) between Two Peaks for 10 kHz and 120 kHz Measurement Bandwidths	Peak Noise Level (dBµV) at 47.02 MHz for 12 dB SINAD with 1.0 µV FM Signal (10 kHz and 120 kHz Measurement Bandwidths)	
				Motorola MaraTrac No. 2	GE RANGR No. 2
70	3	3	0	-3.0, -3.0	-3.2, -3.2
60	4	4	0	-3.0, -3.0	-3.2, -3.2
50	6	6	0	-2.4, -2.4	-2.2, -2.2
40	8	8	0	-2.4, -2.4	-1.9, -1.9
30	10	10	0	-2.4, -2.4	-1.5, -1.5
20	14	14	0	-1.2, -1.2	-1.3, -1.3
15	16	14	2	-1.0, 0	-1.1, -0.1
10	20	15	5	-1.5, 3.5	-1.8, 3.2
5	26	15	11	-1.5, 9.5	-2.0, 9.0
3	30	15	15	-0.3, 14.7	-1.2, 13.8
1*	40	16	20	20, 40	15, 35
0.3*	50	16	20	27, 47	23, 43
0.1*	60	10	22	18, 40	17, 39
0.03*	70	10	34	10, 44	9, 43

Note:

* For these duty cycles the radio noise blankers were triggered.

measurement bandwidth. Also measured on the EMI receiver was the difference between the two peak readings corresponding to two different bandwidths, 10 kHz and 120 kHz. The peak noise level for the 12 dB SINAD with a 1.0 μV FM signal versus the duty cycle (two right-most columns) is plotted in Figure 17. It can be seen that both radios are very sensitive to the noise until the duty cycle goes down to 1%, and thereafter the radios become less sensitive and can tolerate higher noise levels. Therefore, it is reasonable to put a boundary between the narrow-band and broad-band noise at the point of 1% duty cycle. The boundary is shown in Figure 17 as a part of the new limit, which will be discussed in a later section. The 6 dB bandwidth of such a signal at 1% duty cycle is about 180 kHz. Furthermore, only the last four noise waveforms triggered the radio noise blanker in the tests, which also indicates that they are broad-band.

It is clear from above that in order to make an accurate narrow-band or broad-band determination, it is necessary to add the measurement-bandwidth-increasing method as an extra test step in the current SAE test procedure. The reason for retaining the 6 dB method is that if only this two-bandwidth method is used, the measuring instrument might pick up more than one narrow-band RF emission, one in the radio's passband and others outside the passband, and thus mistakenly identify them as a broad-band noise. The new procedure can be expressed as follows: first, use a narrow measurement bandwidth on the receiver; if the difference between the peak value and the average value is less than 6 dB for a noise source, it is classified as narrow-band, otherwise increase the bandwidth; if the peak level changes by 20 dB or more, this noise may be defined as broad-band, otherwise it is a narrow-band noise source.

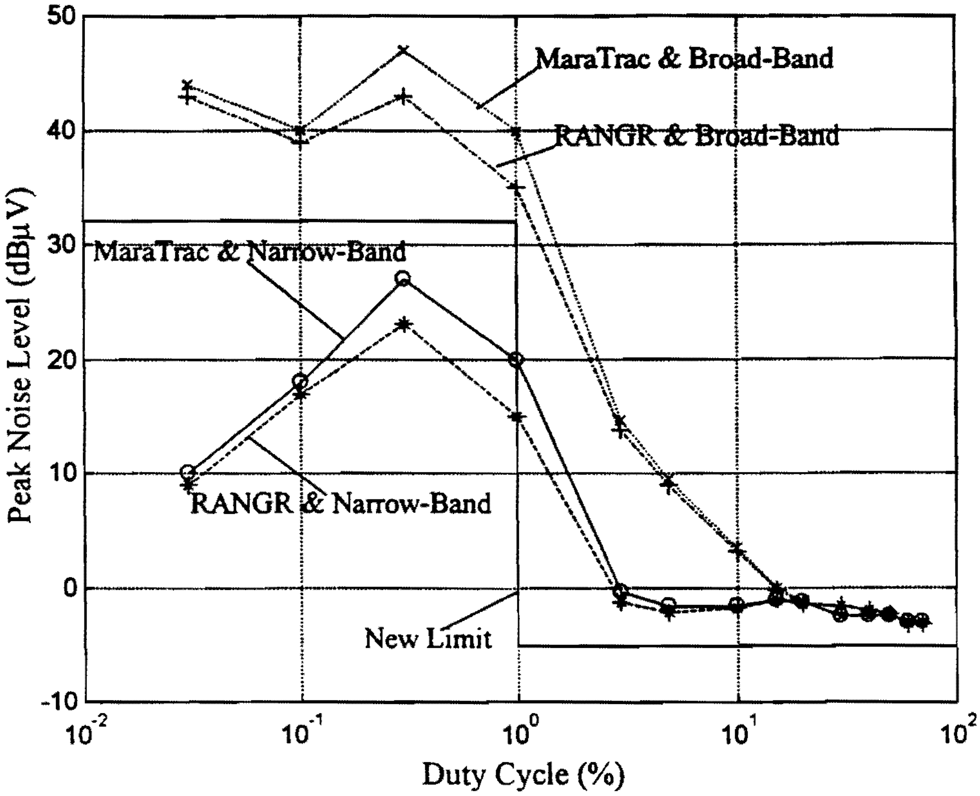


Figure 17. Peak Level for 12 dB SINAD from Table 18

Further Study of AM/FM Noise

A further study of AM/FM noise was also done on the bench. We used the internal FM modulator of the R&S CMS54 radiocommunication service monitor to generate an FM signal while applying the same switch setup as in the above section to form the pulses. Thus we got the AM and FM waveforms simultaneously as the output of the switch, which was connected to the bench-top test system. The measurement was carried out on GE RANGR No. 2 at 47.02 MHz and the noise blanker was turned on. It turned out that doing this did not cause any worse interference to the radio than just having the pulses as we did before.

Thermal Noise

For the sake of completeness in our noise tests, thermal noise was also simulated. A Mini-Circuits ZFL-500HLN amplifier with its input terminated by a 50 Ω resistor was used. Its output, which was the thermal noise of the resistor and the internal noise of this amplifier, was connected into the bench-top test system. The measurements were done on two radios, Motorola MaraTrac No. 2 and GE RANGR No. 2, at 47.02 MHz. The observation found that the radio noise blanker is not effective with this type of noise. The test results are included in Table 21 for the 12 dB SINAD with a 1.0 μV FM signal. From the table, it is clear that both radios are very sensitive to the noise. This phenomenon indicates that as far as the radio is concerned, the thermal noise is a narrow-band noise. Moreover, this postulate can be confirmed using our new narrow-band versus broad-band working definition because the difference between two peak readings for 10 kHz and 120 kHz bandwidths is 12 dB, which is less than our 20 dB criterion.

Table 21. Bench Test Data for Thermal Noise

Radio Brand & Model	Noise Level of Thermal Noise (dBμV) at 47.02 MHz for 12 dB SINAD with 1.0 μV FM Signal with Two Measurement Bandwidths			
	120 kHz		10 kHz	
	PK	AV	PK	AV
GE RANGR (No. 2)	13.2	1.0	1.6	-9.2
Motorola MaraTrac (No. 2)	13.0	0.3	1.0	-10.7

New Limit

As plotted in Figure 17, the new limit is composed of three parts: the narrow-band limit, the broad-band limit, and the boundary between the narrow-band and broad-band limits.

The narrow-band limit corresponds to the cases in which the radios are very sensitive to the noise and is the low limit on the figure. The data shown in Figure 17 to the right of the narrow-band/broad-band boundary lie at about –3 dBμV. In addition, the data from other narrow-band sources show that the worst peak noise level lies at about –4 dBμV. So it is reasonable to set the new limit below that level, such as –5 dBμV, for the narrow-band noise sources.

The broad-band limit applies to the case where radios are not sensitive to the noise and is the high limit on the graph. In Figure 17, crossing the boundary at the 1% duty cycle, we enter this broad-band region. Here following the SAE J551/4 requirement to increase the measurement bandwidth, we have to jump from the narrow-band points to the broad-band ones. From the figure, it can be seen that the peak noise levels lie higher than 35 dBμV. Furthermore, the data from other broad-band sources measurements give a peak noise level lying at 38 dBμV or higher. Therefore, the 34 dBμV new limit is a reasonable limit for broad-band sources.

Conclusions

From the discussion in the previous chapters and sections, the following conclusions can be made:

First, although the test results vary somewhat from one radio to another, the overall performance of all ten radios is similar.

Second, in the bench-top tests, the radio noise blankers are ineffective against the narrow-band noise while they can improve the test results by at least 8 dB in the broad-band noise tests.

Third, among all the simulated narrow-band noise sources, the TxDOT radios are most sensitive to the presence of FM noise in their passband. And the worst case occurred when the FM waveform had 6.0 kHz or greater frequency deviation.

Fourth, in the broad-band noise sources, the ignition noise is the least important in causing radio interference even with the radio noise blanker turned off.

Fifth, on the bench, the current probe can be used to couple the HVAC fan noise because the transfer function between the fan currents and the radio noise input is transparent to the radio. Moreover, this is probably also true for the fuel pump noise.

Sixth, in the back-door penetration investigation, only the CW noise at the same frequency as the radio affected the performance of the radios, while the other two CW noise at the first or second IF of the radio and the HVAC fan noise had no effects.

Seventh, as far as the radio is concerned, the thermal noise is a narrow-band noise, which was confirmed by both the test data and our new narrow-band/broad-band definition.

Eighth, the current SAE limit for the broad-band noise, that is, 28 dBμV, can remain unchanged or even be raised if one wishes to use the SAE standard in place of the TxDOT standard. Meeting this limit guarantees passing the TxDOT test.

Ninth, if using the SAE standard in place of the TxDOT for narrow-band noise, the present 0 dBμV peak amplitude limit is too high. A lower narrow-band peak limit of –5 dBμV is needed in order to pass the TxDOT test.

Tenth, in the SAE test, the new test procedure for the narrow-band and broad-band determination should be used, that is, following the old 6 dB limit and adding the two-bandwidth method as an extra step.

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APPENDIX A

TEX-899-B TEST

RADIO FREQUENCY INTERFERENCE (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 on 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 volt 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 in 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 uv (-114 dBm) for 12 dB SINAD.

- The receiver bandwidth shall be a minimum of ± 6.5 kHz and a maximum of ± 8.0 kHz.

- 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 roof.
4	Disconnect the vehicle battery cable.
5	Terminate the RF line into the RF load termination.
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 load 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.

- 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 uv (-113 dBm).

Egress Compatibility (continued)

- Egress Compliance 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 RF 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 that 1 microvolt (-107 dBm) to produce 12 dB or greater SINAD. The effective sensitivity should not exceed 1 microvolt 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 six 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 reflected 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 watts and reflected power is less than 10% of the forward power.

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 Operations - Correct nuisance operations of any vehicle system and/or accessory.

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

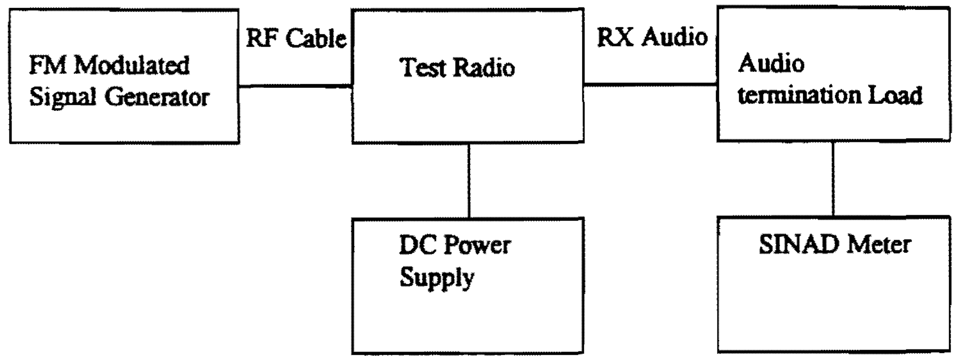

Figure1

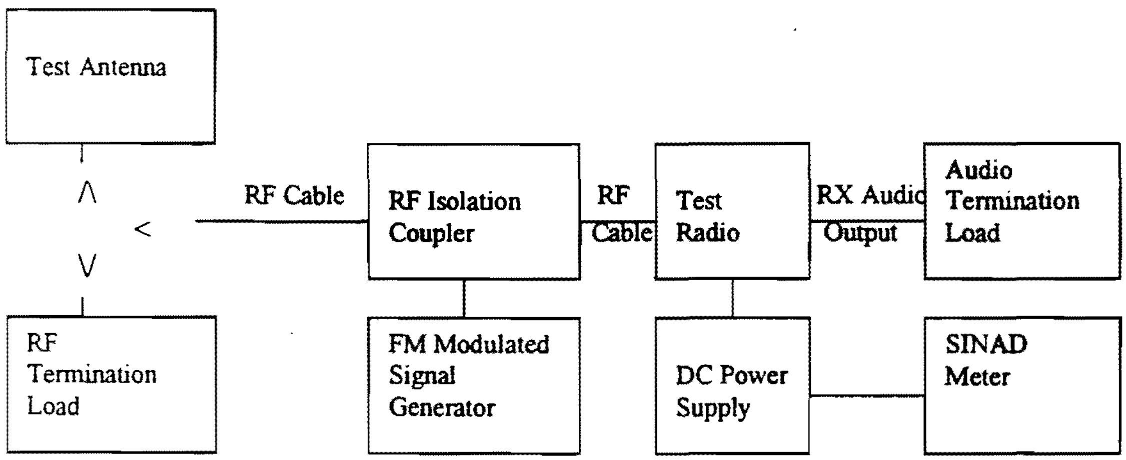

Figure 2

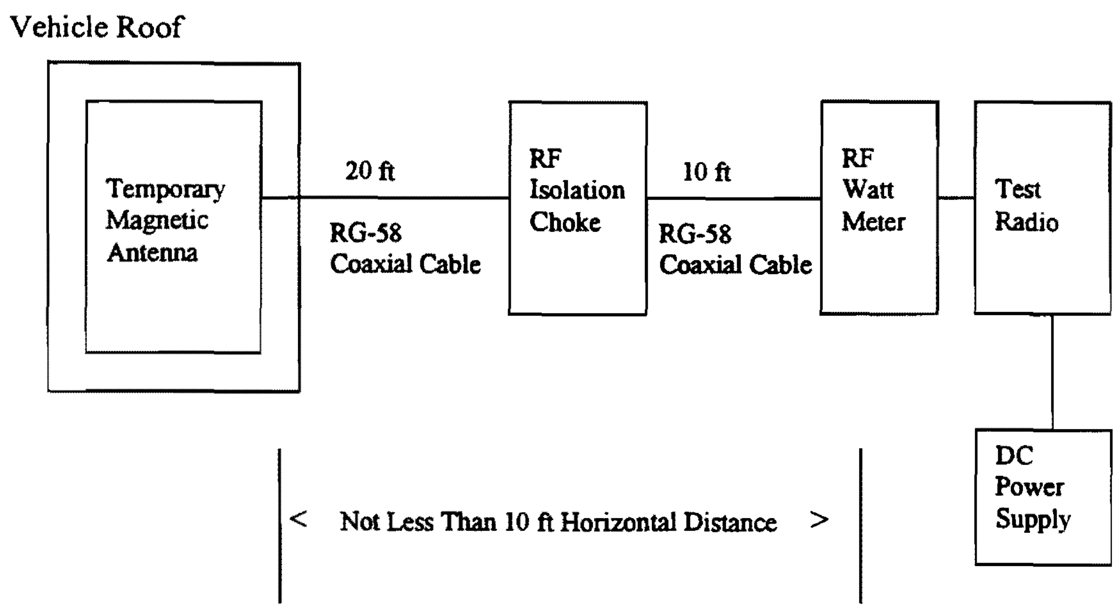
Vehicle Roof
Temporary Magnetic Antenna
20 ft
RG-58 Coaxial Cable
RF Isolation Choke
10 ft
RG-58 Coaxial Cable
RF Watt Meter
Test Radio
DC Power Supply
< Not Less Than 10 ft Horizontal Distance >

Figure 3

APPENDIX B

SAE J551/4 TEST

TEST LIMITS AND METHODS OF MEASUREMENT OF RADIO DISTURBANCE CHARACTERISTICS OF VEHICLES AND DEVICES, BROADBAND AND NARROWBAND, 150 kHz TO 1000 MHz

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Foreword—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 provides test limits and procedures for the "protection of vehicle receivers from radio frequency (RF) emissions caused by on-board vehicle components."

NOTE—Appendix B 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 Telecommunications Union (ITU) Publications for details of frequency allocations. The test limits 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.

[1] Only a vehicle test can be used to determine the component compatibility to a vehicle limit.
[2] Adjacent vehicles 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, tests at 150 kHz 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.

2.1.1 SAE PUBLICATION—Available from SAE, 400 Commonwealth Drive, Warrendale, PA 15096-0001.

SAE J551/1 MAR94— Performance Levels and Methods of Measurement of Electromagnetic Compatibility of Vehicles and Devices (60 Hz to 18 GHz)

2.1.2 CISPR PUBLICATION—Available from ???

CISPR 16-1:1993-08— 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 NOTE—A test plan should be established for each item to be tested. The test plan should specify the frequency range to be tested, the emissions limits, the disturbance classification [broadband (long or short duration) or narrowband], antenna types and locations, test report requirements, supply voltage, and other relevant parameters.

