U.S. Department
of Transportation
Federal Railroad Administration

The Safety of Highway - Railroad Grade Crossings

Office of Research and Development
Washington, DC 20590

The Effectiveness of Railroad Horn Systems

Amanda S. Rapoza
Edward J. Rickley

U.S. Department of Transportation
Research and Special Programs Administration
John A. Volpe
National Transportation Systems Center
Cambridge, MA 02142

DOT/FRA/ORD-XX/X.X
DOT-TSC-FRA-XX-X.X

Final Report
December 1995

This document is available to the public through the National Technical Information Service, Springfield, VA 22161

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	December 1995	Final Report January 1992 - December 1995

4. TITLE AND SUBTITLE	5. FUNDING NUMBERS
THE EFFECTIVENESS OF RAILROAD HORN SYSTEMS	RR697/R6033
6. AUTHOR(S) Amanda S. Rapoza, Edward J. Rickley	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U. S. Department of Transportation Research and Special Programs Administration Volpe National Transportation Systems Center Cambridge, MA 02142	8. PERFORMING ORGANIZATION REPORT NUMBER DOT-VNTSC-FRA-X-X
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U. S. Department of Transportation Federal Railroad Administration Office of Research and Development Equipment and Operating Practices Research Division Washington, D.C. 20590	10. SPONSORING/MONITORING AGENCY REPORT NUMBER FRA-XX-XXX

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT	12b. DISTRIBUTION CODE
This document is available to the public through the National Technical Information Service, Springfield, VA 22161	

13. ABSTRACT (Maximum 200 words)

The U.S. Department of Transportation, Research and Special Programs Administration, Volpe National Transportation Systems Center, in support of the Federal Railroad Administration is conducting a research program with the goal of reducing the number of accidents and resulting casualties at highway-railroad grade crossings. As a part of this program, a study is being conducted to determine the effectiveness of railroad horn systems in reducing accidents at highway-railroad grade crossings. The first publication supporting this study, The Acoustic Characteristics of Railroad Horn Systems, presented the acoustic characteristics of several types of railroad horn systems. This document, the second publication supporting the study, addresses the effectiveness of railroad horn systems and their resulting impact on the community noise environment. The insertion loss and interior noise levels of several motor vehicles were measured to determine if the warning signals created by railroad horn systems provide effective warning for the motorist. Acoustic data were also obtained for a horn system through wayside measurements of in-service locomotives to determine the community noise exposure. Also addressed is the distance from the crossing at which the signaling cycle should be actuated to minimize the community noise exposure.

14. SUBJECT TERMS	15. NUMBER OF PAGES
Whistles, Horns, Highway-Rail Grade Crossings, Audible Warning Devices, Community Noise	98
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18 298-102

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in²	square inches	645.2	millimeters squared	mm²
ft²	square feet	0.093	meters squared	m²
yd²	square yards	0.836	meters squared	m²
ac	acres	0.405	hectares	ha
mi²	square miles	2.59	kilometers squared	km²
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	ml
gal	gallons	3.785	liters	l
ft³	cubic feet	0.028	meters cubed	m³
yd³	cubic yards	0.765	meters cubed	m³

NOTE: Volumes greater than 1000 l shall be shown in m³.

Symbol	When You Know	Multiply By	To Find	Symbol
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	l
fl	foot-Lamberts	3.426	candela/m²	cd/m²
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
psi	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm²	millimeters squared	0.0016	square inches	in²
m²	meters squared	10.764	square feet	ft²
m²	meters squared	1.195	square yards	ac
ha	hectares	2.47	acres	mi²
km²	kilometers squared	0.386	square miles	
		VOLUME		
ml	milliliters	0.034	fluid ounces	fl oz
l	liters	0.264	gallons	gal
m³	meters cubed	35.71	cubic feet	ft³
m³	meters cubed	1.307	cubic yards	yd³
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg	megagrams	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m²	candela/m²	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	psi

* SI is the symbol for the International System of Units

(Revised January 1992)

PREFACE

This document presents the results of a study conducted by the U.S. Department of Transportation, Research and Special Programs Administration, Volpe National Transportation Systems Center (Volpe Center), in support of the Federal Railroad Administration (FRA). This study evaluated the community noise impact and effectiveness of railroad horn systems, both conventional and alternative, in reducing highway railroad grade crossing accidents.

The authors would like to thank the following for their support: Claire Orth, Chief, Equipment and Operating Practices Research Division, Garold Thomas, Research Manager, and Thomas Raslear, all of the FRA's Office of Research and Development; Anya Carroll, Program Manager, Highway-Railroad Grade Crossing Safety Research Program, and John Hitz of the Volpe Center's Accident Prevention Division; Jordan Multer of the Volpe Center's Operator Performance and Safety Analysis Division; W. Douglass DeBoer, Railroad Safety Inspector of the FRA's Office of Safety; and Hank Dickinson and Jerry Hall of the Florida East Coast Railway. The authors would also like to thank the following Volpe Center personnel for the use of their vehicles: Gregg Fleming, Claire Judge, Joseph Marotte, Michael McDonald, Walter Messcher, and Kevin Yearwood.

EXECUTIVE SUMMARY

The U.S. Department of Transportation, Research and Special Programs Administration, Volpe National Transportation Systems Center (Volpe Center), in support of the Federal Railroad Administration, is conducting safety research to evaluate the effectiveness of various methods for reducing the number of accidents and resulting casualties at highway-railroad grade crossings. The overall research effort is investigating the use of rail equipment warning and alerting devices, (e.g., horns, alerting lights, and reflectorization), and the use of track systems devices (e.g., signs, signals and lighting systems). As part of this research, the current effort reported here evaluates the effectiveness of horn systems used as audible warning for motorists at highway-railroad grade crossings, and their resulting impact on the community noise environment.

This study was prompted by the results of a nighttime (10 pm to 6 am) railroad horn ban by the Florida East Coast Railway. These results suggested that the motorist in Florida could almost always detect the railroad horns. This is not consistent with the conclusions in this report. These conclusions are based upon measurements of a vehicle traveling 48 km/hr (30 mph) with closed windows, not of a vehicle which is stopped with open windows, as may have been the case in Florida. In order to resolve these inconsistencies, a more detailed set of automotive insertion loss and interior noise data must be collected. These data would include insertion loss characteristics for motor vehicles with windows both opened and closed, and interior noise data for vehicles traveling at a variety of speeds, especially at idle. This would allow far a more accurate representation of the situations that may have been encountered in Florida during the whistle ban.

Since the majority of highway-railroad grade crossing accidents involve in-transit locomotives, acoustic data are presented for a conventional three-chime horn system, obtained through wayside measurements of locomotives as they move through the crossing at six different grade crossings. Sound levels were measured perpendicular to the track at two locations at each crossing to determine the effects on the signal strength of buildings and vegetation along the right-of-way. This information, coupled with the number of trains traversing the crossing during the daytime and nighttime hours, was used to compute the community noise exposure, measured in terms of an average day-night sound level, in the vicinity of the grade crossing. It was found that at locations less than 61.0 m (200 ft) from the crossings, which have trains traversing the crossing at a rate of one per hour, the estimated day-night sound levels are greater than 65 dBA. This is characterized as "normally unacceptable" by the Department of Housing and Urban Development[8].

The sound insulation characteristics (insertion loss) of motor vehicles were obtained by measuring the sound level at a reference position inside the vehicle and at the same position with the vehicle removed. The insertion loss of the motor vehicles tested was found to be approximately 25-35 dBA. The interior noise levels were measured while the motor vehicles traveled at a constant speed of 48.3 km/hr (30 mph), with windows closed, ventilation systems off, and radios off. Interior noise levels were found to be approximately 55-65 dBA. The interior noise levels, coupled with the vehicle insertion loss values, were used to determine the sound level of the warning signal that is necessary to effectively alert the motorist.

Effective warning signal sound levels were determined for three highway-railroad grade crossing scenarios: (1) the passive crossing; (2) the active crossing; and, (3) the active crossing equipped with a wayside horn system (i.e., a horn system located directly at the crossing instead of on the locomotive). For each crossing scenario, a different detection criterion was used, based upon the motorists expectation of encountering a train at that type of crossing. The following tables summarize the results of the study in terms of the maximum locomotive speeds and/or motor vehicle speeds at which the warning signals will effectively alert the motorist at the minimum safe stopping distance of 74 m (243 ft) for each scenario.