4.1.2 DETERMINATION OF CONFORMANCE WITH LIMITS—If the type of disturbance is unknown, tests shall be made to determine whether measured emissions are narrowband and/or broadband 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:[*]

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

[*] For examples see 4.1.4 and 4.1.5 and Table 1

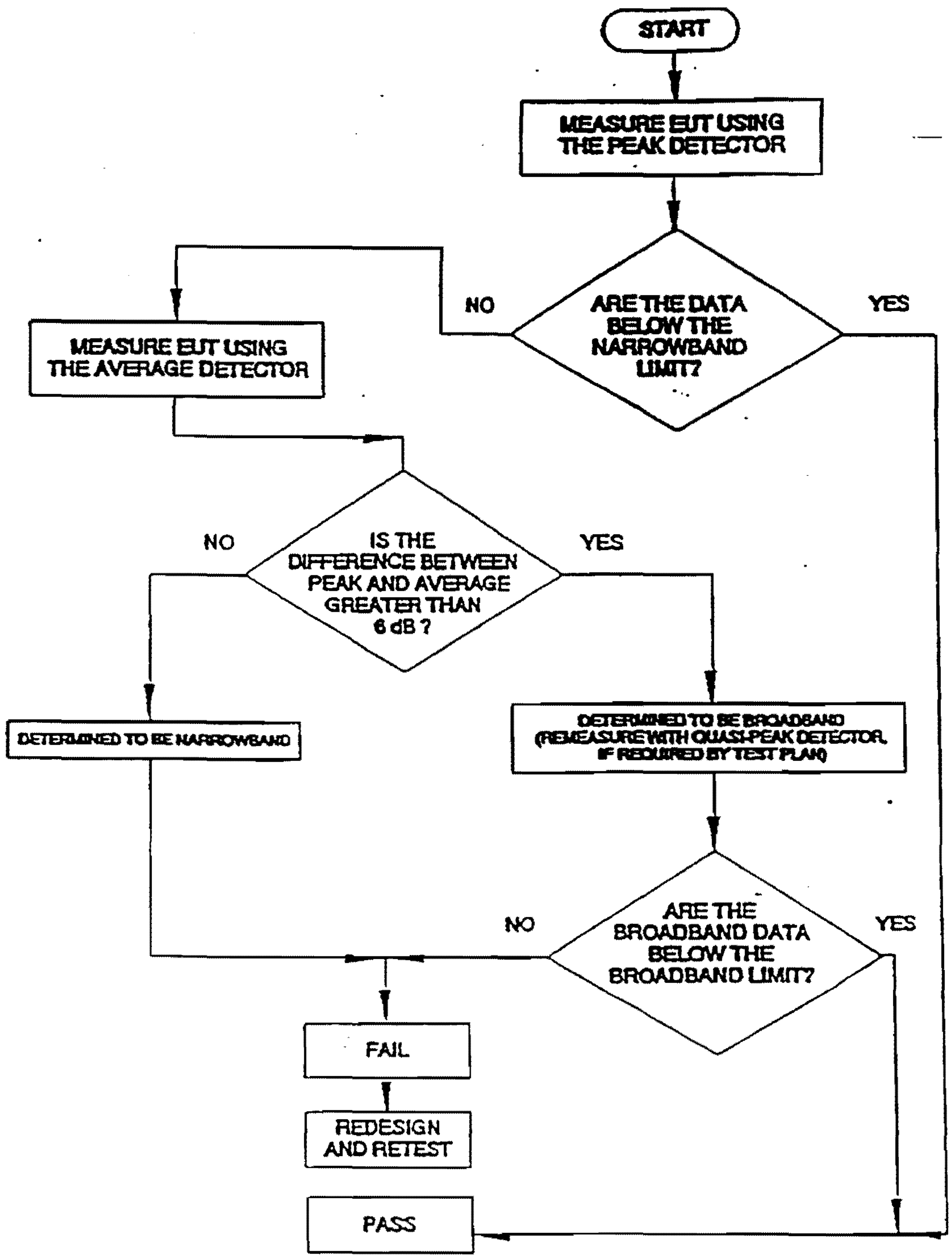


FIGURE 1—METHOD OF DETERMINATION OF CONFORMANCE OF RADIATED/CONDUCTED DISTURBANCE

4.1.4 Examples 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—EXAMPLES 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 microprocessors, digital logic, oscillators or clock generators, etc., cause narrowband emissions.

4.1.6 Operating Conditions—All continuous and long duration systems 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 the 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 the 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 as much 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 emissions measurements. No absorber material is required for the floor. The following ALSE requirements shall also be met for performing radiated RF emissions measurements:

4.4.1 REFLECTION CHARACTERISTICS—The reflection characteristics of the ALSE shall be such that the maximum error caused by reflected energy from the walls 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 emissions 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, chairs, 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 analyzers and scanning receivers are particularly useful for interference measurements. Special consideration shall be given to overload, linearity, selectivity, and the normal response to pulses. The peak detection mode of spectrum analyzers and scanning receivers 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 Table 2:

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 signals) may require slower 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 narrowband/broadband discrimination according to Figure 1, 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	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 Broadcast 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 envelope for each frequency band as shown in Figure 2. Calibration shall be performed in accordance with Appendix A.
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 A.

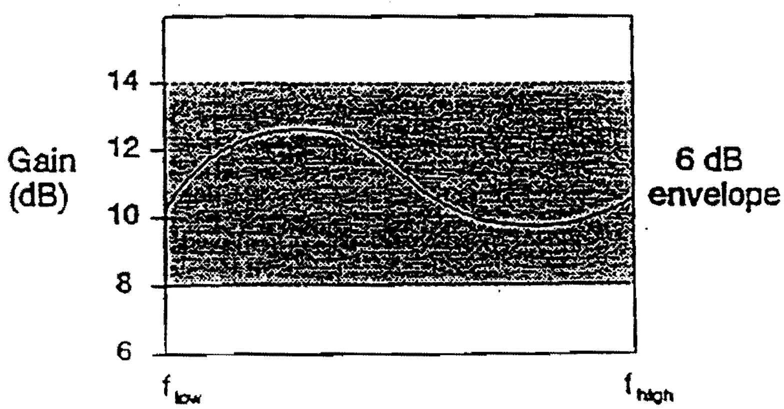


FIGURE 2—EXAMPLE GAIN CURVE

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 COMMUNICATIONS 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 factor shall be used.

[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 terminals 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.

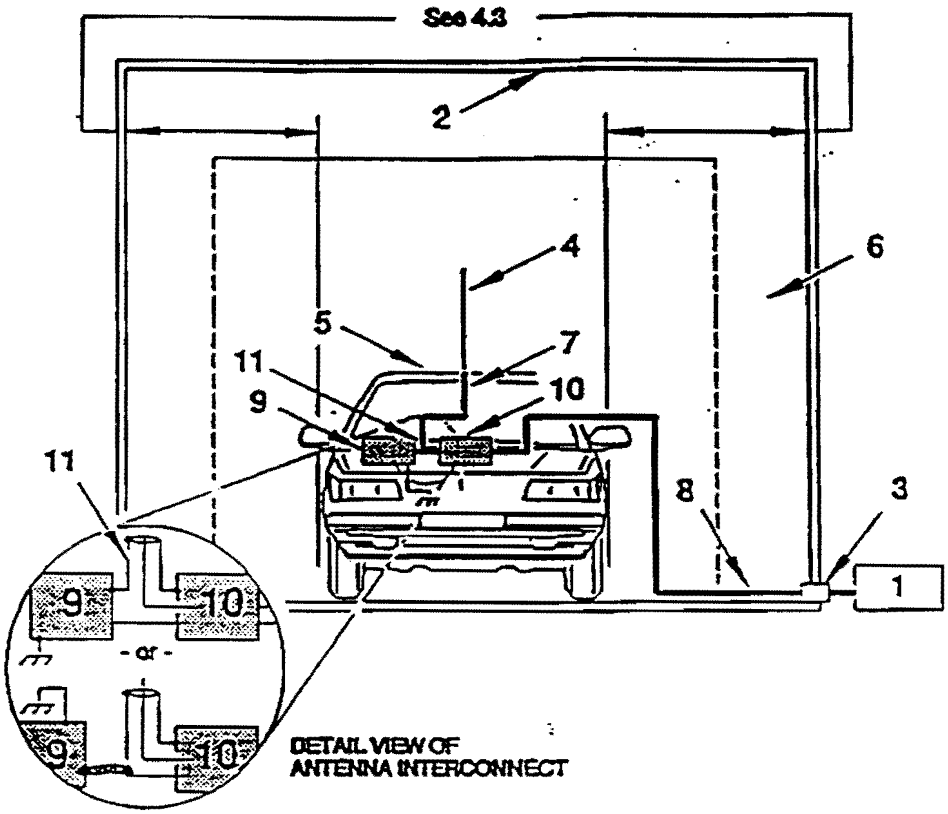
NOTE—The use of ferrite or other suppression material on the exterior of the coax is recommended, particularly below 2 MHz, for suppression of surface currents.

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. *Limits 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 sources may be decided upon by the vehicle manufacturer. For example, door mirror operation may be allowed at a higher 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 signals 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 - 0.30	9	22	15	28	6
MW	0.53 - 2.0	6	19	15	28	0
SW	5.9 - 6.2	6	19	6	19	0
VHF	30 - 54	6 (15*)	28	15	28	0
VHF	70 - 87	6 (15*)	28	15	28	0
VHF	87 - 108	6 (15*)	28	15	28	6
VHF	144 - 172	6 (15*)	28	15	28	0
UHF	420 - 512	6 (15*)	28	15	28	0
UHF	800 - 1000	6 (15*)	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.

* Limit for ignition systems only

APPENDIX A
(Normative)

ANTENNA MATCHING UNIT—VEHICLE TEST

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

A.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 car radio.

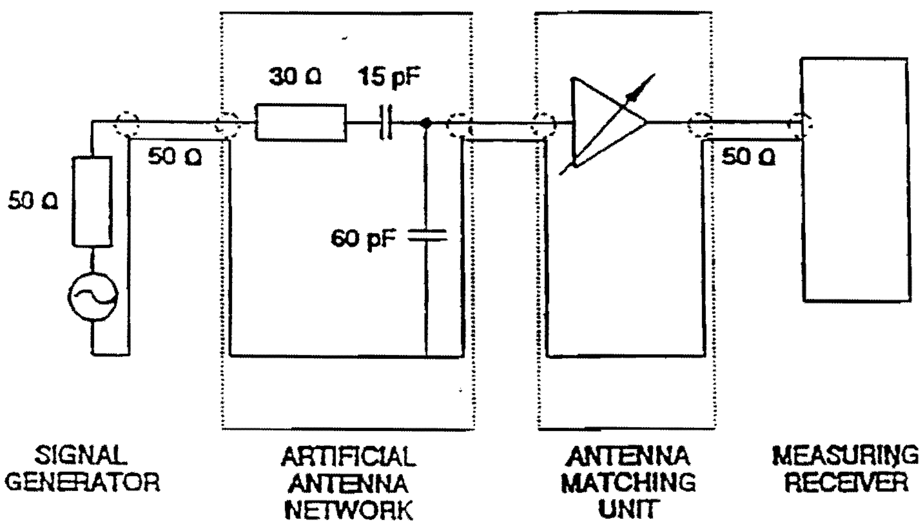


FIGURE A1—CALIBRATION SET-UP

A.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 A1.

A.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.

A.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 lie 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 B
(Informative)

NOTES ON THE SUPPRESSION OF INTERFERENCE

B.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. Disturbances coupled to the antenna
b. Disturbances 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. Disturbances 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.

B.2 Disturbances 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.

B.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.

B.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 oscillators 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.

B.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 TxDOT LOW-BAND-VHF RADIO FREQUENCIES (MHz)

45.680 *

45.720 *

45.800 *

45.840 *

47.020

47.040

47.060

47.080

47.100

47.120

47.140

47.160

47.180

47.200

47.220

47.240

47.260

47.340

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

TESTING MOTOR VEHICLES FOR

RADIO INTERFERENCE

by

QIANLIN ZHOU, B.S.

A THESIS

IN

. ELECTRICAL ENGINEERING

Submitted to the Graduate Faculty
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IN

ELECTRICAL ENGINEERING

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August, 1998

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CHAPTER I

INTRODUCTION – THE TXDOT PROJECT

TXDOT (Texas Department of Transportation) purchases about 800 vehicles from automobile companies every year. The increased use of electronics in modern vehicles has led to compatibility problems between vehicle electronic systems and aftermarket electronic equipment typically installed in these vehicles. Interference with TXDOT onboard two-way communication systems, which TXDOT uses to conduct daily business, can significantly reduce the useful communication range. TXDOT found a lot of interference in some channels of the radio a few years ago. This interference problem must be analyzed and studied from the standpoint of the FM two-way radio's characteristics and the automotive systems. The overall objective of the TXDOT project is to develop and verify effective RFI (radio frequency interference) test procedures that will allow TXDOT to identify potential compatibility and RFI problems related to the use of these radios.

The Society of Automotive Engineers (SAE) has been involved in writing electromagnetic compatibility standards since 1957. These standards are continually examined and upgraded to keep pace with technology. TXDOT also has developed an electromagnetic compatibility standard for its own systems. Vehicle manufacturers prefer to use an SAE test, rather than the TXDOT test, to check for vehicle interference. But recently the new vehicles frequently failed the TXDOT test. The SAE J551/4 test[1] and the TXDOT TEX-899-B test[2] are the two standards investigated in this thesis. After investigating both test standards we found the relationship between them. And we also devised a revised SAE J551/4 test which can be substituted for TEX-899-B test by the vehicle manufacturers.

Figure 1.1 shows the equipment setup of the TEX-899-B test. The antenna on the roof of the vehicle receives the noise from the vehicle. The noise is transferred to a directional coupler by a coaxial cable. A signal generator produces an FM signal which is also transferred to the directional coupler. The noise plus signal coming out of the directional coupler is transferred to a TXDOT radio. Then the audio output from the radio feeds into an audio termination load and a SINAD (signal, noise and distortion) meter. SINAD is defined as:

$$\text{SINAD (dB)} = 20\log_{10}\left[\frac{\text{rms value of signal, noise, and distortion(Volts)}}{\text{rms value of noise and distortion(Volts)}}\right] \quad \text{1.1}$$

In the TXDOT test the amplitude of the FM signal is changed to obtain a 12-dB SINAD level. The measured signal amplitude of the FM signal is the final result of the TXDOT test. The TXDOT test limit is 0-dB μV or 6-dB μV above the ambient noise level, which ever is less. The dB μV unit is defined as:

$$\text{A (dB } \mu\text{V)} = 20\log_{10}\left[\frac{\text{A }(\mu\text{V})}{1(\mu\text{V})}\right] \quad \text{1.2}$$

Figure 1.2 shows the equipment setup used for the SAE J551/4 test. In the SAE test the test receiver directly measured the noise from the antenna. There are three limits in the SAE test: narrow-band peak, broad-band peak and broad-band quasi-peak. The last one is usually used in Europe and will not be mentioned in this thesis. The narrow-band peak limit is 0-dB μV and the broad-band peak limit is 28-dB μV. The TEX-899-B test and SAE J/551 test are described in Appendicies A and B.

SwRI (Southwest Research Institute) did both the SAE test and the TXDOT test on three groups of TXDOT trucks in San Antonio. The Electrical Engineering Department of Texas Tech University in Lubbock also did additional tests on TXDOT vehicles. All the tests were done outdoors and in Lubbock the testing place is at 23 miles north of Texas Tech University. TXDOT project could be separated into two parts: the whole-vehicle tests and some auxiliary laboratory tests. This thesis only investigates the whole-vehicle tests. The laboratory tests will be discussed in another graduate student's thesis.

Chapter II investigates the data from SwRI and makes a few comparisons. Chapter III analyses the narrow-band noise data, which was scanned in Lubbock. Chapter IV gives the proposed changes of the SAE limits and discusses the additional tests done in Lubbock to validate these changes. In this chapter we also investigate the test procedures of both tests and make some additional comparisons. Chapter V reports the conclusions for the TXDOT project.

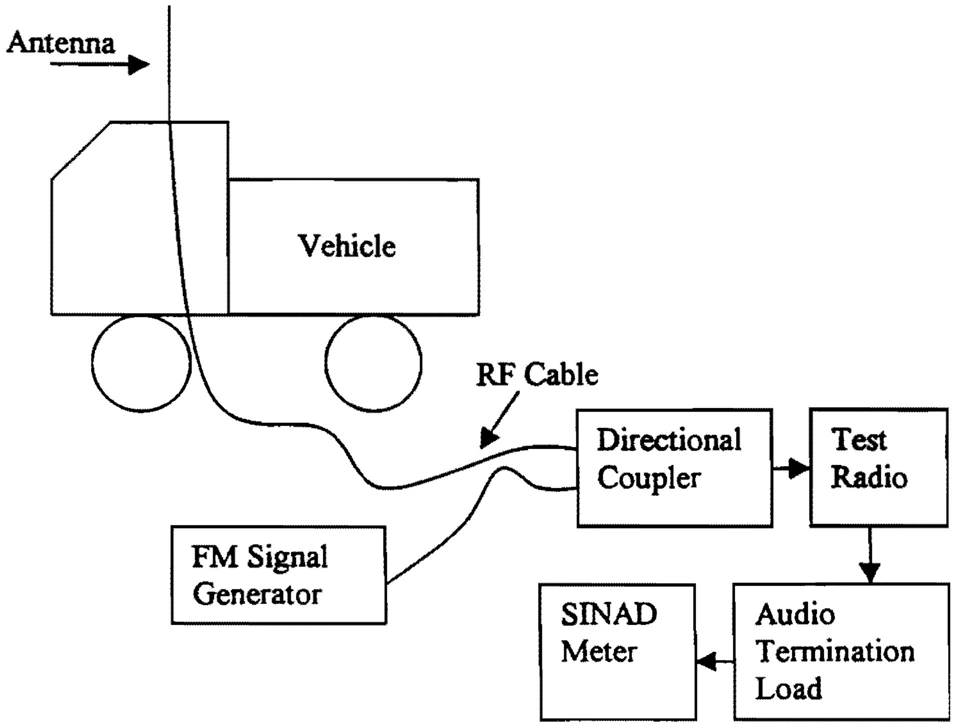


Figure 1.1 Equipment Setup of the TEX-899-B Test

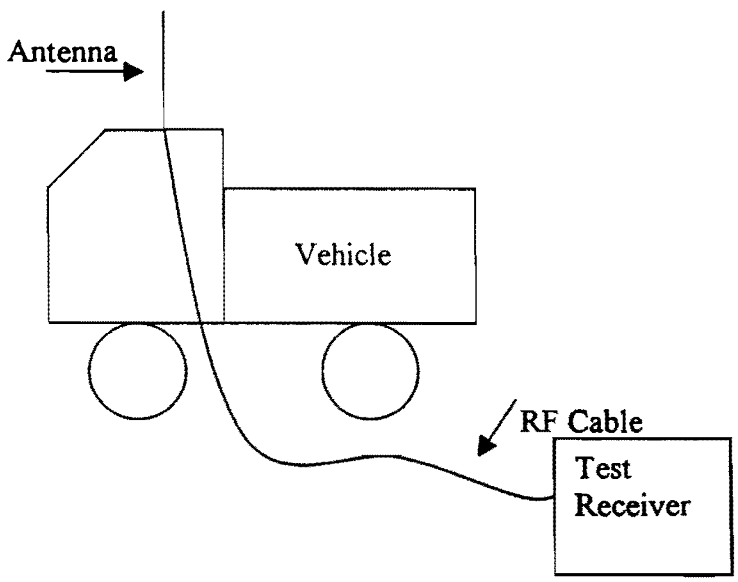


Figure 1.2 Equipment Setup of the SAE J551/4 Test

CHAPTER II

ANALYSIS OF SwRI DATA

Introduction to the Tests at SwRI

Both the SAE test and the TXDOT test were done at SwRI. Several noise sources, which included ignition noise, fuel pump noise, wiper noise, and HVAC noise, were used in both tests. In doing the TXDOT test, the radio used at SwRI was Motorola Maratrac#2. The tests were done with the radio noise blanker circuit switched on and switched off. Only two frequencies (47.02 MHz and 47.18 MHz) were chosen for the tests. A complete list of TXDOT low-band VHF frequencies is contained in Appendix C. Three groups of TXDOT trucks were tested. Each group included a Chevrolet (S10), a Ford (F150), and a Dodge (Ram1500) truck.

A few comparisons were made to investigate both tests. These comparisons are useful to get more information about the two tests, propose new test limits, and change the test procedures.

Comparisons of the Same Brands of Vehicles

Table 2.1 through Table 2.4 demonstrate a comparison of the TXDOT test results for the three groups of the same brand vehicle. In these tables the term "Effective Radio Sensitivity" is the signal level corresponding to the ambient noise from the antenna at 12-dB SINAD. "EI" means engine idle and "HVAC" means heating, ventilation, and air conditioning. In order to reduce the noises from the Dodge trucks, filters had been installed in the trucks. So the Dodge trucks were tested in both "Filters Installed" and "Filters Removed" conditions. From the tables, the standard deviation of most results of the same brand vehicle is less than 2 dB and all the trucks passed the TXDOT test if the noise blanker was turned on. Table 2.5 through Table 2.8 present a comparison of the SAE test results for the broad-band peak level of the same brand vehicle, since all the noise was identified as broad-band noise. The term "Baseline" means the ambient noise level. From the table, we can see that the engine noise (EI) is the most important noise from the vehicle. All the vehicles could not pass the SAE test under the engine idle condition. The noise levels from other noise sources, such as fuel pump noise, wipers noise, HAVC fan noise, and flashers noise, are much lower. But the standard deviations of these noise levels are much larger than for the engine noise level. That means the amplitude of these noise sources changes a lot (3-7 dB) from truck to truck.

Table 2.1 TEX-899-B, Comparison of the Same Brand Vehicle (Chevrolet)

FM Signal for 12-dB SINAD (Unit: dB µV)																				
Test Frequency	47.02 MHz										47.18 MHz									
Noise Blanker	On					Off					On					Off				
Group	1	2	3	AVG	STD	1	2	3	AVG	STD	1	2	3	AVG	STD	1	2	3	AVG	STD
Radio Sensitivity	-13.1	-13.0	-12.9	-	-	-13.1	-13.0	-12.9	-	-	-13.0	-12.8	-12.9	-	-	-13.0	-12.8	-12.9	-	-
Effective Radio Sensitivity	-6.5	-8.0	-7.2	-	-	-6.5	-8.0	-7.2	-	-	-6.9	-7.7	-7.2	-	-	-6.9	-7.7	-7.2	-	-
Ignition On	-6.5	-7.8	-7.2	-7.2	0.7	-6.2	-7.4	-7.1	-6.9	0.6	-6.7	-7.7	-7.2	-7.2	0.5	-6.9	-7.8	-7.3	-7.3	0.5
Fuel Pump On	-5.9	-7.0	-6.9	-6.6	0.6	-6.0	-5.3	-4.0	-5.1	1.0	-6.6	-7.3	-7.0	-7.0	0.4	-6.4	-4.3	-4.0	-4.9	1.3
EI	-5.8	-6.6	-5.3	-5.9	0.7	-3.6	-3.2	-2.4	-3.1	0.6	-5.6	-6.8	-6.0	-6.1	0.6	-3.4	-1.9	-2.6	-2.6	0.8
EI, Wipers High	-5.4	-6.0	-5.1	-5.5	0.5	-3.5	-1.2	-0.9	-1.9	1.4	-5.5	-6.5	-5.7	-5.9	0.5	-3.0	-1.9	-2.5	-2.5	0.6
EI, HVAC Fan High	-4.3	-5.2	-5.4	-5.0	0.6	-0.8	-1.4	-1.9	-1.4	0.6	-4.6	-5.8	-5.8	-5.4	0.7	-0.6	-1.0	-2.4	-1.3	0.9
EI, Wipers/HVAC High	-4.3	-4.8	-5.2	-4.8	0.5	-0.8	-1.1	-0.7	-0.9	0.2	-4.6	-5.2	-5.4	-5.1	0.4	-0.6	-0.4	-2.4	-1.1	1.1
Wipers High	-6.0	-7.0	-5.9	-6.3	0.6	-6.1	-6.8	-3.6	-5.5	1.7	-6.5	-7.5	-7.1	-7.0	0.5	-6.2	-7.0	-6.5	-6.6	0.4
HVAC Fan High	-5.8	-6.7	-6.2	-6.2	0.5	-4.0	-6.1	-4.3	-4.8	1.1	-6.2	-7.1	-7.2	-6.8	0.6	-4.2	-6.3	-6.5	-5.7	1.2

Note: AVG = Average, STD = Standard Deviation.

TXDOT Test Limit: 0 dB µV.

Table 2.2 TEX-899-B, Comparison of the Same Brand Vehicle (Ford)

FM Signal for 12-dB SINAD (Unit: dB μV)																				
Test Frequency	47.02 MHz										47.18 MHz									
Noise Blanker	On					Off					On					Off				
Group	1	2	3	AVG	STD	1	2	3	AVG	STD	1	2	3	AVG	STD	1	2	3	AVG	STD
Radio Sensitivity	-13.0	-13.1	-13.3	-	-	-13.0	-13.1	-13.3	-	-	-13.1	-13.0	-13.2	-	-	-13.1	-13.0	-13.2	-	-
Effective Radio Sensitivity	-6.2	-7.5	-7.3	-	-	-6.2	-7.5	-7.3	-	-	-6.1	-8.3	-8.5	-	-	-6.1	-8.3	-8.5	-	-
Ignition On	-6.2	-7.5	-7.3	-7.0	0.7	-5.8	-7.4	-7.6	-6.9	1.0	-5.8	-8.3	-8.5	-7.5	1.5	-5.8	-8.2	-8.4	-7.5	1.4
Fuel Pump On	-6.2	-7.5	-7.3	-7.0	0.7	-6.2	-7.4	-7.6	-7.1	0.8	-5.7	-8.3	-8.4	-7.5	1.5	-5.3	-8.2	-8.4	-7.3	1.7
EI	-5.8	-6.2	-7.1	-6.4	0.7	-4.0	-5.2	-6.4	-5.2	1.2	-5.8	-7.3	-8.0	-7.0	1.1	-3.1	-5.8	-6.7	-5.2	1.9
EI, Wipers High	-4.4	-5.6	-6.3	-5.4	1.0	-1.7	-3.8	-5.5	-3.7	1.9	-5.2	-6.9	-7.8	-6.6	1.3	-2.1	-3.6	-5.1	-3.6	1.5
EI, HVAC Fan High	-3.5	-4.5	-4.9	-4.3	0.7	4.3	1.0	2.7	2.7	1.7	-3.4	-6.5	-7.8	-5.9	2.2	5.6	0.7	-3.3	1.0	4.6
EI, Wipers/HVAC High	-3.5	-4.1	-3.6	-3.7	0.3	4.4	1.0	2.7	2.7	1.7	-3.4	-5.8	-7.1	-5.4	1.9	5.6	1.0	1.4	2.7	2.5
Wipers High	-5.4	-6.3	-6.9	-6.2	0.8	-4.6	-6.6	-6.6	-5.9	1.2	-5.3	-6.8	-8.0	-6.7	1.4	-4.7	-6.5	-7.3	-6.2	1.3
HVAC Fan High	-5.3	-6.2	-6.7	-6.1	0.7	-3.1	-0.3	-0.7	-1.4	1.5	-5.0	-5.9	-7.6	-6.2	1.3	2.1	-0.5	-4.9	-1.1	3.5

Note: AVG = Average, STD = Standard Deviation.

TXDOT Test Limit: 0 dB μV.

Table 2.3 TEX-899-B, Comparison of the Same Brand Vehicle (Dodge, Filters Installed)

FM Signal for 12-dB SINAD (Unit: dB μV)																				
Test Frequency	47.02 MHz										47.18 MHz									
Noise Blanker	On					Off					On					Off				
Group	1	2	3	AVG	STD	1	2	3	AVG	STD	1	2	3	AVG	STD	1	2	3	AVG	STD
Radio Sensitivity	-13.3	-13.2	-13.1	-	-	-13.3	-13.2	-13.1	-	-	-13.2	-13.1	-12.9	-	-	-13.2	-13.1	-12.9	-	-
Effective Radio Sensitivity	-7.2	-7.8	-7.1	-	-	-7.2	-7.8	-7.1	-	-	-6.4	-8.1	-7.1	-	-	-6.4	-8.1	-7.1	-	-
Ignition On	-6.8	-6.2	-7.0	-6.7	0.4	-6.9	-7.1	-7.1	-7.0	0.1	-6.4	-6.9	-7.1	-6.8	0.4	-6.8	-7.5	-6.9	-7.1	0.4
Fuel Pump On	-6.7	-5.5	-6.1	-6.1	0.6	-5.3	0.3	-4.7	-3.2	3.0	-5.6	-6.2	-5.9	-5.9	0.3	1.5	1.6	-4.7	-0.5	3.6
EI	-4.9	-3.5	-4.8	-4.4	0.8	6.6	4.6	4.1	5.1	1.3	-4.1	-3.3	-4.9	-4.1	0.8	7.5	5.1	5.1	5.9	1.4
EI, Wipers High	-4.2	-3.5	-4.3	-4.0	0.4	7.3	4.6	4.3	5.4	1.6	-3.7	-3.3	-5.5	-4.2	1.1	7.5	6.2	5.1	6.3	1.2
EI, HVAC Fan High	-4.1	-3.5	-2.9	-4.0	0.6	7.3	5.3	6.6	6.4	1.0	-3.5	-3.4	-3.8	-3.6	0.2	7.5	7.4	7.2	7.4	0.2
EI, Wipers/HVAC High	-3.8	-3.4	-4.3	-3.4	0.5	7.3	5.3	6.6	6.4	1.0	-3.5	-3.0	-3.6	-3.4	0.3	7.7	7.5	7.2	7.5	0.3
Wipers High	-6.4	-6.6	-6.5	-5.8	0.1	-5.6	-6.2	-6.5	-6.1	0.5	-5.9	-5.3	-6.5	-5.9	0.6	-6.1	-5.9	-6.6	-6.2	0.4
HVAC Fan High	-6.1	-6.1	-5.8	-6.2	0.2	-4.3	-5.7	-0.4	-3.5	2.7	-5.9	-5.4	-5.7	-5.7	0.3	-0.4	-5.7	-4.0	-3.4	2.7

Note: AVG = Average, STD = Standard Deviation.

TXDOT Test Limit: 0 dB μV.

Table 2.4 TEX-899-B, Comparison of the Same Brand Vehicle (Dodge, Filters Removed)

FM Signal for 12-dB SINAD (Unit: dB μV)																				
Test Frequency	47.02 MHz										47.18 MHz									
Noise Blanker	On					Off					On					Off				
Group	1	2	3	AVG	STD	1	2	3	AVG	STD	1	2	3	AVG	STD	1	2	3	AVG	STD
Radio Sensitivity	-13.3	-13.2	-12.9	-	-	-13.3	-13.2	-12.9	-	-	-13.2	-13.0	-12.9	-	-	-13.2	-13.2	-12.9	-	-
Effective Radio Sensitivity	-7.2	-7.7	-7.6	-	-	-7.2	-7.7	-7.6	-	-	-7.1	-7.6	-7.7	-	-	-7.1	-7.6	-7.7	-	-
Ignition On	-6.5	-7.5	-7.2	-7.1	0.5	-6.5	-7.4	-7.2	-7.0	0.5	-7.1	-7.1	-7.7	-7.3	0.3	-6.5	-7.1	-7.6	-7.1	0.6
Fuel Pump On	-5.9	-4.1	-6.2	-5.4	1.1	-2.0	2.0	2.1	0.7	2.3	-6.1	-4.5	-6.3	-5.6	1.0	2.2	1.1	2.0	1.8	0.6
EI	-3.9	-2.7	-4.9	-3.8	1.1	7.1	7.0	6.2	6.8	0.5	-4.5	-3.1	-5.5	-4.4	1.2	7.0	7.0	6.3	6.8	0.4
EI, Wipers High	-4.2	-2.7	-4.8	-3.9	1.1	8.5	6.9	5.8	7.1	1.4	-4.2	-3.1	-5.5	-4.3	1.2	7.0	7.4	6.3	6.9	0.6
EI, HVAC Fan High	-2.6	-2.7	-3.8	-3.4	0.7	8.5	7.0	6.9	7.5	0.9	-3.8	-3.1	-4.1	-3.7	0.5	7.0	7.6	6.7	7.1	0.5
EI, Wipers/HVAC High	-2.7	-2.3	-3.7	-2.9	0.7	8.7	7.0	6.9	7.5	1.0	-3.9	-3.1	-4.1	-3.7	0.5	7.4	8.1	6.6	7.4	0.8
Wipers High	-6.5	-6.7	-7.2	-5.6	0.4	-5.6	-7.2	-6.6	-6.5	0.8	-6.6	-6.7	-7.6	-7.0	0.6	-5.9	-7.0	-7.1	-6.7	0.7
HVAC Fan High	-6.0	-6.3	-6.6	-6.5	0.3	0.7	-3.2	-4.8	-2.4	2.8	-5.9	-7.2	-6.9	-6.7	0.7	0.8	-6.6	-3.6	-3.1	3.7

Note: AVG = Average, STD = Standard Deviation.

TXDOT Test Limit: 0 dB μV.

Table 2.5 SAE J551/4, Comparison of the Same Brand Vehicle (Chevrolet)

Broad-Band Peak Level (Unit: dB μV)										
Frequency	47.02 MHz					47.18 MHz				
Group	1	2	3	AVG	STD	1	2	3	AVG	STD
Baseline	12.0	13.0	12.0	-	-	12.0	8.0	12.0	-	-
Fuel Pump On	16.0	28.0	27.0	23.7	6.7	14.0	18.0	27.0	19.7	6.7
Fuel Pump and Ignition On	17.0	30.0	27.0	24.7	6.8	16.0	18.0	27.0	20.3	5.9
EI	44.0	48.0	46.0	46.0	2.0	47.0	46.0	47.0	46.7	0.6
EI, Wipers High	45.0	48.0	46.0	46.3	1.5	47.0	47.0	48.0	47.3	0.6
EI, HVAC Fan High	46.0	48.0	46.0	46.7	1.2	47.0	46.0	47.0	46.7	0.6
EI, Flashers On	46.0	48.0	47.0	47.0	1.0	47.0	47.0	47.0	47.0	0.0
Wipers High	18.0	24.0	29.0	23.7	5.5	18.0	18.0	30.0	22.0	6.9
Fan High	19.0	22.0	16.0	19.0	3.0	19.0	16.0	15.0	16.7	2.1
All	46.0	48.0	47.0	47.0	1.0	47.0	47.0	47.0	47.0	0.0

Note: AVG = Average, STD = Standard Deviation.

SAE Broad-Band Limit: 28 dB μV

Table 2.6 SAE J551/4, Comparison of the Same Brand Vehicle (Ford)

Broad-Band Peak Level (Unit: dB μV)										
Frequency	47.02 MHz					47.18 MHz				
Group	1	2	3	AVG	STD	1	2	3	AVG	STD
Baseline	13.0	10.0	8.0	-	-	13.0	8.0	8.0	-	-
Fuel Pump On	15.0	13.0	12.0	13.3	1.5	13.0	14.0	12.0	13.0	1.0
Fuel Pump and Ignition On	16.0	14.0	12.0	14.0	2.0	13.0	14.0	12.0	13.0	1.0
EI	31.0	35.0	30.0	32.0	2.6	31.0	35.0	30.0	32.0	2.6
EI, Wipers High	31.0	35.0	30.0	32.0	2.6	32.0	37.0	30.0	33.0	3.6
EI, HVAC Fan High	36.0	37.0	33.0	35.3	2.1	36.0	35.0	30.0	33.7	3.2
EI, Flashers On	34.0	36.0	33.0	34.3	1.5	33.0	36.0	33.0	34.0	1.7
Wipers High	22.0	28.0	25.0	25.0	3.0	23.0	23.0	24.0	23.3	0.6
Fan High	31.0	30.0	26.0	29.0	2.6	32.0	27.0	23.0	27.3	4.5
All	34.0	37.0	33.0	34.7	2.1	46.0	37.0	33.0	38.7	6.7

Note: AVG = Average, STD = Standard Deviation.

SAE Broad-Band Limit: 28 dB μV

Table 2.7 SAE J551/4, Comparison of the Same Brand Vehicle (Dodge, Filters Installed)

Broad-Band Peak Level (Unit: dB μV)										
Frequency	47.02 MHz					47.18 MHz				
Group	1	2	3	AVG	STD	1	2	3	AVG	STD
Baseline	13.0	14.0	12.0	-	-	11.0	12.0	10.0	-	-
Fuel Pump On	30.0	31.0	26.0	28.7	2.6	30.0	31.0	28.0	29.7	1.5
Fuel Pump and Ignition On	30.0	31.0	26.0	28.7	2.6	30.0	31.0	28.0	29.7	1.5
EI	50.0	52.0	53.0	51.0	1.5	50.0	53.0	53.0	52.0	1.7
EI, Wipers High	50.0	53.0	55.0	51.7	2.5	50.0	54.0	55.0	53.0	2.6
EI, HVAC Fan High	50.0	53.0	54.0	51.3	2.1	50.0	53.0	55.0	52.7	2.5
EI, Wipers and HVAC Fan High	50.0	54.0	55.0	51.7	2.6	50.0	54.0	55.0	53.0	2.6
EI, Flashers On	50.0	53.0	55.0	51.7	2.5	50.0	54.0	55.0	53.0	2.6
Wipers High	16.0	30.0	37.0	26.0	10.7	25.0	26.0	33.0	28.0	4.3
Fan High	28.0	23.0	31.0	29.0	4.0	28.0	22.0	27.0	25.7	3.2
Flashers On	36.0	20.0	36.0	37.3	9.2	40.0	36.0	30.0	35.3	5.0
All, Ignition only	36.0	40.0	37.0	37.7	2.1	40.0	37.0	34.0	37.0	3.0

Note: AVG = Average, STD = Standard Deviation.

SAE Broad-Band Limit: 28 dB μV

Table 2.8 SAE J551/4, Comparison of the Same Brand Vehicle (Dodge, Filters Removed)

Broad-Band Peak Level (Unit: dB µV)										
Frequency	47.02 MHz					47.18 MHz				
Group	1	2	3	AVG	STD	1	2	3	AVG	STD
Baseline	12.0	12.0	12.0	-	-	11.0	11.0	10.0	-	-
Fuel Pump On	30.0	37.0	32.0	30.7	3.6	30.0	31.0	33.0	31.3	1.5
Fuel Pump and Ignition On	30.0	37.0	32.0	31.0	3.6	31.0	31.0	33.0	31.7	1.2
EI	49.0	52.0	52.0	50.3	1.7	50.0	54.0	53.0	52.3	2.1
EI, Wipers High	50.0	52.0	52.0	50.7	1.2	50.0	54.0	54.0	52.7	2.3
EI, HVAC Fan High	50.0	52.0	52.0	50.7	1.2	50.0	54.0	54.0	52.7	2.3
EI, Wipers and HVAC Fan High	50.0	52.0	52.0	50.7	1.2	50.0	55.0	55.0	53.3	2.9
EI, Flashers On	50.0	54.0	52.0	50.7	2.0	50.0	56.0	54.0	53.3	3.1
Wipers High	21.0	21.0	38.0	27.0	9.8	22.0	26.0	34.0	27.3	6.1
Fan High	28.0	22.0	33.0	30.0	5.5	29.0	21.0	29.0	26.3	4.6
Flashers On	16.0	30.0	27.0	27.3	7.3	39.0	37.0	32.0	36.0	3.6
All, Ignition only	28.0	43.0	26.0	31.3	9.3	40.0	39.0	36.0	38.3	2.1

Note: AVG = Average, STD = Standard Deviation.