Passive Crossings

Horn system	Motor vehicle speed, km/hr (mph)	Locomotive speed, km/hr (mph)
Nathan K-5-LA	48.3 (30)	<177 (110)
Leslie RSL-3L-RF	48.3 (30)	*
Leslie RS-3L	48.3 (30)	*

* A motorist traveling 48.3 km/hr (30 mph) requires a minimum safe stopping distance of 74 m (243 ft). These warning systems will not alert the motorist at a distance of 74 m (243 ft).

Active Crossings

Horn system	Motor vehicle speed**	Locomotive speed, km/hr (mph)
Nathan K-5-LA	0	<177 (110)
Leslie RSL-3L-RF	0	< 48 (30)
Leslie RS-3L	0	< 32 (20)

** It is assumed that the motorist has stopped before the lowered gate, and is waiting to detect the horn as confirmation of the approaching train.

Active Crossings Equipped with Wayside Horn Systems

Horn system	Motor vehicle speed, km/hr (mph)	Locomotive speed
AHS	<16.1 (10)	N/A

The warning signal duration is also addressed to determine if it can be changed to reduce the community noise impact. Historically, the signalling cycle is actuated 20 seconds before the locomotive reaches the crossing. It may be possible to actuate the signalling cycle 15 seconds before the crossing, reducing by 25 percent the community area along the rail corridor exposed to a normally unacceptable noise environment. Reducing the signal duration would require a change in the characteristics of the signal. The signal could be changed from the current long-long-short-long to either long-short-long-short or short-long-short-long, neither of which are currently in use as warning signals.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1.0 INTRODUCTION

The Federal Railroad Administration (FRA), is conducting a comprehensive research program to develop means of reducing the number of accidents and resulting casualties at highway-railroad grade crossings. In support of this effort, the Volpe National Transportation Systems Center's (Volpe Center) Acoustics Facility is conducting a study with the goal of optimizing the performance of railroad horn systems.

This study, the second in a series, evaluates the effectiveness of railroad horn systems used as audible warning for motorists at highway-railroad grade crossings. The effectiveness of railroad horn systems is evaluated using information on the acoustic characteristics of both the horn systems and motor vehicles. This information was obtained through field measurements and a literature search. The objective of the study was to determine how to: (1) optimize the effectiveness of railroad horn systems in warning motorists of the impending arrival of a train; and, (2) minimize the resulting community noise impact.

2.0 BACKGROUND

One of the functions of a railroad horn system is to warn the motorist, who may be approaching a grade crossing, of the impending arrival of a train. However, previous studies have concluded that the motorist is unable to hear the horn's warning signal in a majority of situations. In 1971(1) it was reported that "horns are not a suitable primary warning in high-speed encounters." It was reported in 1972(2) that "Recent attempts by the motor vehicle manufacturers to reduce the internal noise levels in their products have been very successful; too successful for warning signal effectiveness according to some authorities."

However, a July 1990(3) report by the FRA contradicts these conclusions. The 1990 report summarized the effects of a nighttime railroad horn ban enacted at a number of grade crossings, equipped with active signaling systems, along the Florida East Coast Railway corridor. After six years of enforcement, it was concluded that the horn ban resulted in a tripling of the accident rate at these crossings. Then, in 1991, when horn use was resumed, nighttime accidents at these crossings returned to pre-ban levels. These statistics indicate that, under certain conditions, motorists rely on the railroad horn as a warning.

The conflicting findings described above regarding the effectiveness of train horns highlights the need for the current study. The primary objective of this study is to determine under what conditions horns are effective, and how, in general, to improve their overall effectiveness.

The effectiveness of a railroad horn system is reliant upon: (1) its ability to direct its sound toward the approaching motorist; and, (2) the ability of the sound to penetrate the motor vehicle at a level that can be detected by the motorist in time to avoid a collision. In general, there are two methods to increase the ability of a sound to penetrate the motor vehicle. The first, and most common, is to increase the loudness of the sound it produces. The second is to change or modify the frequency content (i.e., pitch) of the sound.

A point has been reached where the sound level can not be increased further without causing an unacceptable impact on the surrounding communities, and indeed the locomotive occupants as well. In fact, many communities (such as those along Florida's east coast) have recently indicated that current horn systems cause an unacceptable noise environment. It has been suggested that for any major improvement, alternative warning methods must be developed which only affect the approaching motorist and not the surrounding community. One such method may be to locate the railroad horn system directly at the crossing, aimed down the approaching roadway. A prototype of this type of system is evaluated in this report.

The focus of this report is to determine the effectiveness of railroad horn systems and evaluate methods for improving their effectiveness. Pertinent data were obtained through measurements of the acoustic characteristics (i.e., the interior noise levels and sound insulation of the passenger compartment) of late model motor vehicles, as discussed herein, and the acoustic characteristics of both conventional and alternative railroad horn systems (i.e., the level, frequency content and directional characteristics). The latter are discussed in the Volpe Center report, <u>The Safety of Highway-Railroad Grade Crossings: Study of The Acoustic Characteristics of Railroad Horn Systems</u>[4]. It details the acoustic characteristics of four selected types of railroad horn systems. These horn systems are as follows: (1) The Leslie RSL-3L-RF, a three-chime system with two horns facing forward and one facing to the rear; (2) The Leslie RS-3L, a three-chime system with all horns facing forward; (3) The Nathan K-5-LA, a five-chime system with all horns facing forward; (4) The Automated Horn

System (AHS), a prototype of an alternative warning system consisting of one horn (i.e., a one-chime system) placed at the crossing and aimed down the approaching roadway.

3.0 THE ACOUSTIC CHARACTERISTICS OF RAILROAD HORN SYSTEMS ON IN-SERVICE LOCOMOTIVES

A previous Volpe Center report[4] focused on the acoustic characteristics of railroad horns mounted on stationary locomotives. Since the majority of highway-railroad grade crossing accidents involve in-transit locomotives, the analysis presented in this section focuses on the acoustic characteristics of railroad horn systems mounted on locomotives in revenue service. The effects on the warning signal due to acoustic obstructions (i.e., buildings, vegetation, etc.) along the propagation path are specifically examined.

3.1 EXPERIMENTAL METHOD

Acoustic data were collected from horn systems on locomotives in revenue service at highway-railroad grade crossings along the Florida East Coast Railway's main line. Data were collected during the period July 8-9, 1992, in Jacksonville, FL. Specific grade crossings were selected to represent a variety of building/ vegetation scenarios.

All locomotives measured were equipped with Leslie Model RS-3L horn systems on both the front and rear of the locomotive. The specific horn system activated (i.e., front or rear) was dependent upon the direction of travel of the locomotive. The horn system mounted on the front of the locomotive was modified to include an air pressure regulator, which fixed the sound level output at approximately 104 dBA at 30.5 m (100 ft). The horn system mounted on the rear of the locomotive, rated by the manufacturer to have a sound level output of 114 dBA at 30.5 m (100 ft), was not equipped with a regulator. Both types of horn systems (i.e., with and without the regulator) were measured in this study.

3.1.1 Data Acquisition Equipment

At each highway-railroad grade crossing, a digital recording system (DAT type, see Appendix A) and a sound level meter were used to collect and store acoustic data. A detailed description of this equipment can be found in Appendix A. The sound level meter was used to collect and store discrete samples of data every 0.5 second (with slow sound level meter response characteristics) over an operator-defined time period. The digital recording system was used to record the acoustic signal on magnetic tape for off-line listening and analysis.

Temperature and relative humidity were monitored, with a sling psychrometer; wind speed was monitored, with a hand held anemometer. Train speed was measured, with a portable doppler radar gun.

3.1.2 Test Sites / Microphone Locations

Measurements were made at the following six grade crossings located in Jacksonville, FL:

Site #	Crossroad Name	AAR/DOT#*
1	Sunbeam Road	271824W
2	Shad Road	271825D
3	Mussels Acres Road	271827S (Private)
4	Cedar Street	271828Y
5	Greenland Road	271829F
6	Old St. Augustine Road	271830A

*The AAR/DOT# is the designation assigned to each grade crossing by the AAR and the USDOT for inventory purposes.