SAE Broad-Band Limit: 28 dB µV

Comparisons of the Different Brands of Vehicles

Table 2.9 shows a comparison of the broad-band peak noise level of the three different brand vehicles. According to the information in the table, we can see that the engine noise from the Dodge is the highest among the three vehicles, while the engine noise from the Ford is the lowest. The noise from other sources looks no different from vehicle to vehicle, except the noise from the Dodge is a little higher than the noise from the others.

Table 2.10 presents a comparison of the signal level for 12-dB SINAD for the different vehicles. The table shows that if the noise blanker is turned on, the signal levels of the three vehicles are almost the same. One reason is that the noise level is nearly as low as the ambient noise level. Another reason could be that the noise blanker reduced all the noise to the same low level. When the noise blanker was turned off, we also got the same conclusion as in the SAE test: the noise from the Dodge is the highest while the noise from the other two vehicles is almost the same.

Table 2.9 SAE J551/4, Comparison of the Different Vehicles

Broad-band Peak Level (Unit: dB μV)				
Noise Source	Chevrolet	Ford	Dodge (Filters Installed)	Dodge (Filters Removed)
EI	45-50	30-40	50-55	50-55
Wipers	20-30	20-30	15-40	20-40
HVAC Fan	15-25	20-30	20-30	20-35
Fuel Pump	15-30	10-15	25-30	30-40
Flashers	-	-	20-40	15-40

Table 2.10 TEX-899-B, Comparison of Different Vehicles

Signal Level for 12-dB SINAD (Unit: dB μV)					
Noise Blanker	Noise Source	Chevrolet	Ford	Dodge(Filters Installed)	Dodge(Filters Removed)
On	EI	-6~-4	-8~-3	-5~-3	-5~-3
	Wipers	-7~-6	-8~-5	-7~-5	-7~-6
	HVAC Fan	-7~-6	-7~-6	-6~-5	-7~-6
	Fuel Pump	-7~-6	-7~-6	-7~-5	-6~-4
Off	EI	-4~0	-6~6	4~8	6~9
	Wipers	-7~-3	-7~-5	-7~-5	-7~-5
	HVAC Fan	-6~-4	-5~3	-6~0	-6~1
	Fuel Pump	-6~-4	-8~-5	-6~2	-2~2

A Comparison between Noise Blanker On and Noise Blanker Off

The noise blanker of a radio is used to reduce the ignition noise received by the radio. Figure 2.1 through Figure 2.4 show the signal increase with the noise blanker off. From the data sheet in Table 2.1 through Table 2.4 we can conclude that all of the vehicles passed the TXDOT test with the noise blanker turned on. The four figures demonstrate that the noise blanker reduces the high level noise, engine noise, from 4 dB (Chevrolet) to 12 dB (Dodge), which means the noise blanker is very effective in reducing the engine noise. Actually from Table 2.1 through Table 2.4 we find that most vehicles could not pass the TEX-899-B test under "EI" condition when the noise blanker was turned off. For the low-level noise, such as wiper noise, the effect of the noise blanker is not so obvious because the noise level is as low as the ambient noise level.

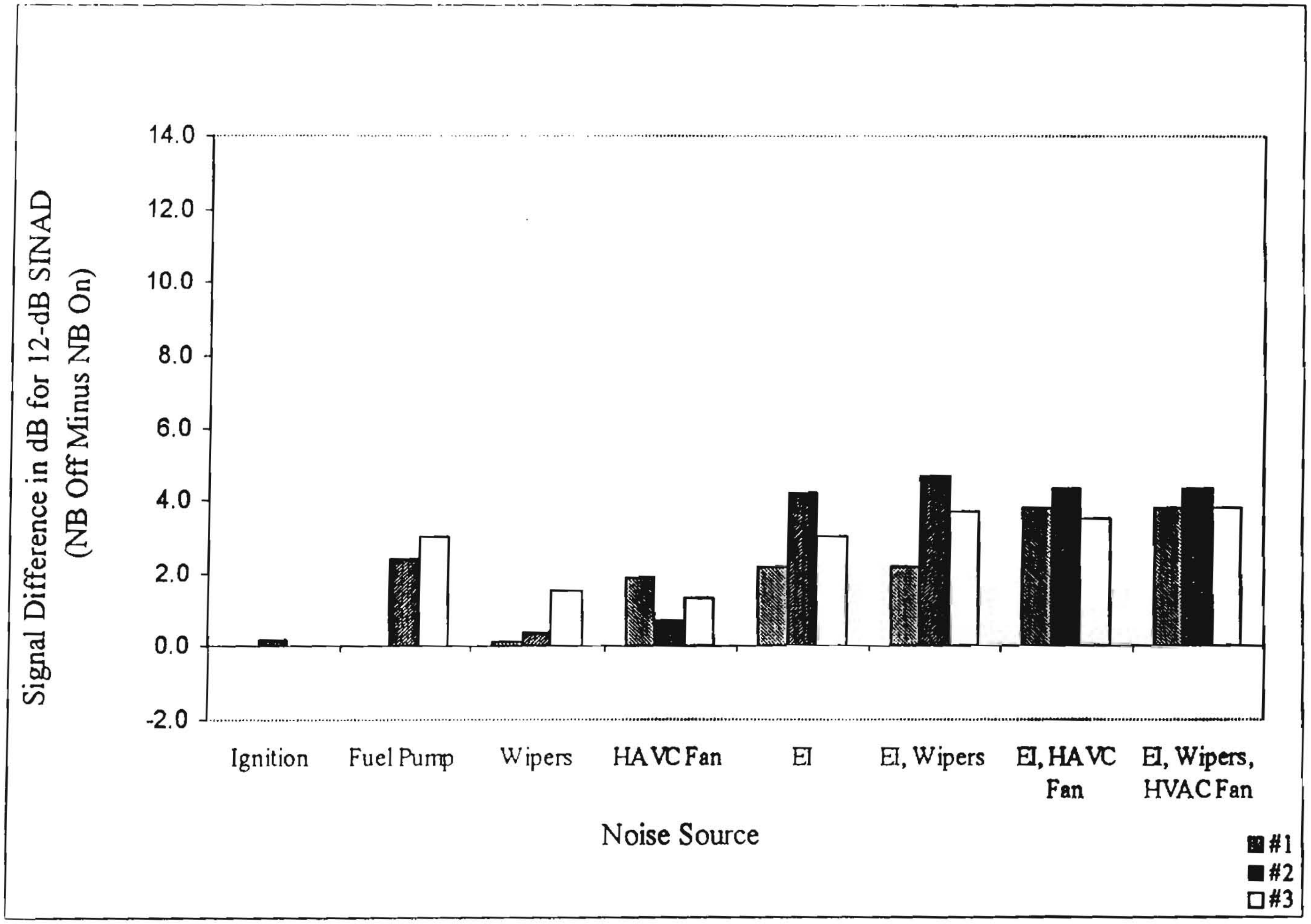


Figure 2.1 TEX-899-B, Signal Increase with Noise Blanker Off (Chevrolet, Unit: dB µV)

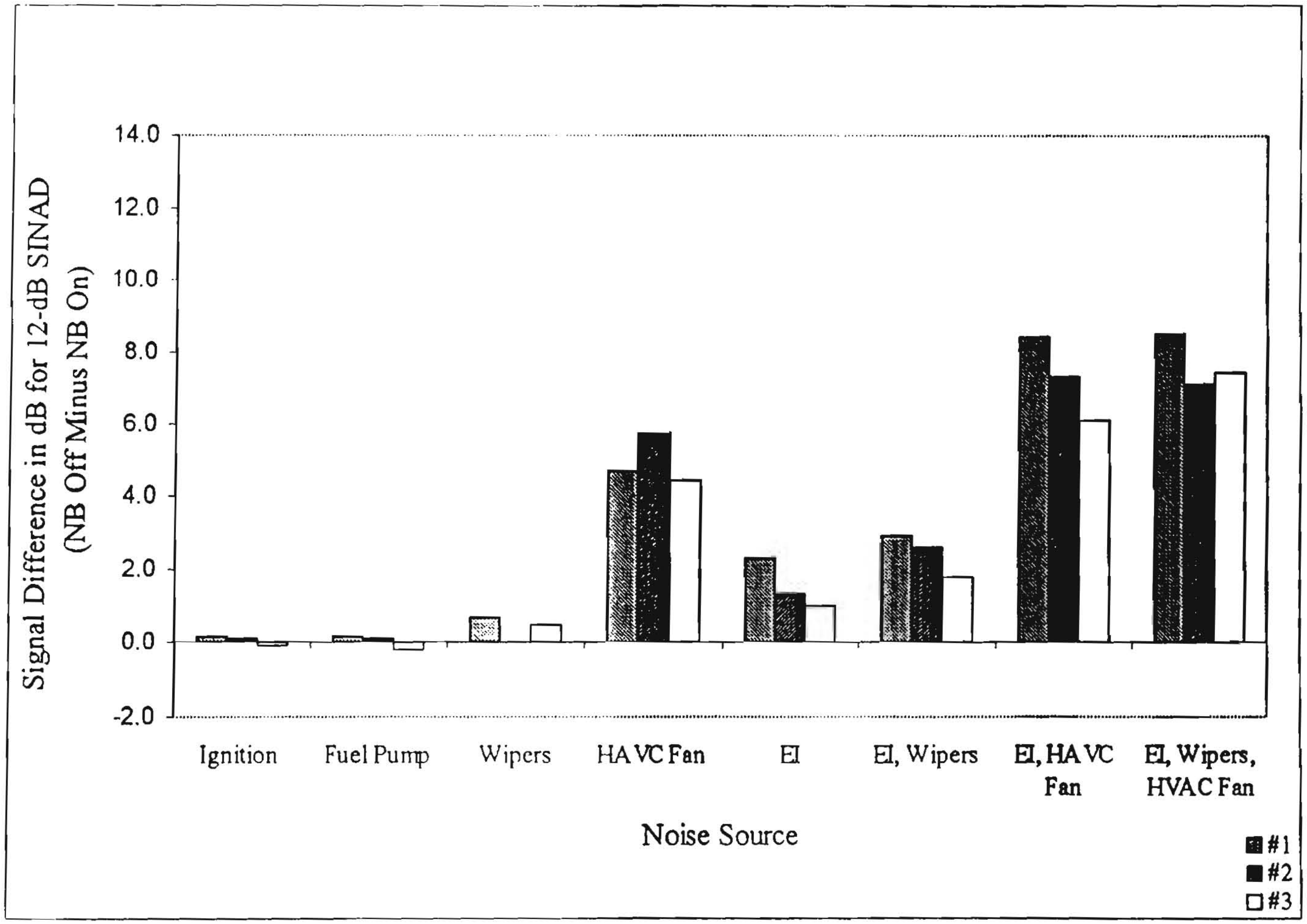


Figure 2.2 TEX-899-B, Signal Increase with Noise Blanker Off (Ford, Unit: dB μV)

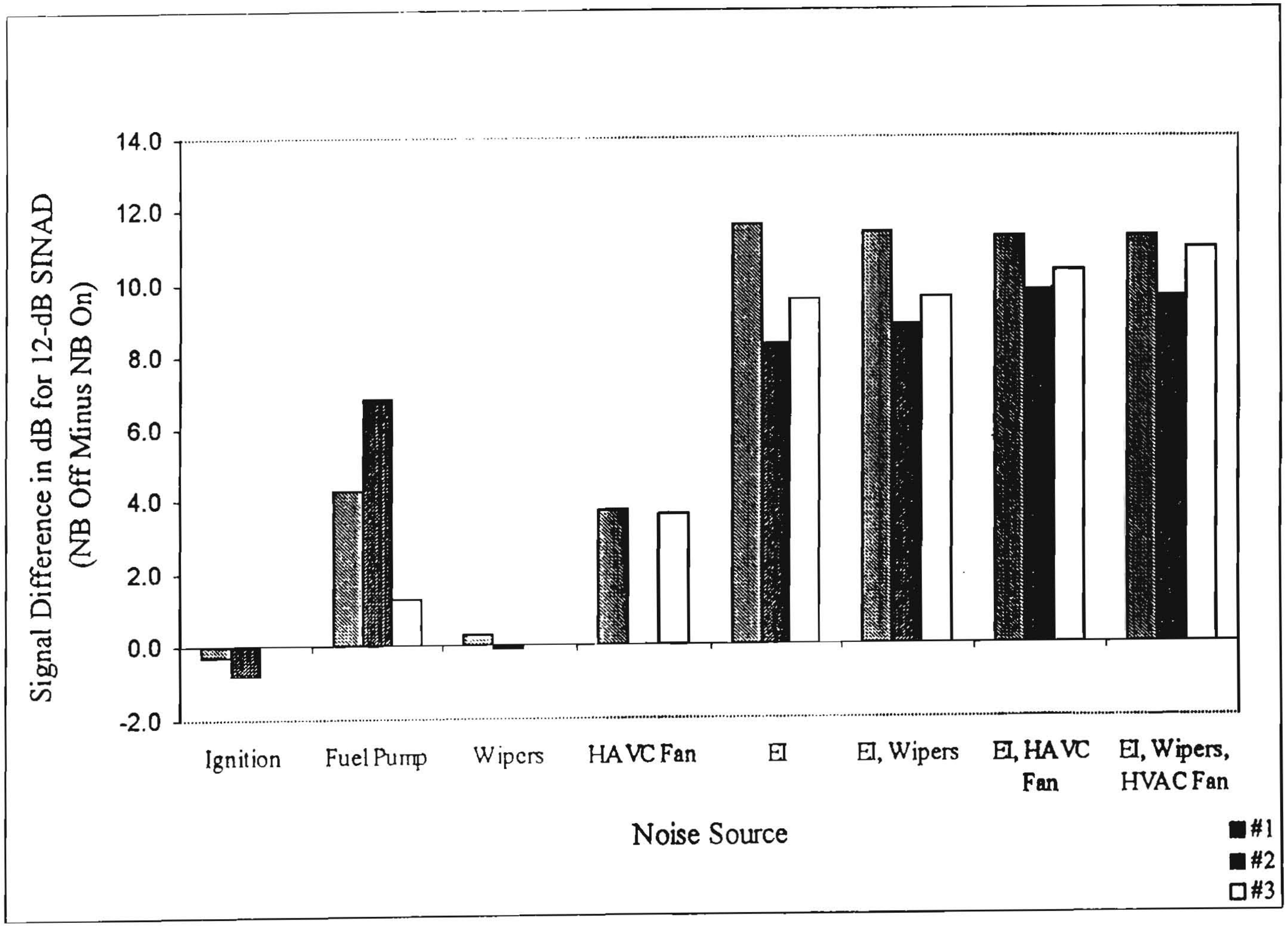


Figure 2.3 TEX-899-B, Signal Increase with Noise Blanker Off (Dodge, Filters Installed, Unit: dB μV)

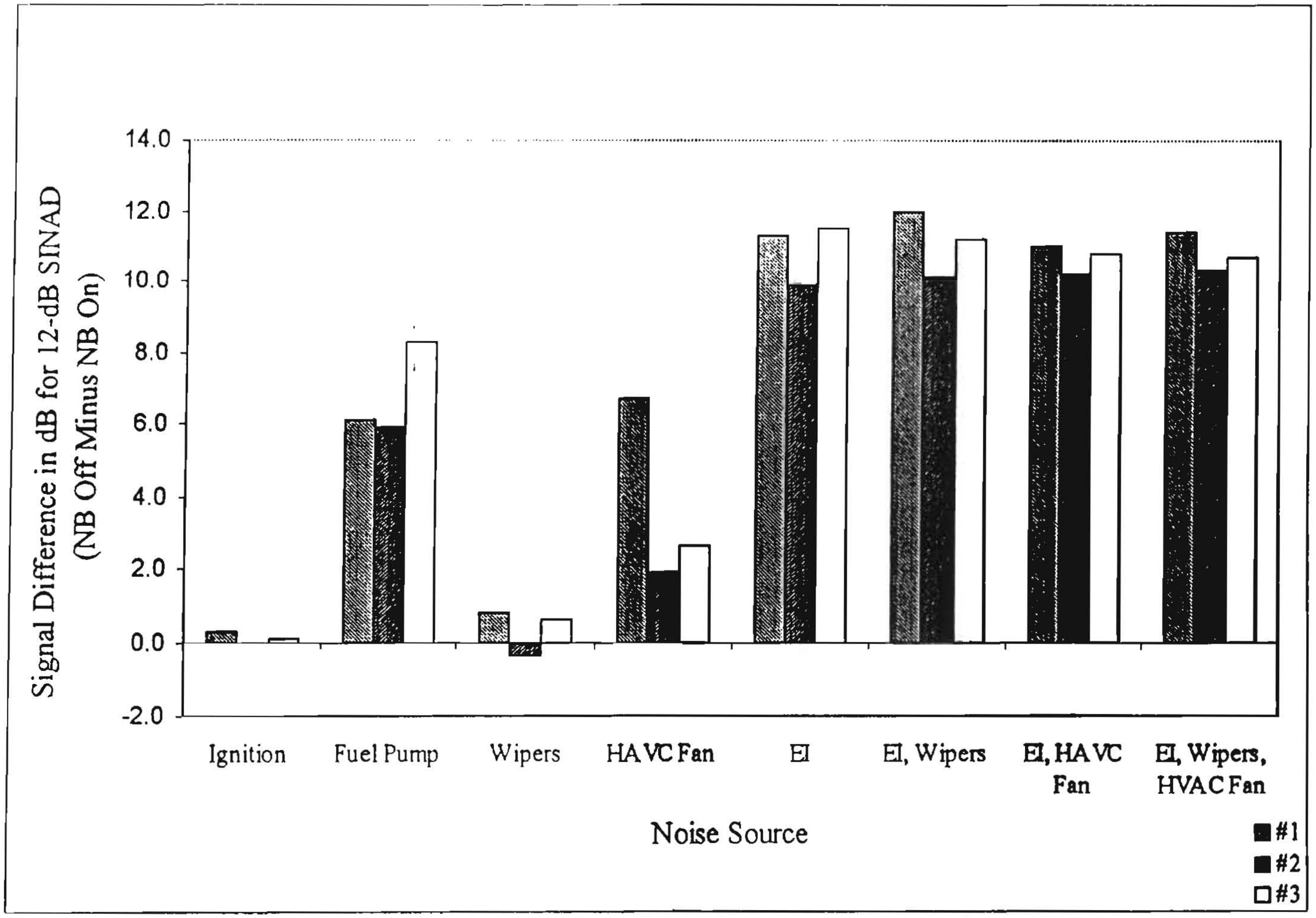


Figure 2.4 TEX-899-B, Signal Increase with Noise Blanker Off (Dodge, Filters Removed, Unit: dB µV)

Comparisons between Filters Installed and Filters Removed

In order to reduce the noise amplitude from the fuel pump and the HVAC fan, two filters were installed by TXDOT. Figure 2.5 and Figure 2.6 show the signal increase with filters removed in the TXDOT test under the "Fuel Pump On Only" and the "HAVC Fan On Only" conditions. From these two figures we can see that when the noise blanker was turned on, the signal level of the test changed very little whether the filters were installed or not. The reason could be that the noise from the two sources is almost as low as the ambient. If noise blanker was turned off, from Figure 2.6 we can conclude that the filters are effective only on some vehicles. In the #2 vehicle, the filters are not effective.

Figure 2.7 shows the noise increase with filters removed in the SAE test. The same conclusion can be made as the TXDOT test: the filters are only effective in reducing noise for some of the vehicles.

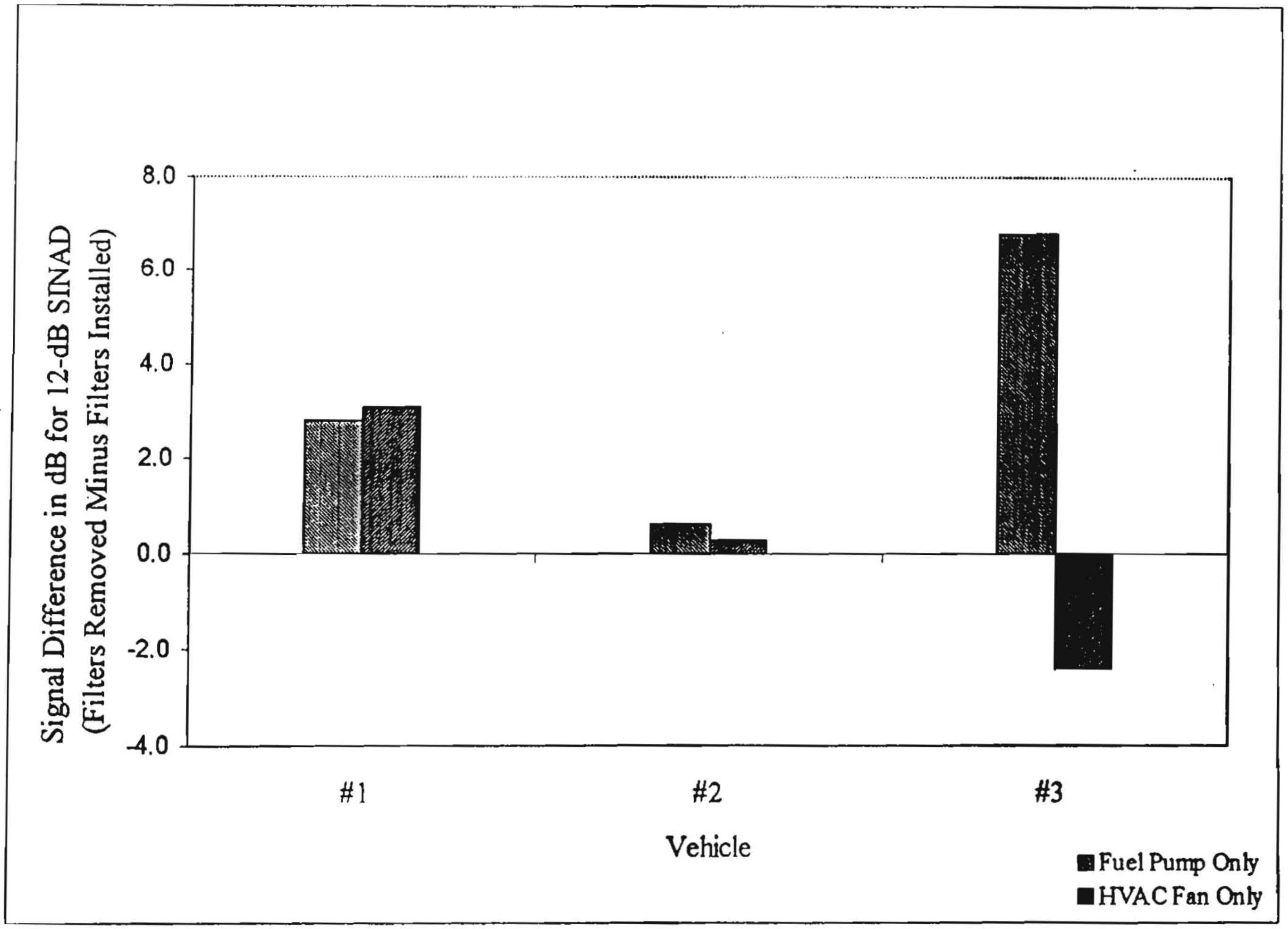


Figure 2.6 Tex-899-B, Signal Increase with Filters Removed
(Dodge, Noise Blanker Off, Unit: dB μV)

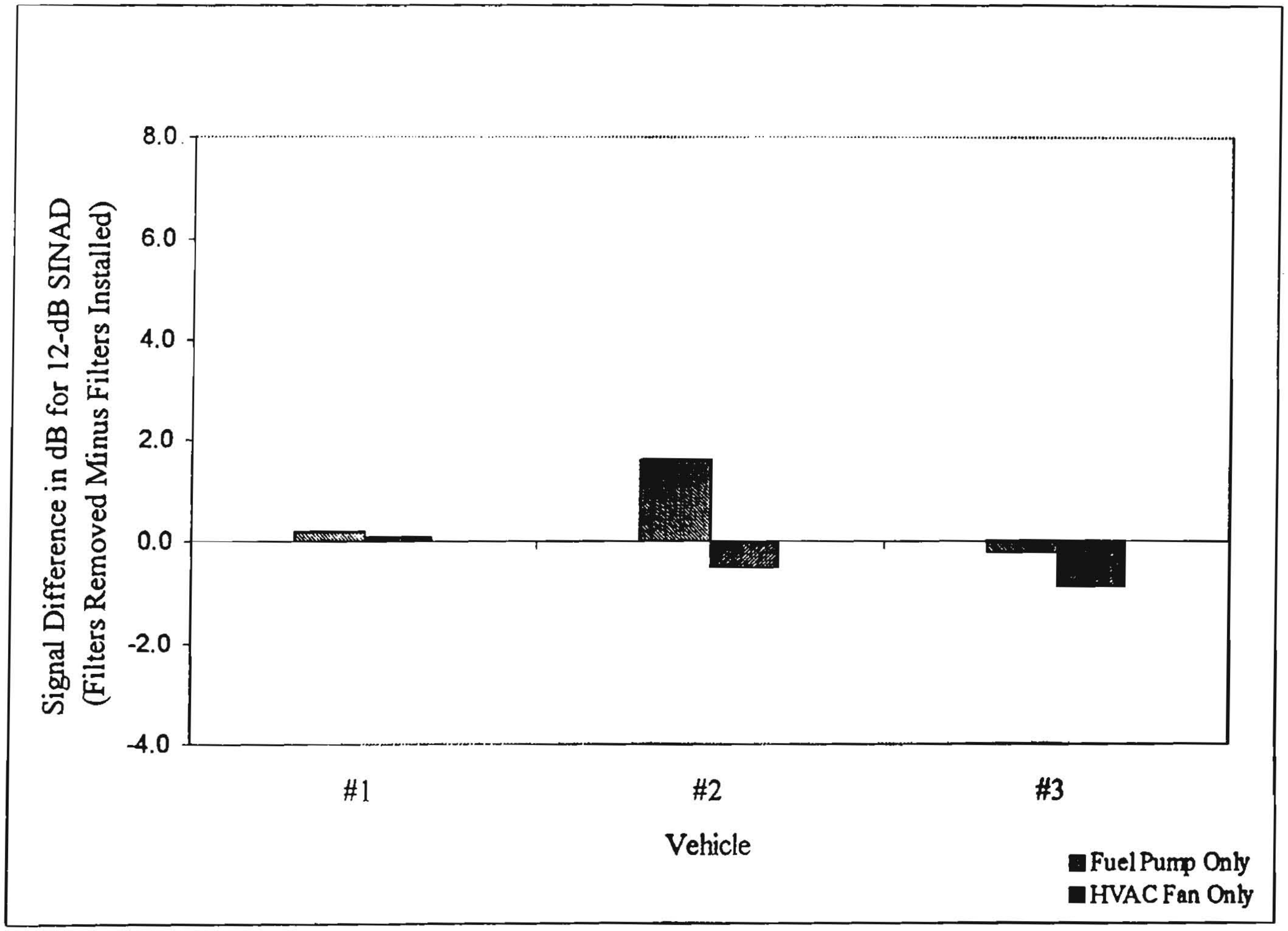


Figure 2.5 Tex-899-B, Signal Increase with Filters Removed
(Dodge, Noise Blanker On, Unit: dB μV)

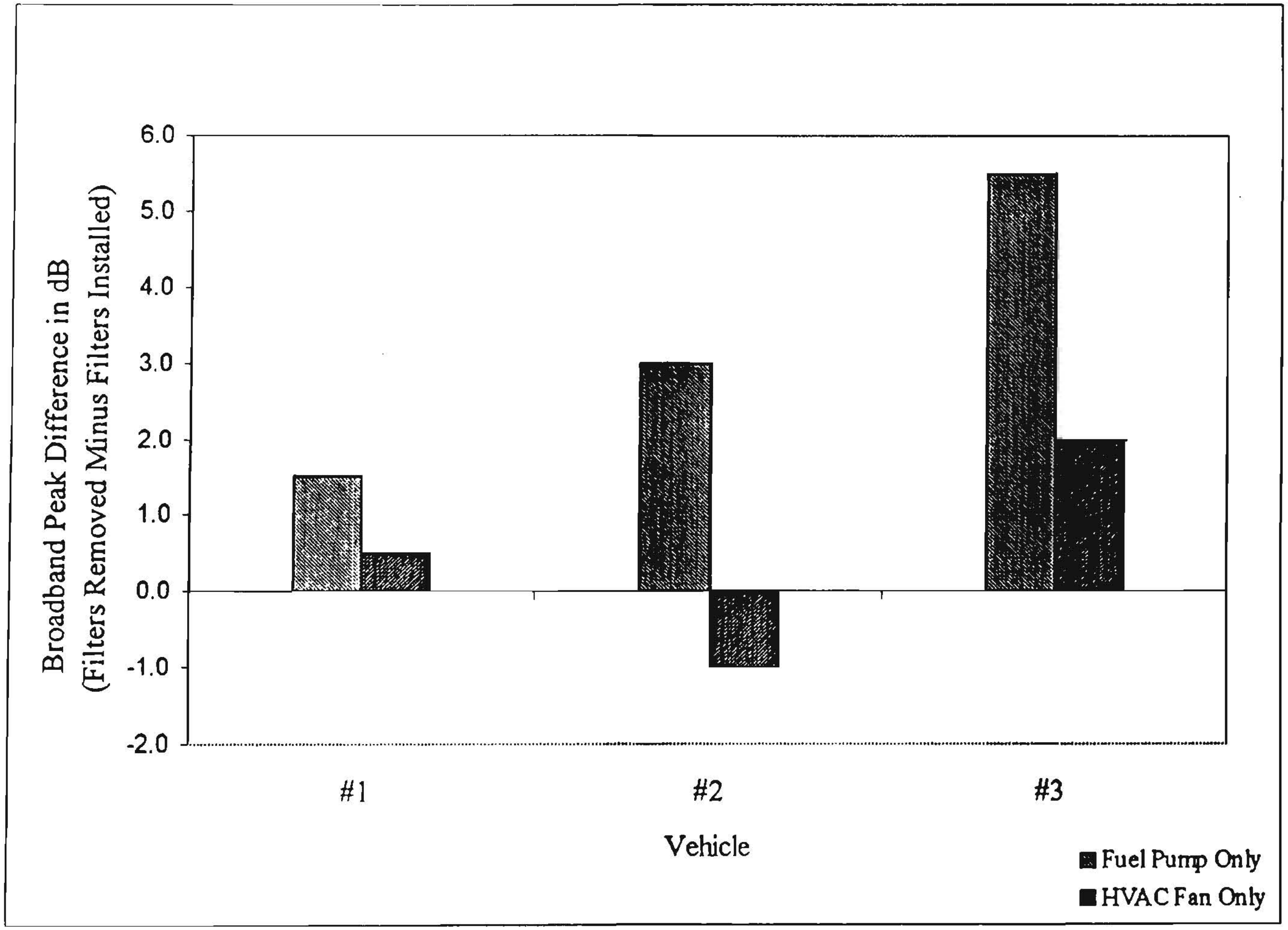


Figure 2.7 SAE J551/4, Noise Increase with Filters Removed
(Dodge, Unit: dB μV)

A Comparison of the Installed Radio and the Installed Antenna with the External Radio and the MM Antenna

From the test procedures of the TEX-899-B test, the radio should be 10 feet away from the vehicle, but when in service, the radio is always installed inside the vehicle. Also for the test, a temporary magnetic-mount (MM) antenna is used rather than a permanently installed one. Table 2.11 shows the comparison between the installed radio and the installed antenna with the external radio and the MM antenna. From the table, we can see that there is no significant difference between the two antennas when the noise blanker was turned on. And there is a few dB difference in the "Fan only" case when the noise blanker was turned off. Figure 2.8 shows the equivalent circuits of the MM antenna and the installed antenna. There is a capacitor between the MM antenna and the vehicle's roof while the installed antenna connects directly to the vehicle's body.

Table 2.11 TEX-899-B, Comparison of The Installed Radio and The Installed Antenna With The External Radio and The MM Antenna (Unit: dB μV)

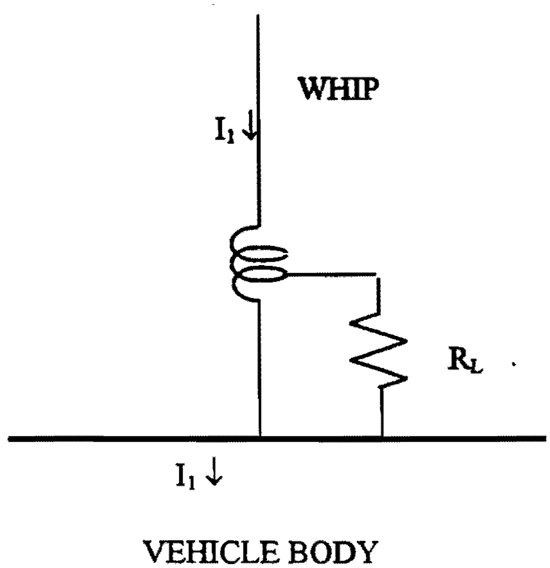
Noise Blanker	On					Off				
Filters	Installed		Removed			Installed		Removed		
Radio type	E	I	E	I	Avg. of E - I	E	I	E	I	Avg. of E - I
Radio Sensitivity	-13.3	-13.1	-13.3	-13.3	-0.1	-13.3	-13.1	-13.3	-13.3	-0.1
Effective Radio Sensitivity	-7.2	-7.5	-7.2	-7.7	0.4	-7.2	-7.5	-7.2	-7.7	0.4
Ignition On	-6.8	-7.0	-6.5	-6.5	0.1	-6.9	-7.0	-6.5	-6.7	0.2
Fuel Pump On	-6.7	-5.9	-5.9	-5.8	-0.5	-5.3	-4.2	-2.0	-0.5	-1.3
EI	-4.9	-4.1	-3.9	-4.0	-0.4	6.6	6.0	7.1	7.1	0.3
EI, Wipers High	-4.2	-3.8	-4.2	-3.9	-0.4	7.3	6.3	8.5	7.5	1.0
EI, Fan High	-4.1	-3.3	-2.6	-1.8	-0.8	7.3	9.0	8.5	11.0	-2.1
EI, Wipers and Fan	-2.8	-3.3	-2.7	-1.8	-0.2	7.3	9.3	8.7	11.0	-2.2
Wipper only	-6.4	-5.6	-6.5	-7.3	0.0	-5.6	-6.3	-5.4	-6.1	0.7
Fan only	-6.1	-4.7	-6.0	-4.7	-1.4	-4.3	0.8	0.7	2.0	-3.2

Note:

1.E = External Radio and MM Antenna, I = Installed Radio and Installed Antenna;

2.Vehicle: Dodge #1, Frequency: 47.02 MHz.

INSTALLED ANTENNA



MAGNETIC-MOUNT TEST ANTENNA

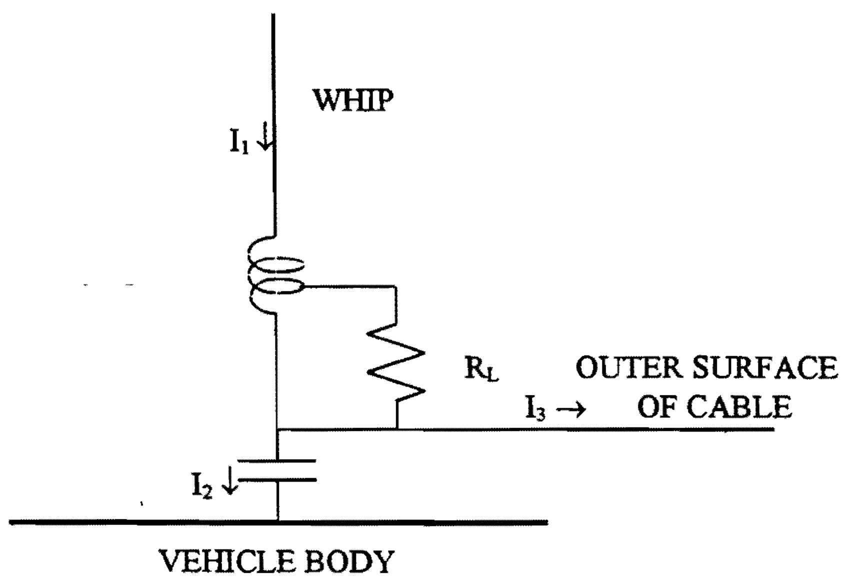


Figure 2.8 Antenna Equivalent Circuits

A Comparison of Engine Speeds

Table 2.12 demonstrates the comparison of the TXDOT test with the different engine speeds. The result shows that the noise from the engine changes little with the speed of the engine because almost all the differences are less than 2 dB.

Table 2.12 Comparison of Engine Speed

TEX-899-B, FM Signal for 12-dB SINAD (Unit: dB μV)			
Condition	EI	EI @ 1500 rpm	Difference
Chevy, NB On, 47.02 MHz	-5.3	-5.2	-0.1
Chevy, NB Off, 47.02 MHz	-2.4	-0.8	-1.6
Chevy, NB On, 47.18 MHz	-6.0	-6.6	0.6
Chevy, NB Off, 47.18 MHz	-2.6	-3.3	0.7
Ford, NB On, 47.02 MHz	-7.1	-7.0	-0.1
Ford, NB Off, 47.02 MHz	-6.4	-5.9	-0.5
Ford, NB On, 47.18 MHz	-8.0	-8.0	0.0
Ford, NB Off, 47.18 MHz	-6.7	-5.7	-1.0
Dodge, NB On, 47.02 MHz, Filters Installed	-4.8	-3.8	-1.0
Dodge, NB Off, 47.02 MHz, Filters Installed	4.1	10.1	-6.0
Dodge, NB On, 47.18 MHz, Filters Installed	-4.9	-5.2	0.3
Dodge, NB Off, 47.18 MHz, Filters Installed	5.1	8.2	-3.1
Dodge, NB On, 47.02 MHz, Filters Removed	-4.9	-3.6	-1.3
Dodge, NB Off, 47.02 MHz, Filters Removed	6.2	9.1	-2.9
Dodge, NB On, 47.18 MHz, Filters Removed	-5.5	-4.4	-1.1
Dodge, NB Off, 47.18 MHz, Filters Removed	6.3	7.8	-1.5

Note: Vehicles are all in group3.