Figures B-1 through B-6 present a plan view of each test site, including placement of the acoustic data acquisition systems. At each site, with the exception of Shad Road (see Fig B-2), the digital recording system was placed 15.2 m (50 ft) from the track and the sound level meter was placed 61.0 m (200 ft) from the track. The digital recording system at the Shad Road site was placed 22.9 m (75 ft) from the track and the sound level meter was placed 45.7 m (150 ft) from the track due to space restrictions. All crossings were equipped with an active signalling system consisting of flashing lights and gates.

3.1.3 Test Procedure

Acoustic data were collected simultaneously at the two microphone locations during the pass-by of the test train, with the data acquisition systems time-synchronized using a master clock. The operator-defined data acquisition period was chosen to capture the acoustic signature of the test train including the warning signal associated with its impending arrival. Two trains were recorded at each crossing (12 total pass-by events). It should be noted that, as the trains were operating on their normal timetable, the test train personnel were unaware that acoustic measurements were being conducted. System calibration was performed at the beginning and end of the data acquisition period at each test site.

3.1.4 Acoustic Data Reduction

The digital tape recordings were first monitored by ear to insure that no extraneous sounds contaminated the data. Fortunately, due to the low ambient noise levels in the test areas (less than 65 dBA, since highway traffic at the crossings was stopped by the active signaling system before the warning signal was initiated), none of the data were found to be contaminated. If any of the data were found to be contaminated, they would have been eliminated from any further analysis.

The data were then filtered into one-third octave band levels using a Brüel & Kjær Model 2131 Digital Frequency Analyzer and stored in a Volpe Center computer in contiguous ⅛ second exponentially averaged (i.e., with slow sound level meter response characteristics) data records. The warning signal associated with each locomotive approach was identified and treated as a separate pass-by event. Each event was processed over the 10-dB down duration (i.e., a time period defined by the instant when the warning signal first reached a level 10 dB less than the maximum level to the instant when the warning signal last reached a level of 10 dB below the maximum level). Each event was also broken down into its signaling components (long or short), and each component was treated as a separate sub-event and processed over its 10 dB down duration. Processing yielded the following set of data:

- Maximum A-weighted sound level (L_{Amax})
  The maximum A-weighted sound level (measured in A-weighted decibels, dBA) observed during the period of the event (signaling cycle). The A-weighting response closely simulates the response of the human ear.
- Frequency Spectra at the Time of L_{Amax}
  A plot of sound level vs. frequency at the time when the maximum A-weighted sound level was observed.
- Spectral time history
  The three-dimensional representation (level vs. frequency vs. time) of each event (one-eighth second data records).
- A-weighted time history
  The contiguous A-weighted ⅛ second sound level records over the duration of the measured event.
- Sound exposure level (SEL)
  The energy summation of the A-weighted sound level over time with a reference duration of one second. The SEL is a computed sound level which characterizes the total noise exposure of an event where the acoustic levels vary substantially over time.

The A-weighted time history data stored in the sound level meter and down-loaded to a portable notebook computer on-site were transferred into a Volpe Center computer for processing. After calibration adjustments were applied to these data, the precise 10-dB down duration of each event was identified, as above. Processing yielded the maximum A-weighted sound level (L_{Amax}), A-weighted time histories, and the sound exposure level (SEL) for each event.

3.2 ACOUSTIC DATA ANALYSIS

3.2.1 SOUND PROPAGATION

As the warning signal propagates over the distance from source to receiver (i.e., from the railroad horn to the motorist), it changes in both level and frequency content (i.e., loudness and pitch). These changes can include the effects due to spherical spreading, absorption and/or reflection of the sound due to the acoustic impedance of the ground, meteorological conditions, and shielding by buildings and vegetation along the propagation path. The following are typical rules of thumb for quantifying these effects; where simple rules of thumb do not exist, references are cited which describe detailed computational methodologies to account for these effects:

- Spherical spreading is the natural reduction in sound level with increasing distance from a sound source. It is due to the spreading of the sound wave over a progressively larger area. For a point source such as a railroad horn system, this spreading results in a reduction of 6 dB per doubling of the distance (i.e., a 6 dB drop-off rate).
- Soft ground (i.e., loose dirt, grass), can account for a reduction of approximately 1.5 dB in sound level per doubling of the distance.
- Sound energy is absorbed when propagating through the atmosphere. The reduction in sound level in each one-third octave-band due to atmospheric absorption is a function of temperature, relative humidity and distance[5].
- Wave refraction caused by wind conditions can affect sound levels as a function of wind direction. Wind blowing from source to receiver can refract the sound waves downward and cause an increase in levels at the receiver. Wind blowing from receiver to source can refract the waves upward and cause a decrease in levels at the receiver[6].

- Shielding from buildings has been shown to provide a reduction of 3 to 10 dB over the propagation path[7]. Shielding from dense vegetation has been shown to provide a reduction of 5 to 10 dB at low frequencies, and up to 20 dB at 8000 Hz (providing the vegetation extends over a distance greater than 30 m (100 ft))[7].

3.2.2 Analysis of Measured Sound Levels

Tables B-1 through B-12, Appendix B, present summary information for each train pass-by event, including date, time, operating conditions of the train, roadway conditions, and meteorological conditions. The L_{Amax}, duration and distance from the microphone for each signal component, and the overall SEL for the entire warning signal are presented for each of the two microphone positions. Appendix B also contains the frequency spectra at the time of L_{Amax} (Figures B-1 through B-12), the spectral time histories, and the A-weighted time histories for each pass-by event (Figures B-13 through B-24).

The variations in the signal duration (Tables B-1 through B-12) and A-weighted time histories (Figures C-13 through C-22) can be attributed to the specific signaling techniques of the individual locomotive personnel. Specifically, the long components range from 1.88 seconds to as long as 9 seconds, while the short components range from 0.75 second to 3.75 seconds. The duration of the signaling components can have a significant effect on the sound exposure level and therefore the community noise impact (see Section 3.2.3 below).

Figure 1 is a plan view of the Shad Road site where pass-by events 3 and 4 were measured. As shown, the building close to the tracks blocks the direct path from the locomotive to the receiver (sound level meter). This building acts as a sound barrier and attenuates the level of the first components of the signaling cycles. This is most evident when the L_{Amax} for the first and second signaling components are compared. The direct path distance from the train to the sound level meter at the time of emission of the first and second signaling components of train number 4 are 178 and 105 m (584 and 345 ft) respectively. Assuming fairly standard over-ground propagation characteristics, i.e., approximately 7.5 dBA per doubling of distance, the 73 m (240 ft) difference in distance accounts for only 5.7 dBA of the total measured sound level difference. The remaining 9.0 dBA can be attributed to building attenuation. Shielding attenuation levels of this magnitude due to highway noise barriers are fairly common[7].