Comparisons of the SAE Test with the TXDOT Test

Table 2.13 shows the comparison between the SAE test and the TXDOT test when the noise blanker was on. According to the table, we can see that all of the vehicles passed the TXDOT test when the noise blanker was turned on. On the other hand, for the SAE test, the vehicles only passed 44 times in a total of 170 tests. And the vehicles almost failed all of the SAE tests when the engine was idle. From these, we can conclude that the SAE test limit for the broadband noise is so low that most of the vehicles can not pass the test.

Table 2.14 shows the comparison between the SAE test and the TXDOT test when the noise blanker was off. The agreement percentage of the SAE test and TXDOT test is much larger than the agreement in Table 2.13. Table 2.15 shows a comparison of the percentage of agreement between the noise blanker on and off. The agreement of the SAE test and the TXDOT test is always higher when the noise blanker was in the off condition. But actually when the radio is used for communication by TXDOT, the noise blanker is always turned on, because the high level noise from the engine and other sources are greatly reduced by the noise blanker. In the next chapter we will give further result of the noise blanker performance.

Table 2.13 Comparison of Two Tests (Noise Blanker On)

Frequency	47.02 MHz									47.18 MHz								
Group	1			2			3			1			2			3		
Chevrolet	T	S	A	T	S	A	T	S	A	T	S	A	T	S	A	T	S	A
Fuel Pump On	+	+	y	+	-	n	+	+	y	+	+	y	+	+	y	+	+	y
EI	+	-	n	+	-	n	+	-	n	+	-	n	+	-	n	+	-	n
Engine @ 1500 rpm							+	-	n							+	-	n
EI, Wipers High	+	-	n	+	-	n	+	-	n	+	-	n	+	-	n	+	-	n
EI, Fan High	+	-	n	+	-	n	+	-	n	+	-	n	+	-	n	+	-	n
EI, Wipers and Fan High							+	-	n							+	-	n
Wipers High	+	+	y	+	+	y	+	-	n	+	+	y	+	+	y	+	-	n
Fan High	+	+	y	+	+	y	+	+	y	+	+	y	+	+	y	+	+	y
Ford	T	S	A	T	S	A	T	S	A	T	S	A	T	S	A	T	S	A
Fuel Pump On	+	+	y	+	+	y	+	+	y	+	+	y	+	+	y	+	+	y
EI	+	-	n	+	-	n	+	-	n	+	-	n	+	-	n	+	-	n
Engine @ 1500 rpm							+	-	n							+	-	n
EI, Wipers High	+	-	n	+	-	n	+	-	n	+	-	n	+	+	y	+	-	n
EI, Fan High	+	-	n	+	-	n	+	-	n	+	-	n	+	+	y	+	-	n
EI, Wipers and Fan High	+	-	n				+	-	n	+	-	n				+	-	n
Wipers High	+	+	y	+	-	n	+	+	y	+	+	y	+	+	y	+	+	y
Fan High	+	-	n	+	-	n	+	+	n	+	-	n	+	+	y	+	+	y
Dodge (Filter Installed)	T	S	A	T	S	A	T	S	A	T	S	A	T	S	A	T	S	A
Fuel Pump On	+	-	n	+	-	n	+	+	y	+	-	n	+	-	n	+	-	n
EI	+	-	n	+	-	n	+	-	n	+	-	n	+	-	n	+	-	n
Engine @ 1500 rpm							+	-	n							+	-	n
EI, Wipers High	+	-	n	+	-	n	+	-	n	+	-	n	+	-	n	+	-	n
EI, HVAC Fan High	+	-	n	+	-	n	+	-	n	+	-	n	+	-	n	+	-	n
EI, Wipers and Fan High	+	-	n	+	-	n	+	-	n	+	-	n	+	-	n	+	-	n
Wipers High	+	+	y	+	-	n	+	-	n	+	+	y	+	+	y	+	-	n
Fan High	+	-	n	+	+	y	+	-	n	+	-	n	+	+	y	+	-	n
Dodge (Filter Removed)	T	S	A	T	S	A	T	S	A	T	S	A	T	S	A	T	S	A
Fuel Pump On	+	+	y	+	-	n	+	-	n	+	-	n	+	-	n	+	-	n
EI	+	-	n	+	-	n	+	-	n	+	-	n	+	-	n	+	-	n
Engine @ 1500 rpm							+	-	n							+	-	n
EI, Wipers High	+	-	n	+	-	n	+	-	n	+	-	n	+	-	n	+	-	n
EI, Fan High	+	-	n	+	-	n	+	-	n	+	-	n	+	-	n	+	-	n
EI, Wipers and Fan High	+	-	n	+	-	n	+	-	n	+	-	n	+	-	n	+	-	n
Wipers High	+	+	y	+	+	y	+	-	n	+	+	y	+	+	y	+	-	n
Fan High	+	-	n	+	+	y	+	+	y	+	-	n	+	+	y	+	-	n

Note:

T : TXDOT 899-B Test, S : SAE J551/4 Test, A : Agreement, + : vehicle passed the test,

-: vehicle did not pass the test, y : two tests agreed, n : two tests did not agree.

Table 2.14 Comparison of Two Tests (Noise Blanker Off)

Frequency	47.02 MHz									47.18 MHz								
Group	1			2			3			1			2			3		
Chevrolet	T	S	A	T	S	A	T	S	A	T	S	A	T	S	A	T	S	A
Fuel Pump On	+	+	y	+	-	n	+	+	y	+	+	y	+	+	y	+	+	y
EI	+	-	n	+	-	n	+	-	n	+	-	n	+	-	n	+	-	n
Engine @ 1500 rpm							-	-	y							+	-	n
EI, Wipers High	+	-	n	-	-	y	-	-	y	+	-	n	+	-	n	+	-	n
EI, Fan High	+	-	n	-	-	y	+	-	n	-	-	y	-	-	y	+	-	n
EI, Wipers and Fan High							-	-	y							+	-	n
Wipers High	+	+	y	+	+	y	+	-	n	+	+	y	+	+	y	+	-	n
Fan High	+	+	y	+	+	y	+	+	y	+	+	y	+	+	y	+	+	y
Ford	T	S	A	T	S	A	T	S	A	T	S	A	T	S	A	T	S	A
Fuel Pump On	+	+	y	+	+	y	+	+	y	+	+	y	+	+	y	+	+	y
EI	+	-	n	+	-	n	+	-	n	+	-	n	+	-	n	+	-	n
Engine @ 1500 rpm							+	-	n							+	-	n
EI, Wipers High	+	-	n	+	-	n	+	-	n	+	-	n	+	+	y	+	-	n
EI, Fan High	-	-	y	-	-	y	-	-	y	-	-	y	-	+	n	+	-	n
EI, Wipers and Fan High	-	-	y				-	-	y	-	-	y				-	-	y
Wipers High	+	+	y	+	-	n	+	+	y	+	+	y	+	+	y	+	+	y
Fan High	+	-	n	-	-	y	-	+	n	-	-	y	-	+	n	+	+	y
Dodge (Filter Installed)	T	S	A	T	S	A	T	S	A	T	S	A	T	S	A	T	S	A
Fuel Pump On	+	-	n	-	-	y	+	+	y	+	-	n	-	-	y	-	-	y
EI	-	-	y	-	-	y	-	-	y	-	-	y	-	-	y	-	-	y
Engine @ 1500 rpm							-	-	y							-	-	y
EI, Wipers High	-	-	y	-	-	y	-	-	y	-	-	y	-	-	y	-	-	y
EI, HVAC Fan High	-	-	y	-	-	y	-	-	y	-	-	y	-	-	y	-	-	y
EI, Wipers and Fan High	-	-	y	-	-	y	-	-	y	-	-	y	-	-	y	-	-	y
Wipers High	+	+	y	+	-	n	+	-	n	+	+	y	+	+	y	+	-	n
Fan High	+	-	n	+	+	y	-	-	y	-	-	y	+	+	y	+	-	n
Dodge (Filter Removed)	T	S	A	T	S	A	T	S	A	T	S	A	T	S	A	T	S	A
Fuel Pump On	-	+	n	-	-	y	+	-	n	-	-	y	-	-	y	-	-	y
EI	-	-	y	-	-	y	-	-	y	-	-	y	-	-	y	-	-	y
Engine @ 1500 rpm							-	-	y							-	-	y
EI, Wipers High	-	-	y	-	-	y	-	-	y	-	-	y	-	-	y	-	-	y
EI, Fan High	-	-	y	-	-	y	-	-	y	-	-	y	-	-	y	-	-	y
EI, Wipers and Fan High	-	-	y	-	-	y	-	-	y	-	-	y	-	-	y	-	-	y
Wipers High	+	+	y	+	+	y	+	-	n	+	+	y	+	+	y	+	-	n
Fan High	+	-	n	+	+	y	+	+	y	-	-	y	+	+	y	+	-	n

Note:

T : TXDOT 899-B Test, S : SAE J551/4 Test, A : Agreement, + : vehicle passed the test,

-: vehicle did not pass the test, y : two tests agreed, n : two tests did not agree.

Table 2.15 Agreement Percentage Comparison between Noise Blanker On and Off (%)

Noise Blanker	On	Off
Chevrolet	37.5	55.0
Ford	35.7	54.8
Dodge	15.9	85.2
Fuel Pump On	53.2	79.2
EI	0.0	50.0
Engine @ 1500 rpm	0.0	62.5
EI, Wipers High	4.2	62.5
EI, Fan High	4.2	79.2
EI, Wipers and Fan High	0.0	94.4
Wipers High	66.7	66.7
Fan High	53.2	70.8
Total	25.9	70.6

A Comparison of the SwRI Data with the Professional Testing Data

PT (Professional Testing (EMI), Inc) is the place where the TXDOT vehicles are tested every year. The testing agent decides whether the vehicle passes the TXDOT test or not. The filters were also installed by this testing place to reduce the noise from the fuel pump and HVAC fan.

Group-1 vehicles were tested at PT. Table 2.16 through table 2.19 present the comparison between the PT and SwRI data. The difference between the two data sets is less than 2.5 dB when the noise blanker was on. On the other hand, when the noise blanker was turned off, there are differences of a few dB between the data of the two testing places. Most of the PT data are larger than the SwRI data. In some cases the difference is even larger than 5 dB, suggesting the existence of a significant difference in equipment or technique. At Professional testing they used a different MM antenna than that used at SwRI.

In order to make an additional comparison of TXDOT test results, Ford#1 was measured at Texas Tech University. All the tests were carried out using Maratrac#2. Table 2.20 is the comparison of the results from all three testing places. The signal level is lowest in the measurement at Texas Tech University. The reason for that is the ambient noise level at Texas Tech University is a few dB lower than the other two places.

Table 2.16 Comparison of Two Testing Places (Chevrolet)

Tex-899-B, FM Signal for 12-dB SINAD (Unit: dB μV)												
Test Frequency	47.02 MHz						47.18 MHz					
Blanker	On			Off			On			Off		
Testing place	PT	SwRI	Dif.	PT	SwRI	Dif.	PT	SwRI	Dif.	PT	SwRI	Dif.
Radio Sensitivity	-13.0	-13.1	0.1	-13.0	-13.1	0.1	-13.0	-13.0	0.0	-13.0	-13.0	0.0
Effective Radio Sensitivity	-8.0	-6.5	-1.5	-8.0	-6.5	-1.5	-6.0	-6.9	0.9	-6.0	-6.9	0.9
Ignition On	-8.0	-6.5	-1.5	-8.0	-6.2	-1.8	-6.0	-6.7	0.7	-6.0	-6.9	0.9
Fuel Pump On	-8.0	-5.9	-2.1	-8.0	-6.0	-2.0	-6.0	-6.6	0.6	-6.0	-6.4	0.4
Engine Idle	-7.0	-5.8	-1.2	-9.0	-3.6	-5.4	-5.0	-5.6	0.6	-1.0	-3.4	2.4
Engine Idle, Wipers High	-7.0	-5.4	-1.6	-9.0	-3.5	-5.5	-4.0	-5.5	1.5	-1.0	-3.0	2.0
Engine Idle, HVAC Fan High	-5.0	-4.3	-0.7	4.0	-0.8	4.8	-4.0	-4.6	0.6	2.0	-0.6	2.6
Engine Idle, Wipers/HVAC High	-5.0	-4.3	-0.7	4.0	-0.8	4.8	-4.0	-4.6	0.6	2.0	-0.6	2.6
Wipers High	-8.0	-6.0	-2.0	-8.0	-6.1	-1.9	-5.0	-6.5	1.5	-5.0	-6.2	1.2
HVAC Fan High	-8.0	-5.8	-2.2	-5.0	-4.0	-1.0	-5.0	-6.2	1.2	-3.0	-4.2	1.2

Note: PT = Professional Test (EMI), Inc. , SwRI = Southwest Research Institute, Dif. =Difference.

Table 2.17 Comparison of Two Testing Places (Ford)

Tex-899-B, FM Signal for 12-dB SINAD (Unit: dB µV)												
Test Frequency	47.02 MHz						47.18 MHz					
Blanker	On			Off			On			Off		
Testing place	PT	SwRI	Dif.	PT	SwRI	Dif.	PT	SwRI	Dif.	PT	SwRI	Dif.
Radio Sensitivity	-12.0	-13.0	1.0	-12.0	-13.0	1.0	-12.0	-13.1	1.1	-12.0	-13.1	1.1
Effective Radio Sensitivity	-8.0	-6.2	-1.8	-8.0	-6.2	-1.8	-5.0	-6.1	1.1	-5.0	-6.1	1.1
Ignition On	-8.0	-6.2	-1.8	-8.0	-5.8	-2.2	-5.0	-5.8	0.8	-5.0	-5.8	0.8
Fuel Pump On	-8.0	-6.2	-1.8	-8.0	-6.2	-1.8	-5.0	-5.7	0.7	-5.0	-5.3	0.3
Engine Idle	-8.0	-5.8	-2.2	-5.0	-4.0	-1.0	-5.0	-5.8	0.8	-3.0	-3.1	0.1
Engine Idle, Wipers High	-5.0	-4.4	-0.6	0.0	-1.7	1.7	-3.0	-5.2	2.2	1.0	-2.1	3.1
Engine Idle, HVAC Fan High	-3.0	-3.5	0.5	11.0	4.3	6.7	-2.0	-3.4	1.4	11.0	5.6	5.4
Engine Idle, Wipers/HVAC High	-2.0	-3.5	1.5	11.0	4.4	6.6	-1.0	-3.4	2.4	11.0	5.6	5.4
Wipers High	-7.0	-5.4	-1.6	-2.0	-4.6	2.6	-4.0	-5.3	1.3	-2.0	-4.7	2.7
HVAC Fan High	-4.0	-5.3	1.3	9.0	-3.1	12.1	-3.0	-5.0	2.0	5.0	2.1	2.9

Note: PT = Professional Test (EMI), Inc. , SwRI = Southwest Research Institute, Dif. =Difference.

Table 2.18 Comparison of Two Testing Places (Dodge, Filters Installed)

Tex-899-B, FM Signal for 12-dB SINAD (Unit: dB μV)												
Test Frequency	47.02 MHz						47.18 MHz					
Blanker	On			Off			On			Off		
Testing place	PT	SwRI	Dif.	PT	SwRI	Dif.	PT	SwRI	Dif.	PT	SwRI	Dif.
Radio Sensitivity	-13.0	-13.3	0.3	-13.0	-13.3	0.3	-13.0	-13.2	0.2	-13.0	-13.2	0.2
Effective Radio Sensitivity	-8.0	-7.2	-0.8	-8.0	-7.2	-0.8	-7.0	-6.4	-0.6	-7.0	-6.4	-0.6
Ignition On	-8.0	-6.8	-1.2	-8.0	-6.9	-1.1	-7.0	-6.4	-0.6	-7.0	-6.8	-0.2
Fuel Pump On	-7.0	-6.7	-0.3	-4.0	-5.3	1.3	-6.0	-5.6	-0.4	-1.0	1.5	-2.5
Engine Idle	-4.0	-4.9	0.9	12.0	6.6	5.4	-3.0	-4.1	1.1	14.0	7.5	6.5
Engine Idle, Wipers High	-4.0	-4.2	0.2	12.0	7.3	4.7	-3.0	-3.7	0.7	14.0	7.5	6.5
Engine Idle, HVAC Fan High	-3.0	-4.1	1.1	12.0	7.3	4.7	-3.0	-3.5	0.5	14.0	7.5	6.5
Engine Idle, Wipers/HVAC High	-3.0	-3.8	0.8	12.0	7.3	4.7	-3.0	-3.5	0.5	14.0	7.7	6.3
Wipers High	-8.0	-6.4	-1.6	-6.0	-5.6	-0.4	-6.0	-5.9	-0.1	-5.0	-6.1	1.1
HVAC Fan High	-7.0	-6.1	-0.9	1.0	-4.3	5.3	-6.0	-5.9	-0.1	4.0	-0.4	4.4

Note: PT = Professional Test (EMI), Inc. , SwRI = Southwest Research Institute, Dif. =Difference.

Table 2.19 Comparison of Two Testing Places (Dodge, Filters Removed)

Tex-899-B, FM Signal for 12-dB SINAD (Unit: dB µV)												
Test Frequency	47.02 MHz						47.18 MHz					
Blanker	On			Off			On			Off		
Testing place	PT	SwRI	Dif.	PT	SwRI	Dif.	PT	SwRI	Dif.	PT	SwRI	Dif.
Radio Sensitivity	-13.0	-13.3	0.3	-13.0	-13.3	0.3	-13.0	-13.2	0.2	-13.0	-13.2	0.2
Effective Radio Sensitivity	-8.0	-7.2	-0.8	-8.0	-7.2	-0.8	-7.0	-7.1	0.1	-7.0	-7.1	0.1
Ignition On	-7.0	-6.5	-0.5	-7.0	-6.5	-0.5	-6.0	-7.1	1.1	-6.0	-6.5	0.5
Fuel Pump On	-6.0	-5.9	-0.1	-6.0	-2.0	-4.0	-5.0	-6.1	1.1	0.0	2.2	-2.2
Engine Idle	-4.0	-3.9	-0.1	13.0	7.1	5.9	-3.0	-4.5	1.5	14.0	7.0	7.0
Engine Idle, Wipers High	-4.0	-4.2	0.2	13.0	8.5	4.5	-3.0	-4.2	1.2	14.0	7.0	7.0
Engine Idle, HVAC Fan High	-2.0	-2.6	0.6	14.0	8.5	5.5	-2.0	-3.8	1.8	14.0	7.0	7.0
Engine Idle, Wipers/HVAC High	-2.0	-2.7	0.7	14.0	8.7	5.3	-2.0	-3.9	1.9	14.0	7.4	6.6
Wipers High	-7.0	-6.5	-0.5	-6.0	-5.6	-0.4	-6.0	-6.6	0.6	-6.0	-5.9	-0.1
HVAC Fan High	-6.0	-6.0	0.0	5.0	0.7	4.3	-6.0	-5.9	-0.1	4.0	0.8	3.2

Note: PT = Professional Test (EMI), Inc. , SwRI = Southwest Research Institute, Dif. =Difference.