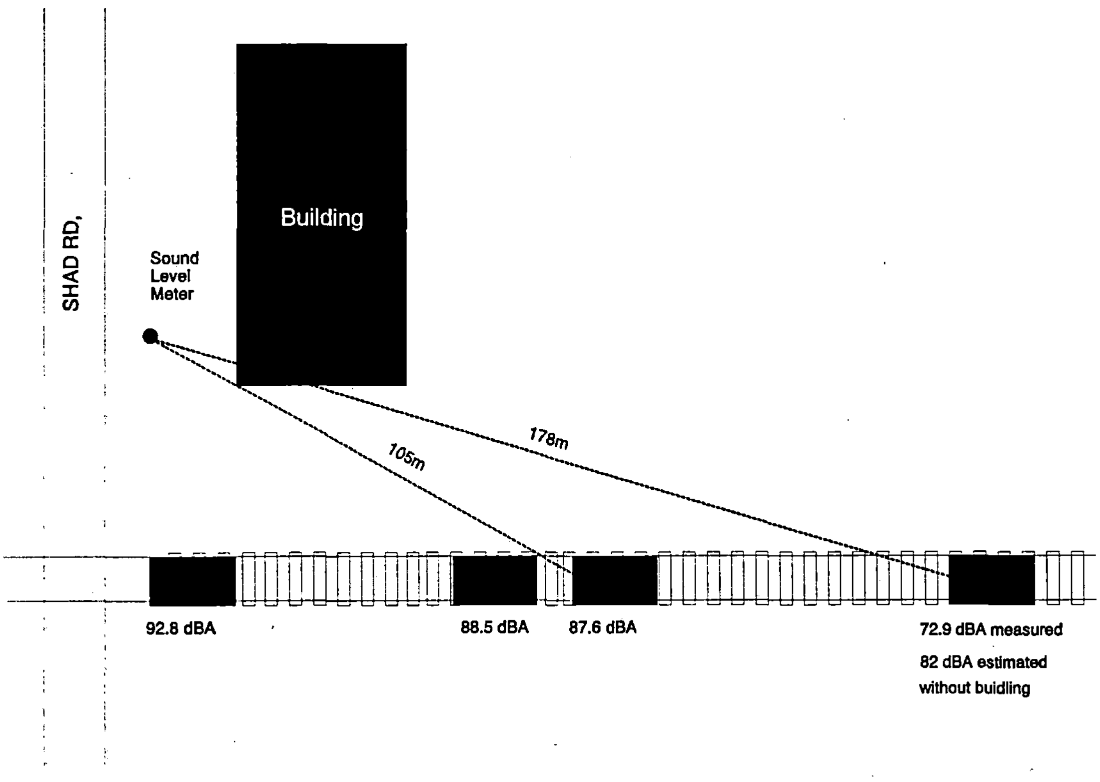


Figure 1. Effect of a Building on the Measured Sound Level During a Locomotive Pass-by

3.2.3 Analysis of Community Noise Impacts

An outdoor day-night average A-weighted sound level (defined as DNL and symbolized by L_{dn}) is a single number metric which is widely used to determine the impact of a noise source on a community. L_{dn} is defined as the average A-weighted sound level over a 24 hour period, with a 10 dB penalty imposed upon sounds occurring between 10 pm and 6 am. The US Department of Housing and Urban Development (HUD) has characterized L_{dn} in terms of degrees of acceptability of an outdoor residential noise environment[8]. The upper limit for a "normally acceptable" environment is L_{dn} = 65 dBA; an L_{dn} from 65 to 75 dBA is defined as "normally unacceptable"; and an L_{dn} above 75 dBA is "unacceptable". L_{dn} can be calculated by summing the SELs from each noise event (in this case, each train pass-by) over a 24 hour period, as follows:

$$L_{dn} = \sum_{i=1}^{n} SEL_i - 49.365 \tag{1}$$

The estimated L_{dn} at each measurement microphone location was computed using the average SEL from Tables B-1 through B-12 and the estimated daily number of trains. The average number of trains passing through each crossing was one train per hour during daytime hours (6 am to 10 pm) and one train per hour during nighttime hours (10 pm to 6 am), as reported by the USDOT/AAR grade crossing inventory, last updated in 1988. Table 1 shows the L_{dn}, computed, as above, for each of the six test grade crossings, assuming the USDOT/AAR average number of daily operations at each crossing.

Residences located less than 61.0 m (200 ft) from the crossing would not meet the HUD's "normally acceptable" criterion of L_{dn} = 65 dBA. Figure 2 shows that these estimated L_{dn} values will change if the actual number of operations at each crossing (especially at night) were different.

Table 1. ESTIMATED DAY-NIGHT SOUND LEVEL

	L_{dn} (Estimated) (dBA)			
Distance from Crossing, m, (ft)	15.2 (50)	22.9 (75)	45.7 (150)	61.0 (200)
Sunbeam Rd.	77.83			69.38
Shad Rd.		68.51	68.56	
Mussels Acres Rd.	78.77			68.86
Old St. Augustine Rd.	79.90			72.56
Cedar St.	74.59			65.65
Greenland Rd.	79.34			70.74

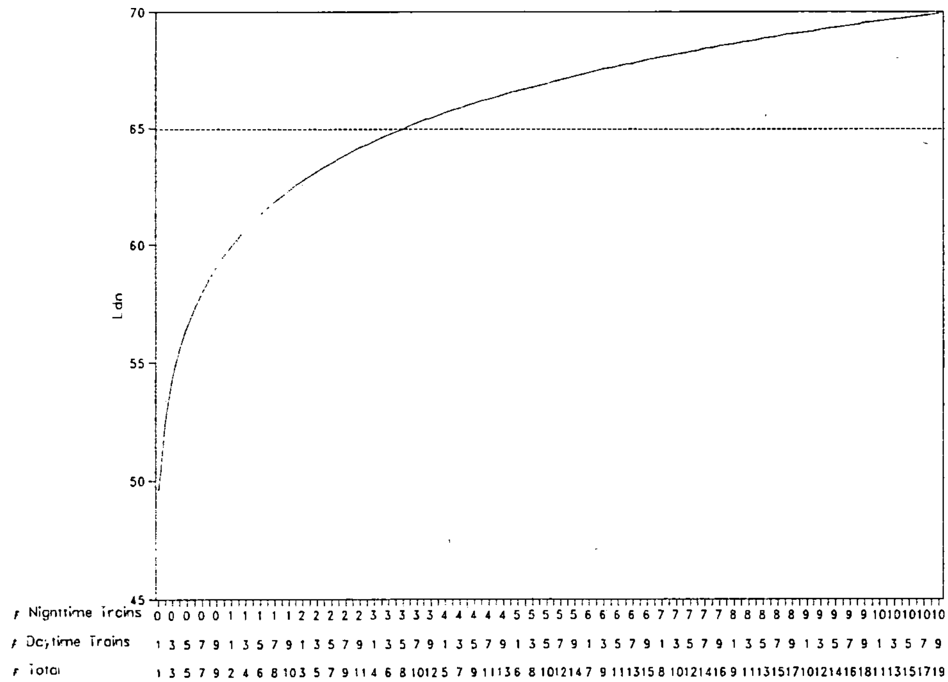


Figure 2. Ldn vs. Number of Train Operations at Sunbeam Rd., 61 m from the Crossing

4.0 ACOUSTIC CHARACTERISTICS OF MOTOR VEHICLES

A measure of the acoustic characteristics (i.e., interior noise levels and the ability of outside noises to penetrate to the interior) of motor vehicles is needed in order to fully understand their effects on the detectability of an audible warning signal. The motor vehicle structure limits the propagation of sound to its interior by absorbing and/or reflecting the incident sound energy. The amount of incident sound energy absorbed and/or reflected is referred to as insertion loss. The interior noise levels resulting from normal vehicle operation can reduce the detectability of a warning signal by acoustic masking.

Various studies[8],[9],[10] on the subject of motor vehicle acoustic characteristics were conducted in the 1970's and 1980's. These studies reported insertion loss and/or interior noise data for a small number of motor vehicles. However, most of these data cannot be applied to late model motor vehicles. Design changes have been made by automotive manufacturers in the areas of sound insulation and vibration control to further limit the penetration of exterior sound. This is evidenced by recent information from General Motors[8] and automotive magazines which suggests that interior noise levels alone have decreased by at least 10 dB since 1970. As a part of this study, acoustic data were collected, through field measurements, to determine the interior noise levels and insertion loss characteristics of late model motor vehicles.

4.1 INTERIOR NOISE

Interior noise is defined as the sound pressure level inside the vehicle resulting from normal vehicle operations. A number of noise sources can contribute to the overall interior noise levels in varying degrees dependent upon the operating conditions of the vehicle. They are: tire/roadway interaction, the engine and drive train, exhaust system, air turbulence resulting from vehicle motion, ventilation system (including fan and windows), and radio, as shown in Figure 3. These interior noise levels may be as loud or louder than the warning signal which penetrates the vehicle, and can reduce its detectability.

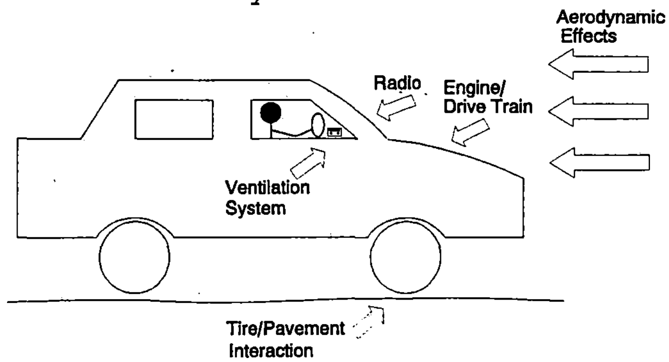


Figure 3. Sources of Interior Noise Due to Normal Vehicle Operation

4.2 INSERTION LOSS

Insertion loss is defined as the difference in noise level at a receiver position before and after the installation of a noise barrier; in this case, the barrier is the motor vehicle structure. The barrier affects the warning signal by absorbing and/or reflecting a portion of the sound, as shown in Figure 4. Insertion loss was calculated by subtracting the sound level measured at a position inside the motor vehicle from the sound level measured at the same position (identical height and offset distance from the source) with the motor vehicle removed. Because of the complex structure and variety of materials used in the body construction of motor vehicles, the insertion loss can vary with vehicle type and source-incidence angle.

4.3 EXPERIMENTAL PROCEDURE

The following sections describe the equipment and procedures used during measurements of interior noise levels and insertion loss.

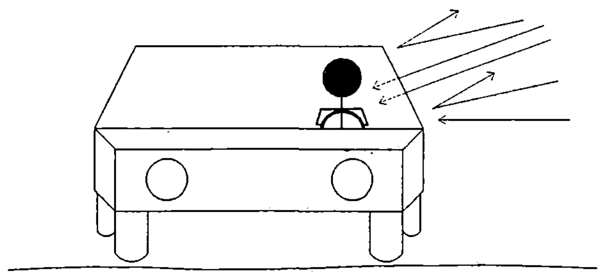


Figure 4. The Effect of Insertion Loss on the Warning Signal

Measurements were conducted during the period June 23-25, 1992. Detailed descriptions of the data acquisition systems, artificial source, and calibration procedures are included in Appendix A.

4.3.1 Test Vehicles

Following is a brief description of each of the motor vehicles tested. Seven late model vehicles were chosen to be representative of a variety of vehicle sizes, types, and manufacturers. The cars were privately owned and provided by Volpe Center employees.

	Honda Civic	**Ford Festiva**
Year:	1990	1991
Class:	Small	Small
Engine:	Four-cylinder	Four-cylinder
Transmission:	Manual	Manual

	Honda Accord LX	**Oldsmobile Cutlass Ciera**	**Chevrolet Lumina**
Year:	1991	1991	1991
Class:	Mid	Mid	Mid
Engine:	Four-cylinder	Four-Cylinder	Four-cylinder
Transmission:	Automatic	Automatic	Automatic

	Mercury Grand Marquis	Dodge Grand Caravan
Year:	1991	1991
Class:	Large	Minivan
Engine:	Six-cylinder	Six-cylinder
Transmission:	Automatic	Automatic

4.3.2 Test Sites

Interior noise level data (dynamic measurements) were collected at speeds of up to 48.3 km/hr (30 mph) on Memorial Drive in Cambridge, MA, a four lane east-west roadway. The level roadway was made up of dense graded pavement. It was bordered by the Charles River to the south and buildings to the north.

Insertion loss data (static measurements) were collected on the Volpe Center grounds. The test area was covered by short cropped grass, bordered by hedges to the east and south, a parking lot to the north and a high-rise building approximately 150 m (492 ft) to the west. The microphone was placed 7.62 m (25 ft) from the noise source in the center of the test area. The noise source was directed to the east at a row of hedges.

4.3.3 Interior Noise Measurements

Dynamic interior noise measurements were conducted following the guidelines of the Society of Automotive Engineers Recommended Practice[11]. Measurements were made with the vehicle operating under the following conditions: a constant speed of 48.3 km/hr (30 mph), windows closed, ventilation systems off, and radio off. Ventilation systems and the radio were left off because the noise levels from these sources are highly dependent upon individual taste. Acoustic data were recorded on a digital recording system (PCM type, see Appendix A). Periods of minimum activity on the roadway were chosen for data acquisition, thereby minimizing acoustic contamination from other sources.

Sound level data was measured inside the motor vehicle utilizing a microphone/preamplifier assembly (oriented for grazing incidence) mounted on a tripod on the right front seat at a height corresponding to the height of the ear of a person sitting in the vehicle (approximately 0.7 m (2.3 ft) above the seat). The tripod and microphone/preamplifier assembly were mounted in a manner that minimized the effects of vehicle vibrations.

4.3.4 Insertion Loss Measurements

A power amplifier/speaker system was used as an artificial noise source, broadcasting octave bands of electrical noise with equal energy in each one-third octave band to be measured at a reference location both inside and outside the test vehicles. The level broadcast was monitored 1.2 m (4 ft) from the source to insure that the acoustic signal was stable and identical for each measurement. A reference position for all measurements was established at a height of 1.2 m (4 ft) above the ground, 7.62 m (15 ft) from the front of the artificial sound source.

Sound level data were measured inside the motor vehicle utilizing a microphone/preamplifier assembly (oriented for grazing incidence) as described in Section 4.3.3. The test was conducted with the vehicle positioned relative to the artificial noise source so the sound was incident upon the front, right, and left sides of the vehicle (0°, -45°, and +45° angles respectively). The recorded octave bands of electrical noise broadcast by the artificial source were measured at the reference position and recorded on magnetic tape by the digital recording system.

The test was repeated with the motor vehicle removed (i.e., outside the motor vehicle). A microphone/preamplifier assembly (oriented for grazing incidence) was mounted on a tripod and positioned 1.2 m (4 ft) above ground level at the reference position (7.62 m (15 ft) from the source). Octave bands of electrical noise broadcast by the artificial source were measured at the reference location and recorded on magnetic tape by the digital recording system. Insertion loss measurements were collected following the guidelines of the American National Standards Institute[12]. All measurements were made during periods of general quiet. Ambient noise levels (with the artificial source off) were also measured and recorded both inside and outside the vehicle. These were used to insure the integrity of the measured noise data.

4.3.5 Meteorological Data

Meteorological data were collected throughout the data acquisition period. A hand-held anemometer was used to monitor wind speed and direction, a sling psychrometer was used to monitor temperature and relative humidity.

Temperatures throughout the test period averaged 21°C (70°F), with a relative humidity of 60%. Wind speeds ranged from 0-10 knots.

4.3.6 Acoustic Data Reduction

Acoustic data were reduced on an event-by-event basis. Dynamic interior noise level events consisted of a period of 30 seconds during which the vehicle was stabilized at a speed of 48.3 km/hr (30 mph) with no extraneous sounds. Static insertion loss events consisted of a 12 second period of recorded octave band pink noise measured at the reference position inside and outside the vehicle (i.e., with the vehicle removed).

The digitally recorded data were processed and filtered into one-third octave-band levels using a Brüel & Kjær Model 2131 Digital Frequency Analyzer, after monitoring to insure that no extraneous sounds contaminated the data. The digitized one-third octave-band sound pressure level data from the analyzer were stored in a Volpe Center computer in contiguous one second linear data records for each event, with appropriate calibration and system adjustments applied. The acoustic data were tested against the ambient noise levels to insure their integrity. The corrected one-second records were then energy-averaged over the duration of the event to produce an average sound pressure level/frequency spectrum for each event.

These spectral data were transferred into a spreadsheet for analysis and computation of insertion loss levels.

4.4 ACOUSTIC DATA ANALYSIS

The following sections present an analysis of interior noise and insertion loss data.