Table 2.20 Comparison of Three Testing Places (Ford#1)

TEX-899-B, FM Signal for 12-dB SINAD (Unit: dB μV)												
Test Frequency	47.02 MHz						47.18 MHz					
Blanker	On			Off			On			Off		
Testing place	PT	SwRI	TTU	PT	SwRI	TTU	PT	SwRI	TTU	PT	SwRI	TTU
Radio Sensitivity	-12.0	-13.0	-13.1	-12.0	-13.0	-13.1	-12.0	-13.1	-13.0	-12.0	-13.1	-13.0
Effective Radio Sensitivity	-8.0	-6.2	-10.0	-8.0	-6.2	-10.0	-5.0	-6.1	-10.0	-5.0	-6.1	-10.0
Ignition On	-8.0	-6.2	-10.0	-8.0	-5.8	-10.0	-5.0	-5.8	-10.0	-5.0	-5.8	-10.0
Fuel Pump On	-8.0	-6.2	-10.0	-8.0	-6.2	-10.0	-5.0	-5.7	-10.0	-5.0	-5.3	-10.0
Engine Idle	-8.0	-5.8	-9.7	-5.0	-4.0	-9.7	-5.0	-5.8	-10.0	-3.0	-3.1	-8.6
Engine Idle, Wipers High	-5.0	-4.4	-9.3	0.0	-1.7	-9.3	-3.0	-5.2	-9.9	1.0	-2.1	-7.6
Engine Idle, HVAC Fan High	-3.0	-3.5	-7.6	11.0	4.3	2.1	-2.0	-3.4	-8.9	11.0	5.6	1.6
Engine Idle, Wipers/HVAC High	-2.0	-3.5	-7.8	11.0	4.4	2.1	-1.0	-3.4	-8.3	11.0	5.6	1.6
Wipers High	-7.0	-5.4	-9.5	-2.0	-4.6	-4.4	-4.0	-5.3	-9.3	-2.0	-4.7	-8.2
HVAC Fan High	-4.0	-5.3	-8.3	9.0	-3.1	-0.2	-3.0	-5.0	-9.3	5.0	2.1	-0.7

Note: PT = Professional Testing, SwRI = Southwest Research Institute, TTU: Texas Tech University

CHAPTER III

ANALYSIS OF NARROW-BAND DATA IN LUBBOCK

In SwRI's SAE J551/4 and TEX-899-B tests, no narrow-band noise was found from the vehicles at 47.02 MHz and 47.18 MHz, which are two typical frequencies of the TXDOT radio channels. The whole TXDOT radio frequency range is from 47.02 MHz to 47.34 MHz. At Texas Tech University we did a frequency scan measurement for the narrow-band emissions. Table 3.1 is the result of the narrow-band noise from the three vehicles. The table shows that there is no narrow-band noise from the vehicles in the TXDOT radio frequency range. The narrow-band noise we found was all at or over 48 MHz. The conclusion based on the narrow-band test is that all the vehicles will pass the SAE narrow-band test in every channel.

Table 3.1 Frequency Scan for Narrow-Band Emissions

	Ford		Chevrolet		Dodge	
Condition	F (MHz)	A(dBμV)	F (MHz)	A(dBμV)	F (MHz)	A(dBμV)
Key Off	48.35	8.20	*	*	*	*
Key On (Gas Controller Only)	48.07	-3.60	48.22	4.50	48.00	2.60
	48.35	10.70	*	*	*	*
Key On (Gas and Propane Controllers)	-	-	-	-	48.00	3.40
EI	48.07	0.30	48.22	4.10	48.00	3.10
	48.35	10.70	*	*	*	*

Note:

Scan Range: 47.00 MHz to 48.60 MHz, Detector: NBAV, Bandwidth: 10 kHz,

Step Size: 10 kHz, Testing Place: North of Lubbock, Ambient Noise Level: -18 dBμV

F = Frequency, A = Amplitude, * = No Peak found, - = Test not available

CHAPTER IV

PROPOSED CHANGES TO THE SAE LIMITS AND VERIFICATION WITH TTU DATA

Proposed Changes to the SAE Limits

From Chapter II, we conclude that at SwRI all the vehicles passed the TXDOT test when the noise blanker was turned on. On the other hand, the vehicles could not pass the SAE test in some cases. New SAE broad-band peak limits can be decided by using these test results. We can separate the noise into two kinds. One is spark-ignition (EI) noise and another one is DC-motor noise (fuel pump, HAVC fan, wipers). From the data, we propose to raise the limit on the first kind of noise to 50 dBμV and the second kind to 35 dBμV. Further tests in Lubbock will confirm these two limits.

Comparisons of the TXDOT Test Results among Different Radios

Thousands of radios are used by TXDOT for communication. The two most widely used radios are the Motorola Maratrac and the GE Rangr. At SwRI the radio used for testing was Maratrac#2. At Texas Tech University we did the TXDOT test on a Dodge truck with using 5 different radios (3 Rangrs and 2 Maratracs). All the tests were done in the "Noise Blanker On" condition. Table 4.1 and Table 4.2 are the results of the comparison of these five radios. These two tables show see that the vehicle passed all of the tests with the noise blanker on no matter whether the filters were installed or not. Another conclusion from the two tables is that the Maratrac#2 result is the lowest and the Rangr#3 is the highest. The difference between these two radios is about 2 dB.

From the results in Chapter II, we know the Dodge truck is the noisiest one among the three brands. And all the trucks passed the TXDOT test limit more than 2dB if the noise blanker was turned on. Therefore, we can conclude that all the vehicles can pass with all the radios if the noise blanker is turned on.

Table 4.1 Comparison of Different Radios (Filters Installed)

TEX-899-B, FM Signal for 12-dB SINAD (dB μV)										
Radio	Rangr 1		Rangr 2		Rangr 3		Maratrac 1		Maratrac 2	
Frequency (MHz)	47.02	47.18	47.02	47.18	47.02	47.18	47.02	47.18	47.02	47.18
Radio Sensitivity	-11.0	-10.8	-11.1	-11.2	-11.6	-11.5	-12.7	-12.0	-13.0	-13.0
Effective Radio Sensitivity	-6.0	-6.4	-6.8	-7.0	-6.9	-6.9	-6.6	-6.2	-7.8	-8.7
Fuel Pump(Key Off)	-5.8	-5.4	-5.9	-6.4	-5.7	-5.4	-6.1	-5.2	-6.3	-6.7
HVAC FAN High	-5.2	-5.2	-5.6	-6.3	-4.7	-4.1	-4.8	-5.1	-7.4	-6.6
Wipers High	-5.5	-5.7	-6.8	-6.9	-5.9	-6.0	-4.7	-6.1	-7.6	-7.3
EI (propane)	-3.7	-2.5	-4.5	-3.8	-3.1	-2.8	-4.3	-4.4	-5.5	-4.2
EI	-3.0	-2.5	-4.1	-3.5	-2.5	-2.0	-3.5	-3.8	-4.7	-3.7
EI, HVAC Fan High	-1.8	-2.3	-2.7	-3.2	-1.7	-0.6	-2.6	-3.3	-4.5	-3.0
EI, Wipers High	-2.4	-2.7	-3.3	-3.4	-2.6	-1.7	-3.0	-4.0	-4.5	-3.2
EI, HVAC Fan High, Wipers High	-1.7	-1.9	-2.3	-3.1	-1.5	-0.7	-2.4	-2.9	-4.0	-3.0

Note:

Vehicle: Dodge of TXDOT at Lubbock

Table 4.2 Comparison of Different Radios (Filters Removed)

TEX-899-B, FM Signal for 12-dB SINAD (dB µV)										
Radio	Rangr 1		Rangr 2		Rangr 3		Maratrac 1		Maratrac 2	
Frequency (MHz)	47.02	47.18	47.02	47.18	47.02	47.18	47.02	47.18	47.02	47.18
Radio Sensitivity	-11.0	-10.8	-11.3	-11.6	-11.7	-11.6	-12.7	-12.1	-13.0	-12.8
Effective Radio Sensitivity	-6.7	-7.3	-7.9	-7.6	-8.1	-7.2	-8.9	-7.9	-8.8	-8.2
Fuel Pump(Key Off)	-5.7	-5.2	-6.0	-5.5	-5.3	-6.2	-7.0	-6.8	-7.3	-7.7
HVAC FAN High	-5.4	-5.3	-5.7	-6.4	-5.2	-6.5	-7.2	-7.6	-7.6	-7.9
Wipers High	-6.0	-6.2	-7.5	-7.3	-7.7	-7.6	-8.0	-7.9	-7.8	-8.0
EI (propane)	-5.0	-3.5	-5.6	-4.4	-3.2	-4.2	-6.1	-5.3	-6.2	-6.0
EI	-4.3	-3.2	-4.8	-4.2	-3.7	-4.2	-5.1	-5.4	-5.8	-5.5
EI, HVAC Fan High	-3.6	-2.2	-3.9	-3.4	-1.8	-2.1	-4.9	-4.6	-5.4	-5.4
EI, Wipers High	-4.2	-2.6	-4.4	-3.6	-2.6	-3.2	-5.1	-4.8	-5.5	-5.5
EI, HVAC Fan High, Wipers High	-3.0	-2.2	-3.7	-3.4	-1.7	-2.0	-4.5	-4.5	-5.3	-5.2

Note:

Vehicle: Dodge of TXDOT at Lubbock

A Comparison of Different Measurement Times in the SAE Test

In the SAE test procedure, no measurement time is specified for doing the broad-band peak and quasi-peak measurements. In order to understand the measurement-time effect on the result, we did four sets of SAE tests using different measurement times. Figure 4.1 is the broad-band peak level at different measurement times. From the figure, we see that the broad-band peak level is higher if the measurement time is longer. The level tends to be a constant when the measurement time is long enough. From Figure 4.1, we can conclude 1 second is long enough to measure the broadband peak level.

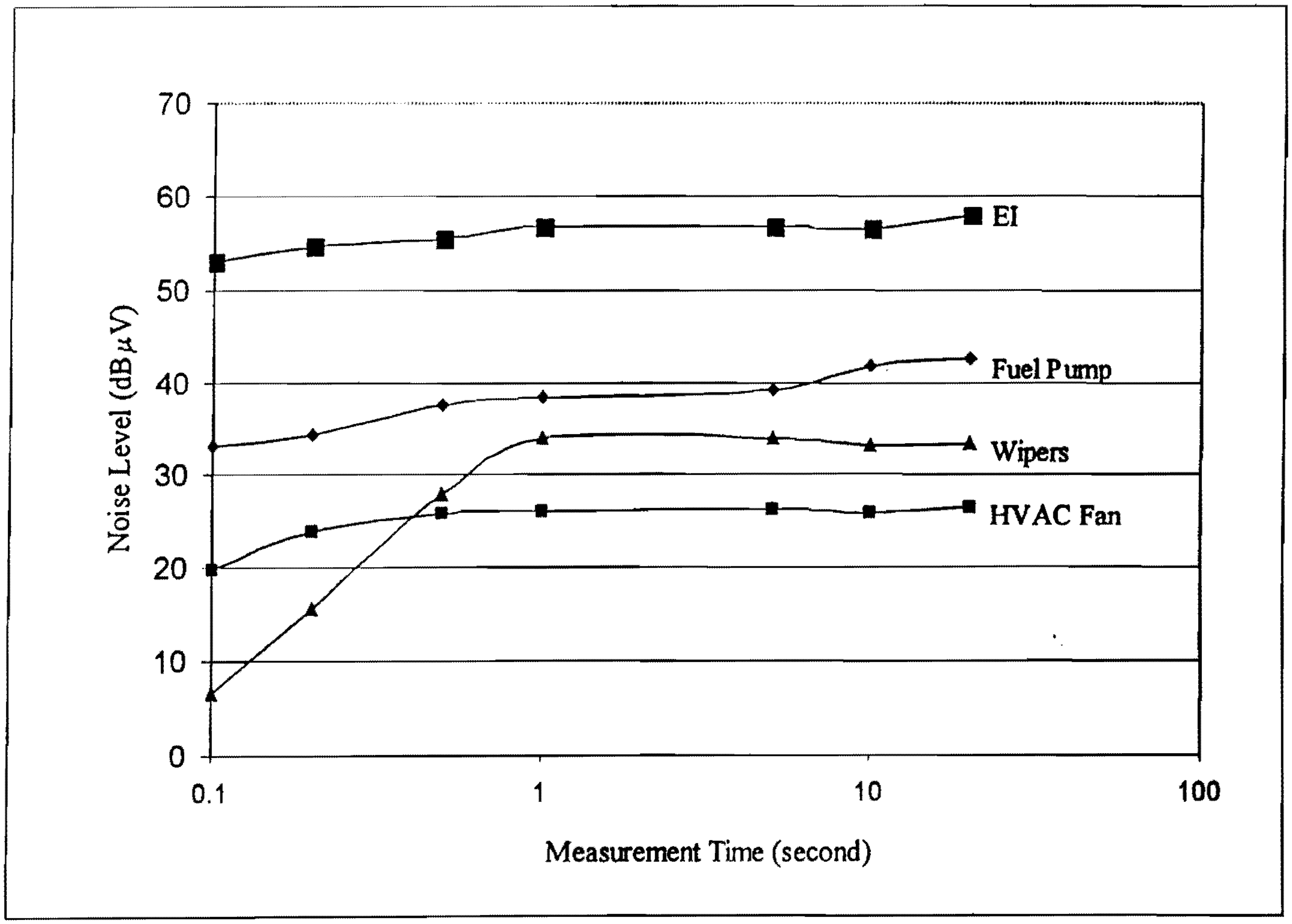


Figure 4.1 SAE J551/4, Broad-Band Peak Level at Different Measurement Times

Additional Cable Tests in Lubbock

In order to reduce the induced current flowing on the coaxial cable leading to the radio, TEX-899-B says to make one loop in the cable which is approximately four feet in diameter. In SwRI, they used five small loops which were all one foot in diameter instead of one large loop. In Lubbock, we did the TXDOT test using both methods. We found that there is no difference between these two methods. We did an additional test with the cable straight, then we put four chokes on the cable and did the tests again. We also moved the cable to different places and did more tests. The radio noise blanker was turned off for maximum sensitivity to vehicle noise. All the tests showed the same result. The conclusion of these cable tests is that the cable position is not critical in the testing.

Comparisons of the 1997 Dodge with the 1996 Dodge

In Lubbock we did the tests on both the 1997-model Dodge and the 1996-model Dodge. Table 4.3 shows the comparison of the broad-band peak level between the two vehicles. The differences are less than 3 dB. The noise from the 96 model truck is a little higher than that from the 97 model. Table 4.4 is the comparison of the signal level at 12-dB SINAD. The signal level is higher for the 96 model when the truck runs with gasoline, and the signal level is higher for the 97 model when the truck runs with propane.

Table 4.3 SAE J551/4, Comparison of 1997-Model Dodge with the 1996 Model

Condition	Broadboad Peak Level (dBµV)					
Frequency (MHz)	47.02			47.18		
Model	1996	1997	Dif.	1996	1997	Dif.
Gasoline (EI)	55.2	57.1	-1.9	59.9	57.3	2.6
Gasoline (EI, HVAC Fan High)	57.4	57.1	0.3	60.5	58.6	1.9
Propane (EI)	60.2	58.0	2.2	58.8	58.1	0.7
Propane (EI, HAVC Fan High)	58.9	59.5	-0.6	59.5	58.7	0.8

Note: Measurement Time: 30 second

Table 4.4 TEX-899-B, Comparison of 1997-Model Dodge with the 1996 Model

Condition	Signal Level at 12-dB SINAD (dBµV)					
Frequency (MHz)	47.02			47.18		
Model	1996	1997	Dif.	1996	1997	Dif.
Gasoline (EI)	-0.4	-3.1	2.7	-1.7	-2.9	1.2
Gasoline (EI, HVAC Fan High)	-0.8	-3.0	2.2	-1.8	-2.8	1.0
Propane (EI)	-5.6	-4.5	-1.1	-6.0	-4.2	-1.8
Propane (EI, HAVC Fan High)	-4.0	-4.1	0.1	-4.6	-3.7	-0.9

CHAPTER V

CONCLUSIONS

The following conclusions can be made from the discussion of the previous chapters:

1. The Dodge trucks were noisier than the Ford trucks and Chevrolet trucks.
2. The performance of Motorola Maratrac radio is a little better than that of GE Rangr radio in the sense of reducing broad-band vehicle noise.
3. There is no need to install the filters on the Dodge truck in order to improve the TXDOT test results, although the filters do reduce the noise measured in the SAE test.
4. There is no difference between the installed radio and the external radio as far as the TXDOT test results are concerned.
5. The broad-band noise is about the same in the TXDOT test when the vehicle runs at 750 rpm and at 1500 rpm except for the Dodge.
6. The position of the antenna cable was not found critical in our TEX-899-B tests.
7. Both 1997 propane-converted Dodge trucks passed the TEX-899-B tests at Lubbock when running on propane and when running on gasoline, so that the installation of the propane fuel system did not adversely affect the noise emission of the trucks.
8. All of the 1997-model trucks performed well in the sense that they passed the TXDOT test (with the noise blanker turned on). Although it was not mentioned

previously, the 1996-model Dodge truck failed the TXDOT test several times by about 1 dB when the engine was running at 1500 rpm.

9. There should be no 6-dB requirement in the TXDOT test because the 1-μV requirement, while less stringent than the 6-dB, is nevertheless adequate, and the 6-dB requirement represents an added complication in the testing.
10. The noise blanker should be always turned on in the TXDOT test because it is on when in normal use. The noise blanker can improve the test results by 4 to 12 dB.
11. One of each brand vehicle was tested and passed the SAE narrow-band limit in every TXDOT channel because no narrow-band noise was found in these channels.
12. A 1-second measurement time is long enough to measure the broadband peak level in the SAE test.
13. The signal level at 12-dB SINAD is highest at PT and is lowest at Lubbock, the reasons are probably that the ambient noise level is lowest at Lubbock and at PT a different antenna was used in doing the test.
14. From one vehicle to another of the same brand the ignition noise doesn't change while the noise from the DC motors changes 3 to 7 dB in the SAE test.
15. The SAE broad-band peak limit may be increased to at least 35 dBμV for the DC-motor noise and 50 dBμV for the spark-ignition noise. The SAE test with this new limit could be substituted for the TXDOT test by the vehicle manufacturers.

REFERENCES

1. Society of Automotive Engineers, SAE J551/4 Test, June 1994, Warrendale, PA.

2. Texas Department of Transportation, TEX-899-B Test, September 1995, Austin, TX.

APPENDIX A

TEX-899-B TEST

RADIO FREQUENCY INTERFERENCE (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 on 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 volt 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 in 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 uv (-114 dBm) for 12 dB SINAD.

- The receiver bandwidth shall be a minimum of ± 6.5 kHz and a maximum of ± 8.0 kHz.

- 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 roof.
4	Disconnect the vehicle battery cable.
5	Terminate the RF line into the RF load termination.
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 load 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.

- 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 uv (-113 dBm).

Egress Compatibility (continued)

- Egress Compliance 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 RF 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 that 1 microvolt (-107 dBm) to produce 12 dB or greater SINAD. The effective sensitivity should not exceed 1 microvolt 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 six 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 reflected 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 watts and reflected power is less than 10% of the forward power.

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 Operations - Correct nuisance operations of any vehicle system and/or accessory.