4.4.1 Interior Noise

Figure C-1 presents the average interior noise levels measured in each one-third octave frequency band (i.e., frequency spectrum) for each of the seven vehicles tested during normal operation at 48.3 km/hr (30 mph). Although the interior noise frequency spectra for each of the seven vehicles are similar, some general trends are discernable. The interior noise levels of the minivan in the range from 500 Hz to 4000 Hz are 5-10 dB lower than those of other vehicles tested. This may, in part, be due to the greater height of the minivan which effectively places the measurement position a further distance from the roadway. The increased distance may decrease the level of the tire/roadway interaction noise. Differences in interior noise spectra are also noted for the small to medium four-cylinder vehicles without overdrive (Honda Civic, Ford Festiva, and Cutlass Ciera), and the medium to large four-/six-cylinder vehicles with overdrive (Honda Accord, Chevrolet Lumina, and Mercury Grand Marquis). Differences occur predominately in the region between 500 and 4000 Hz, presumably due to the reduced engine noise at lower engine rpm and the sound insulation and vibration control features in the medium-large vehicles. An average interior noise spectrum, representative of the seven motor vehicles tested, was calculated and is shown in Figure C-2. This average spectrum will be used in the analysis of railroad horn system effectiveness in later sections of this report.

For comparative purposes, Table 2 presents interior A-weighted noise levels as published in recent automotive magazines[13],[14] for several 1992-1993 model year vehicles.

Table 2. Interior Noise Levels of 1992-1993 Model Year Automobiles

Auto	Interior noise level at idle (dBA)	Interior noise level at 70 mph (dBA)
Audi 100S	47	71
Acura Legend L	44	72
BMW 325i	51	73
BMW 740i	43	61
Eagle Vision TSi	44	70
Ford Tarus SHO Wagon	41	71
Infiniti J30	40	69
Lexus ES300	38	67
Lexus SC400	40	69
Lincoln Mark VIII	44	66
Mazda 626ES	43	70
Mazda 929	40	68
Mercedes-Benz 600SL	48	70
Mitsubishi Diamante LS	43	67
Saab 9000CD	43	70
Volkswagen Passat GLX	43	69
Volvo 960	44	70

A review of interior noise data from previous studies[9],[10],[15] was conducted. The following effects were found to be applicable to late-model motor vehicles.

- Open windows will increase interior noise levels by 2-3 dB at low frequencies (< 1000 Hz) and by 5-10 dB at high frequencies.
- Air conditioning systems operating at medium or high will increase interior noise levels by 2-5 dB at low frequencies (<1000 Hz) and 5 to 10 dB at high frequencies.
- Radio operation at a "normal volume"[10] will increase interior noise levels by 10 to 30 dB.

4.4.2 Insertion Loss

The insertion loss measured in each one-third octave band at each sound incidence angle for the seven vehicles tested is presented in Appendix C, Figures C-3 through C-9. Note: the insertion loss did not vary significantly between the three incidence angles tested in this study. A three-angle average insertion loss was thus calculated to represent each individual vehicle (as shown by the dotted line). They are presented together in a single graph (Figure C-10) for a direct comparison of the insertion loss of each vehicle tested. The average insertion loss did not vary significantly from vehicle to vehicle, thus an average insertion loss was calculated to be representative of the seven vehicles tested in this study (Figure C-11).

A review of the insertion loss data found in previous studies[10] was conducted. The effect of open windows was assumed to be applicable to late model motor vehicles. Open windows cause a decrease in insertion loss of approximately 5 to 15 dB.

5.0 ANALYSIS OF EFFECTIVENESS

Sections 5.1 through 5.4 discuss the ability of the horn systems selected for this study (i.e., Leslie RSL-3L-RF, Leslie RS-3L, Nathan K-5-LA, and Automated Horn System (AHS)) to be detected by the motorist in several scenarios. Section 5.5 recommends an alternative to the conventional signaling cycle which would substantially reduce the noise impact on communities in the vicinity of a grade crossing.

For the warning signal to be detected by the motorist, the warning signal level must be above the background noise level. The difference between the signal level and the background noise level is defined as the signal-to-noise ratio (S/N). The required S/N can be arrived at if the following two factors are known: 1) the desired level of effectiveness of the horn system, and 2) the perceived frequency of trains. For the purpose of this study, the effectiveness of a railroad horn system is defined as the probability that a person with normal hearing will detect the warning signal. Thus, the effectiveness can have values ranging from zero to one. The desired level of effectiveness is set at a value of 0.95 to establish a high degree of certainty that the warning signal will be heard. The perceived frequency of trains can also be likened to a probability and can vary between zero and one. Using signal detection theory[16], the S/N which results in an effectiveness of 0.95 can be calculated for a range of perceived train probabilities. The computed S/N varies between 11 dB for a low perceived train probability of 0.1, and 1 dB for a high perceived train probability of 0.9. The S/N ratio does not need to be present in each one-third octave-band; a minimum of five one-third octave-bands will be sufficient to result in the desired level of effectiveness.

Currently, there are two general types of grade crossing scenarios in which the train/motorist encounter might occur. In addition, there is a third proposed scenario which is being evaluated in the current study. In each scenario, the motorist has a different perceived frequency of trains passing through the crossing. Based upon this, the greatest minimum warning distance (and therefore locomotive speed) at which each horn system has an effectivness of 0.95 was identified according to the computed S/N. The three scenarios are as follows:

- **Passive Crossings** - The train/motorist encounter occurs at a passive crossing. In this scenario, the railroad horn is mounted on the locomotive, rail traffic volume is low, the road traffic volume is low, and the traffic speeds are relatively high. Through previous knowledge of the intersection, the motorist may perceive that there is only a small chance of encountering a train. Therefore, the perceived train frequency probability is set at 0.1, resulting in a S/N of 11 dB for an effectiveness of 0.95.
- **Active Crossings** - The train/motorist encounter occurs at an active crossing. In this scenario, the railroad horn is mounted on the locomotive and the rail traffic volume and/or the road traffic volume is high. The motorist has presumably stopped at the lowered gates. Through previous knowledge of the intersection, the motorist may have a high expectation of encountering a train. Therefore, the perceived train frequency probability is set at 0.9 resulting in a S/N of 1 dB for an effectiveness of 0.95.
- **Active Crossings Equipped with a Wayside Horn System** - The train/motorist encounter occurs at an active crossing equipped with a wayside horn system. In this scenario, the railroad horn is mounted directly at the crossing. The motorist is assumed to be on approach to the active crossing where either the gates have not yet been lowered, or the motorist can not see them. Through previous knowledge of the intersection, but without warning that a train may be on approach, the motorist may have a moderate expectation of encountering a train.

Therefore, the perceived train frequency probabiliy is set at 0.5 resulting in a S/N of 8 dB for an effectiveness of 0.95.

5.1 PASSIVE CROSSINGS

As stated above, during the train/motorist encounter at the passive crossing, the motorist may perceive that there is only a small chance of encountering a train. At a typical passive crossing, most motorists have rarely encountered a train. Therefore they may assume that, based upon prior experience, no trains will be approaching the crossing. Since there is no need to stop at the crossing unless a train is detected, higher vehicle speeds may be encountered.

5.1.1 Minimum Warning Distance

The minimum warning distance (MWD) is defined as the distance between the motor vehicle and the front of the locomotive (Figure 6) at the critical time (T_{cr}), as shown in Equation 2.

$$MWD=\sqrt{(T_{cr}*LocomotiveSpeed)^2+(T_{cr}*VehicleSpeed)^2} \qquad (2)$$

T_{cr} is the instant at which detection must occur to avoid a collision; it is a function of driver reaction time, the minimum motor vehicle stopping distance (MSD), and motor vehicle length, as shown in Equation 3[1].

$$T_{cr} = \frac{MSD\ (m)\ +9.14+ Vehicle\ Length}{Vehicle\ Speed\ (m/s)} + Driver\ Reaction\ Time \qquad (3)$$

Using guidelines in the 1982 Transportation and Traffic Engineering Handbook[17], minimum safe motor vehicle stopping distances (MSD) were calculated as follows:

$$MSD = V_m^2 \ / \ 255(f \pm g), \qquad (4)$$

where V_m is the motor vehicle speed (km/hr), g is the pavement grade, and f is the skidding friction coefficient, in accordance with the American Association of State Highway and Transportation