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

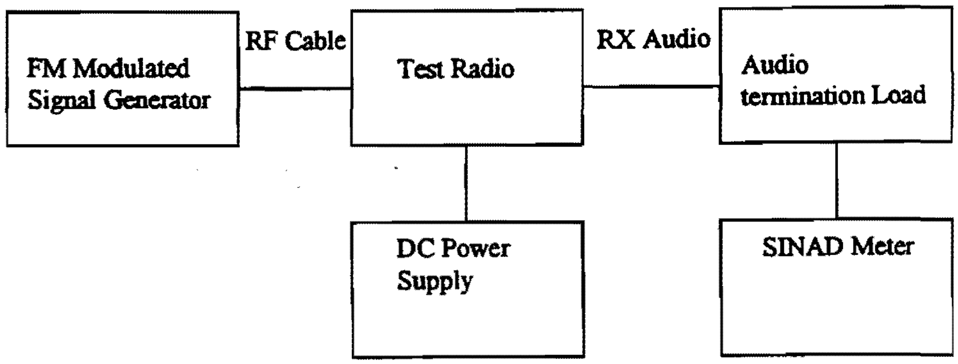


Figure1

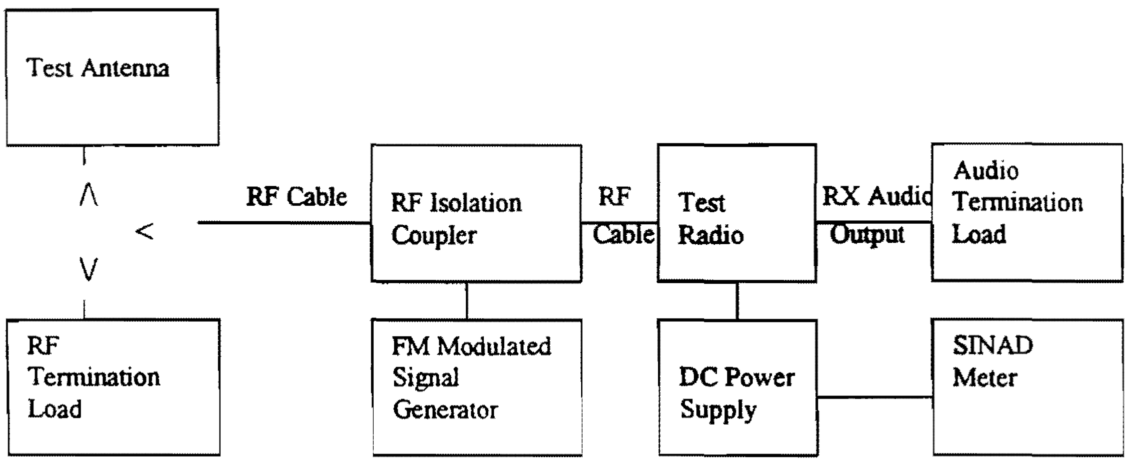


Figure 2

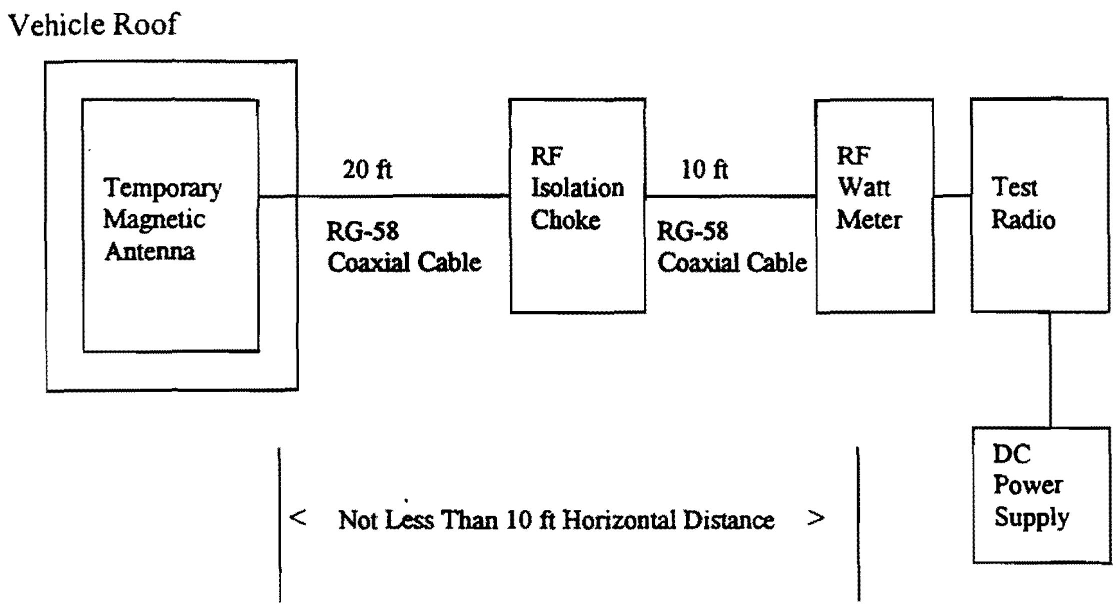

Vehicle Roof
Temporary Magnetic Antenna
20 ft
RG-58 Coaxial Cable
RF Isolation Choke
10 ft
RG-58 Coaxial Cable
RF Watt Meter
Test Radio
DC Power Supply
< Not Less Than 10 ft Horizontal Distance >

Figure 3

APPENDIX B

SAE J551/4 TEST

TEST LIMITS AND METHODS OF MEASUREMENT OF RADIO DISTURBANCE CHARACTERISTICS OF VEHICLES AND DEVICES, BROADBAND AND NARROWBAND, 150 kHz TO 1000 MHz

Foreword—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 provides test limits and procedures for the "protection of vehicle receivers from radio frequency (RF) emissions caused by on-board vehicle components."

NOTE—Appendix B 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 Telecommunications Union (ITU) Publications for details of frequency allocations. The test limits 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.

[1] Only a vehicle test can be used to determine the component compatibility to a vehicle limit.
[2] Adjacent vehicles 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, tests at 150 kHz 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.

2.1.1 SAE PUBLICATION—Available from SAE, 400 Commonwealth Drive, Warrendale, PA 15096-0001.

SAE J551/1 MAR94— Performance Levels and Methods of Measurement of Electromagnetic Compatibility of Vehicles and Devices (60 Hz to 18 GHz)

2.1.2 CISPR PUBLICATION—Available from ???

CISPR 16-1:1993-08— 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 NOTE—A test plan should be established for each item to be tested. The test plan should specify the frequency range to be tested, the emissions limits, the disturbance classification [broadband (long or short duration) or narrowband], antenna types and locations, test report requirements, supply voltage, and other relevant parameters.

4.1.2 DETERMINATION OF CONFORMANCE WITH LIMITS—If the type of disturbance is unknown, tests shall be made to determine whether measured emissions are narrowband and/or broadband 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 examples see 4.1.4 and 4.1.5 and Table 1.

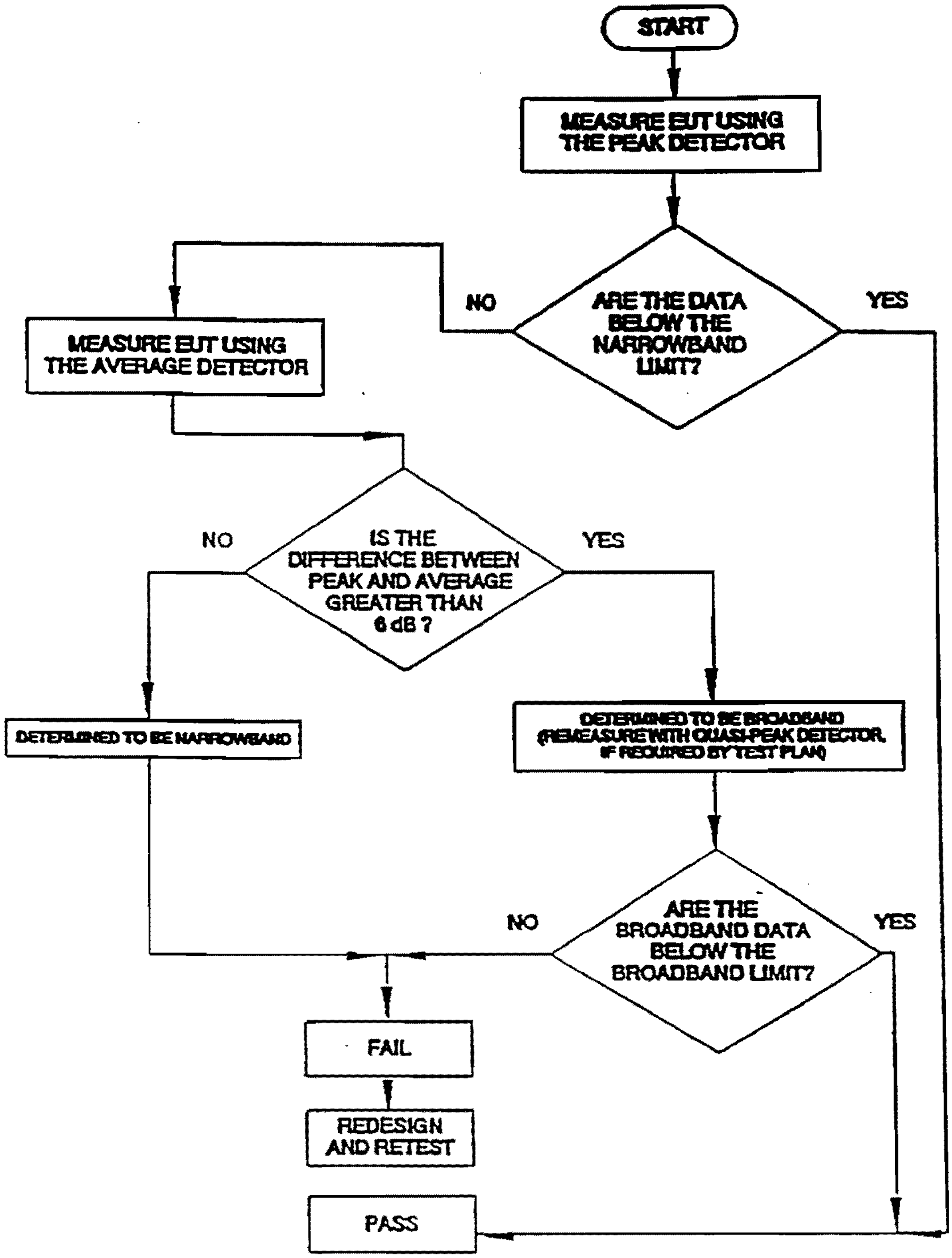


FIGURE 1—METHOD OF DETERMINATION OF CONFORMANCE OF RADIATED/CONDUCTED DISTURBANCE

4.1.4 EXAMPLES 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—EXAMPLES 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 microprocessors, digital logic, oscillators or clock generators, etc., cause narrowband emissions.

4.1.6 OPERATING CONDITIONS—All continuous and long duration systems 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 the 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 the 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 as much 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 emissions measurements. No absorber material is required for the floor. The following ALSE requirements shall also be met for performing radiated RF emissions measurements:

4.4.1 Reflection Characteristics—The reflection characteristics of the ALSE shall be such that the maximum error caused by reflected energy from the walls 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 emissions 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, chairs, 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 analyzers and scanning receivers are particularly useful for interference measurements. Special consideration shall be given to overload, linearity, selectivity, and the normal response to pulses. The peak detection mode of spectrum analyzers and scanning receivers 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 Table 2:

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 signals) may require slower 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 narrowband/broadband discrimination according to Figure 1, 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	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 Broadcast 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 envelope for each frequency band as shown in Figure 2. Calibration shall be performed in accordance with Appendix A.
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 A.

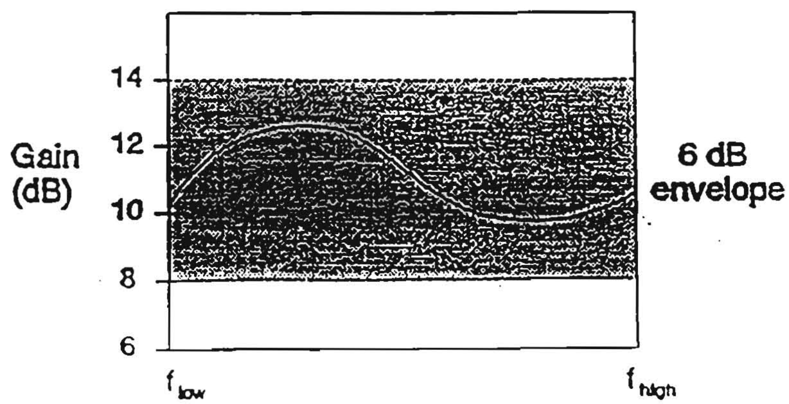


FIGURE 2—EXAMPLE GAIN CURVE

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 COMMUNICATIONS 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 factor shall be used.

[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 terminals 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.

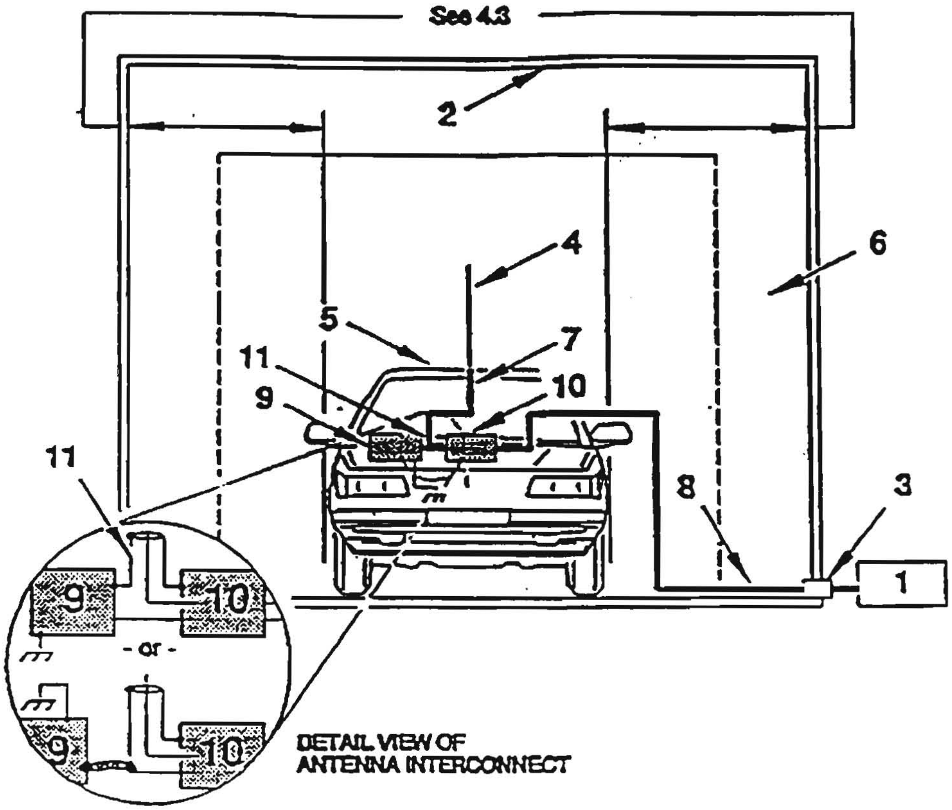
NOTE—The use of ferrite or other suppression material on the exterior of the coax is recommended, particularly below 2 MHz, for suppression of surface currents.

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. *Limits 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 sources may be decided upon by the vehicle manufacturer. For example, door mirror operation may be allowed at a higher 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 signals 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 - 0.30	9	22	15	28	6
MW	0.53 - 2.0	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 systems only

APPENDIX A
(Normative)

ANTENNA MATCHING UNIT—VEHICLE TEST

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

A.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 car radio.

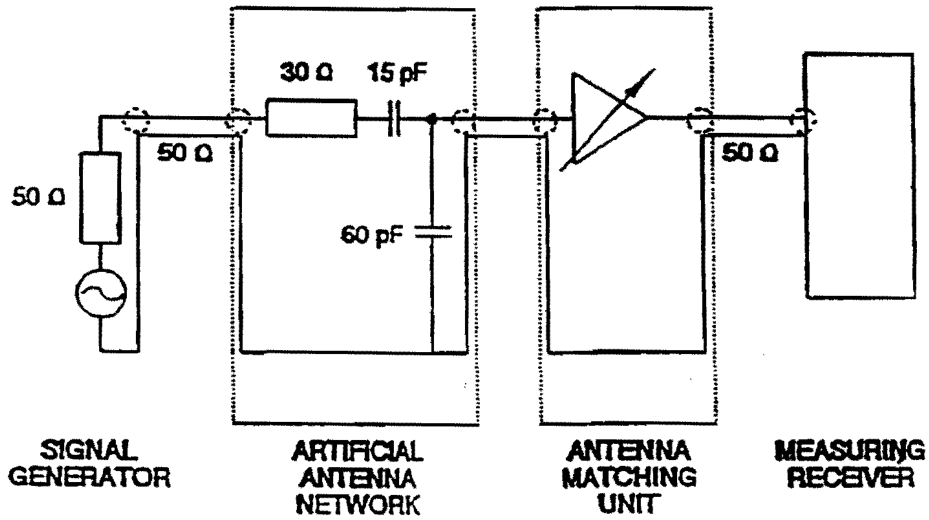


FIGURE A1—CALIBRATION SET-UP

A.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 A1.

A.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.

A.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 lie 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 B
(Informative)

NOTES ON THE SUPPRESSION OF INTERFERENCE

B.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. Disturbances coupled to the antenna
b. Disturbances 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. Disturbances 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.

B.2 Disturbances 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.

B.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.

B.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 oscillators 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.

B.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 TXDOT LOW-BAND-VHF RADIO FREQUENCIES (MHz)

45.680 *

45.720 *

45.800 *

45.840 *

47.020

47.040

47.060

47.080

47.100

47.120

47.140

47.160

47.180

47.200

47.220

47.240

47.260

47.340

* These frequencies used only for mobile-radio transmission to a repeater and not for mobile-radio reception.

APPENDIX D

LIST OF VEHICLES AND THEIR TESTING PLACES

Table D.1 List of Vehicles and Their Testing Places

Vehicle Name	Vehicle Number	Testing Places		
		SwRI	PT	TTU
Ford F150 #1	2-4390-G	X	X	X
Ford F150 #2	2-4391-G	X		
Ford F150 #3	2-4402-G	X		
Chevrolet S10 #1	20-4138-G	X	X	
Chevrolet S10 #2	20-4144-G	X		
Chevrolet S10 #3	20-4137-G	X		
Chevrolet S10 #4 *	222312			X
Dodge Ram 1500 #1	13-4106-G	X	X	
Dodge Ram 1500 #2	13-4484-G	X		
Dodge Ram 1500 #3	13-4105-G	X		
Dodge Ram 1500 #4	5-4173-G			X
Dodge Ram 1500 #5	5-4171-G			X
Dodge Ram 1500 #6 **	5-5865-F	X		X

Note:

1. All vehicles are pickup trucks.
2. All vehicles are gasoline powered expect Dodge #4, 5, 6, which are gasoline and propane powered.
3. SwRI = Southwest Research Institute, PT = Professional Testing, TTU = Texas Tech University.

* : This vehicle number is a TTU number, all the other numbers are TXDOT numbers.

**: This vehicle is 96 model, all the other vehicles are 97 model.

X: vehicle tested in this place.