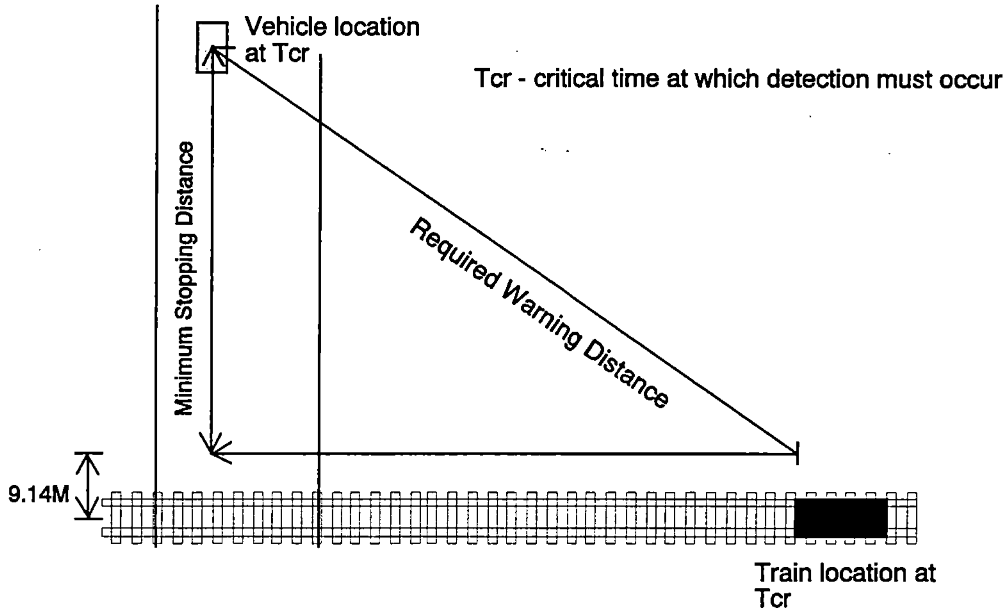


Figure 5. Required Warning Distance

Officials (AASHTO). For the purpose of this study, calculations assumed no grade.

Minimum warning distances for this scenario were calculated and are presented in Table 3 for various vehicle speeds and train speeds, using the methodology outlined by Aurelis and Korobow[1]. These calculations assumed a roadway perpendicular to the railroad track, a vehicle length of 5.8 m (19 ft), and a driver reaction time (i.e., the time elapsed between the instants when the warning signal is heard and when the brake is engaged) of two and one-half seconds[18].

Table 3. MINIMUM REQUIRED WARNING DISTANCE

MOTOR VEHICLE SPEED, km/hr (mph)	TRAIN SPEED, km/hr (mph)	MINIMUM WARNING DISTANCE, m (ft)	MOTOR VEHICLE SPEED, km/hr (mph)	TRAIN SPEED, km/hr (mph)	MINIMUM WARNING DISTANCE, m (ft)
32.2 (20)	32.2 (20)	67 (220)	48.3 (30)	32.2 (20)	88.8 (291)
	48.3 (30)	86 (281)		48.3 (30)	104 (343)
	64.4 (40)	106 (348)		64.4 (40)	123 (404)
	80.5 (50)	128 (419)		80.5 (50)	144 (471)
	96.6 (60)	150 (492)		96.6 (60)	165 (542)
	112.7 (70)	173 (567)		112.7 (70)	188 (615)
	128.8 (80)	196 (642)		128.8 (80)	210 (690)
	144.8 (90)	219 (718)		144.8 (90)	234 (766)
	160.9 (100)	242 (794)		160.9 (100)	257 (843)
	177.0 (110)	265 (870)		177.0 (110)	280 (919)
64.4 (40)	32.2 (20)	122 (399)	80.5 (50)	32.2 (20)	165 (540)
	48.3 (30)	136 (447)		48.3 (30)	178 (584)
	64.4 (40)	154 (505)		64.4 (40)	196 (642)
	80.5 (50)	174 (572)		80.5 (50)	216 (709)
	96.6 (60)	196 (644)		96.6 (60)	239 (783)
	112.7 (70)	220 (720)		112.7 (70)	263 (862)
	128.8 (80)	244 (799)		128.8 (80)	288 (946)
	144.8 (90)	268 (880)		144.8 (90)	315 (1032)
	160.9 (100)	293 (962)		160.9 (100)	342 (1120)
	177.0 (110)	319 (1045)		177.0 (110)	369 (1211)

5.1.2 Signal Detectability

In order for the motorist to take the appropriate action in time to avoid a collision, the warning signal must be detected at or before the instant of reaching the required warning distance. As stated in Section 5.0, the warning signal will have an effectiveness of 0.95 if the S/N is at least 11 dB in five or more one-third octave-bands.

To determine if above effecitiveness criteria is met, the warning signal level inside the vehicle at the required warning distance was compared with the average measured background noise level for a vehicle traveling 48.3 km/h (30 mph). This speed is chosen for this analysis because it was the speed at which interior noise measurements were collected (Section 3.4.1 and Figure C-2). If the vehicle is traveling faster, the interior noise may be greater; if the vehicle is traveling slower, the interior noise may be less. As was stated in Section 5.1, vehicle speeds may be relatively high at this type of crossing, and interior noise levels may be greater. Signal levels **inside** the vehicle were calculated by subtracting the average measured motor vehicle insertion loss (Figure C-11) from the signal levels obtained through measurements, extrapolated to various distances using a drop-off rate of 7.5 dB per distance doubling.

For the Nathan K-5-LA, it was found that the greatest distance at which the S/N is 11 dB in at least five one-third octave-bands is 280 m (919 ft). A motorist traveling 48.3 km/hr (30 mph) requires a warning at a minimum distance of 280 m (919 ft) in an encounter with a locomotive traveling 177 km/hr (110 mph) - the highest allowable speed (see Table 3). Therefore, the Nathan K-5-LA will be effective for motorists traveling 48.3 km/hr (30 mph) in encounters with locomotives traveling less than 177 km/hr (110 mph). Figure 7 shows the interior noise level plus 11 dB compared to the warning signal levels inside the vehicle 280 m (919 ft) from the Nathan K-5-LA.

A motorist traveling 48.3 km/hr (30 mph) requires a minimum stopping distance of 74 m (243 ft). Therefore, this is the minimum distance at which the signal must be detected. For both the Leslie RSL-3L-RF and the Leslie RS-3L, it was found that the S/N is not 11 dB in at least five one-third octave-bands. Figure 8 shows the interior noise level plus 11 dB compared to the warning signal levels inside the vehicle 74 m (243 ft) from the Leslie RSL-3L-RF and the Leslie RS-3L.

5.2 ACTIVE CROSSINGS

As stated in Section 5.0, the active crossing represents a situation where the motorist has stopped before the lowered gate, and is waiting to detect the horn as confirmation of the approaching train. In this scenario, the motorist has a high expectation of encountering a train.

5.2.1 Required Warning Distance

The required warning distance in this scenario is again defined as the distance between the motor vehicle and the front of the locomotive at the critical time (T_{cr}). Because it is assumed that the motorist has slowed down or stopped at the lowered gate, T_{cr} is now only a function of train speed and driver reaction time.

An estimate of T_{cr} is based on the following scenario: The motorist has stopped at a crossing with lowered gates. If the horn is not detected, the motorist will need approximately 2.5 seconds to make the decision whether or not to continue around the gates. If the motorist makes the unsafe and illegal decision to continue around the gates and across the tracks, he will need approximately 7.5 seconds to do so. Thus, T_{cr} is assumed to be 10 seconds before the locomotive arrives at the crossing.

The following Table summarizes the minimum warning distances required at active crossings to allow the 10 seconds needed to circumvent the gate for four locomotive speeds:

Locomotive Speed, km/h (mph)	Distance from Locomotive to Motorist, m (ft)
48.3 (20)	134 (440)
64.4 (40)	178 (584)
96.6 (60)	268 (879)
177.0 (110)	492 (1614)

5.2.2 Signal Detectability

As stated in Section 5.0, the warning signal will have an efffectiveness of 0.95 if the S/N is at least 1 dB in five or more one-third octave-bands. Because a S/N of 1 dB is extremely low (a change in loudness of 1 dB is generally imperceptible to a human), a more conservative estimate of 3 dB will be used in this scenario (a change in loudness of 3 dB is generally slightly perceptible to a human).

To determine the S/N, the warning signal level inside the vehicle (Section 5.1.2) at the required warning distance is compared with the average measured interior noise level for a vehicle traveling 48.3 km/h (30 mph) (Section 3.4.1 and Figure C-2). Although effectiveness is based upon the assumption that the vehicle is at idle, interior noise levels at 48.3 km/hr (30 mph) are used due to a lack of interior noise data at idle. It is noted that the interior noise levels may be on the order of 15-25 dBA lower at idle than at 48.3 km/hr (30 mph). Unfortunately, the necessary one-third octave-band data needed to apply this estimation is unavailable.

For the Nathan K-5-LA, it was found that the greatest distance at which the S/N is at least 3 dB in at least five one-third octave-bands is 492 m (1614 ft). As discussed earlier, 492 m (1614 ft) is the minimum warning distance required for a locomotive traveling 177 km/hr (110 mph). Therefore, this horn system will be effective in situations where the locomotive is traveling at or less than 177 km/hr (110 mph). Figure 9 shows the interior vehicle noise levels

+3 dB compared to the warning signal levels inside the vehicle 492 m (1614 ft) from the Nathan K-5-LA.

For the Leslie RSL-3L-RF, it was found that the greatest distance at which the S/N is 3 dB in at least five one-third octave-bands is 134 m (440 ft). 134 m (440 ft) is the minimum warning distance for a locomotive traveling 48 km/hr (30 mph). Therefore, this horn system will only be effective in situations where the locomotive is traveling at or less than 48 km/hr (30 mph). Figure 10 shows the interior vehicle noise levels +3 dB compared to the warning signal levels inside the vehicle 134 m (440 ft) from the Leslie RSL-3L-RF.

For the Leslie RS-3L, it was found that the greatest distance at which the S/N is 3 dB in at least five one-third octave-bands is 89 m (292 ft). 89 m (292 ft) is the minimum warning distance for a locomotive traveling 32 km/hr (20 mph). Therefore, this horn system will only be effective in situations where the locomotive is traveling at or less than 32 km/hr (20 mph). Figure 11 shows the interior vehicle noise levels +3 dB compared to the warning signal levels inside the vehicle 89 m (292 ft) from the Leslie RS-3L.

5.3 ACTIVE CROSSINGS EQUIPPED WITH WAYSIDE HORN SYSTEMS

As stated in Section 5.0, at an active crossing equipped with a wayside horn system, the motorist is assumed to be on approach to the crossing, and may not yet have seen the gates being lowered. In this case, the wayside horn may serve as a primary source of warning. However, these horn systems will likely be placed at crossings where there is a high volume of locomotive traffic. Therefore, the motorists expectations of encountering a train are moderate (i.e., in-between the expectations at a passive crossing and at an active crossing).

5.3.1 Required Warning Distance

For a wayside horn system, such as the AHS, the required warning distance is the distance between the AHS and the motorist approaching the crossing. Since the AHS is placed directly at the crossing and not on the locomotive, this distance is only a function of motor vehicle speed.

The following Table summarizes the minimum warning distances at AHS-equipped crossings for various motor vehicle speeds:

Vehicle Speed Speed, kph (mph)	Minimum Stopping Distance, m (ft)
16.1 (10)	29 (95)
32.2 (20)	47 (154)
48.3 (30)	74 (243)
64.4 (40)	109 (358)
96.6 (60)	204 (669)

5.3.2 Signal Detectability

As stated in Section 5.0, the warning signal will have an efffectiveness of 0.95 if the S/N is at least 8 dB in five or more one-third octave-bands.

To determine the S/N, the warning signal level inside the vehicle (Section 5.1.2) at the minimum warning distance is compared with the average noise level inside a vehicle traveling 48.3 km/hr (30 mph) (Section 3.4.1 and Figure C-2). Although a determination of effectiveness is made for a range of motor vehicle speeds, interior noise levels at 48.3 km/hr (30 mph) only are used in this determination due to a lack of interior noise data at other speeds. It is noted that if the vehicle is traveling faster, the interior noise may be greater; if the vehicle is traveling slower, the interior noise may be less.

It was found that the greatest distance at which the S/N is 8 dB in at least five one-third octave-bands is 29 m (95 ft). 29 m (95 ft) is the minimum stopping distance for a motorist traveling 16.1 km/hr (10 mph). Figure 12 shows the interior vehicle noise levels

+8 dB compared to the warning signal levels inside a motor vehicle 29 m (95 ft) from the AHS.

5.4 EFFECTIVENESS SUMMARY

There are numerous types of grade crossing scenarios that result in varying motorist expectations of the relative risks. The detectability criteria used for this study were selected to be representative of the range of grade crossing/motorist combinations likely to be encountered. The following tables summarize the locomotive speeds and/or motor vehicle speeds at which the warning signals will be effective in each scenario.

Passive Crossings

Horn system	Motor vehicle speed, km/h (mph)	Locomotive speed, km/h (mph)
Nathan K-5-LA	48.3 (30)	<177 (110)
Leslie RSL-3L-RF	48.3 (30)	*
Leslie RS-3L	48.3 (30)	*

* A motorist traveling 48.3 km/hr (30 mph) requires a minimum safe stopping distance of 74 m (243 ft). These warning systems will not alert the motorist at a distance of 74 m (243 ft).

Active Crossings

Horn system	Motor vehicle speed**	Locomotive speed, km/h (mph)
Nathan K-5-LA	0	<177 (110)
Leslie RSL-3L-RF	0	<48 (30)
Leslie RS-3L	0	<32 (20)

** It is assumed that the motorist has stopped before the lowered gate, and is waiting to detect the horn as confirmation of the approaching train.

Active Crossings Equipped with Wayside Horn Systems

Horn system	Motor vehicle speed, km/h (mph)	Locomotive speed
AHS	<16.1 (10)	N/A

5.5 EFFECTIVENESS OF WARNING SIGNAL DURATION

As stated in Section 3.2.2, for grade crossings having locomotive pass-bys occurring at a rate of one per hour, the community noise environment at distances less than 61.0 m (200 ft) from the grade crossing would be "normally unacceptable" as a result of railroad horn systems. Due to the nature of conventional horn systems, not only is the community in the vicinity of a grade crossing exposed to this "normally unacceptable" noise environment; the entire community along the rail corridor from where the signaling cycle is actuated to the grade crossing is exposed. A reduction in the size of the community impacted can be achieved by reducing (where possible) the distance from the crossing at which the signaling cycle is actuated.

The signal actuation distance is a function of the desired length of the signaling cycle. Typically, signaling cycles have had a duration of 20 seconds. This duration gives the motorist approximately 13-15 seconds of advance warning before the critical time (T_{cr}, see Section 5.1.1). It may be possible to reduce the advance warning time to 10 seconds, resulting in a cycle duration of approximately 15 seconds. This will reduce the size of the community along the rail corridor which is exposed to a normally unacceptable noise environment by approximately 25 percent.

Changing the signaling cycle duration to 15 seconds requires a change in the signalling cycle. Historically, the signaling cycle has consisted of two long components lasting approximately five seconds each, a short component lasting approximately two seconds, followed by a third long component, for a total duration of 17-20 seconds. A signaling cycle with a duration of 15 seconds could consist of two long and two short components: either long-short-short-long, or short-long-short-long; neither of these options are currently in use[19].

Table 4 lists the locomotive's position 15 seconds before it reaches the crossing at a range of speeds. It shows that for a locomotive traveling 96 km/hr (60 mph), a signalling cycle duration of 15 seconds would require actuation at a distance of 400 m (1312 ft) from the crossing. It should be noted that the average distance from the whistle post to the grade crossing is 400 m (1312 ft) in most states[20]. Therefore, for locomotives traveling faster than 96 km/hr (60 mph), the signaling cycle should be actuated before passing the whistle post, and for locomotives traveling slower than 96 km/hr (60 mph), after passing it. By following these guidelines, a relatively constant warning time could be achieved and the size of the community exposed by the warning signal to a normally unacceptable noise environment could be reduced by approximately 25 percent.

Table 4. Locomotive Position at Signaling Cycle Actuation

Locomotive Speed, km/hr (mph)	Locomotive Position Where 15 Second Signal Should be Actuated, m (ft)
32.2 (20)	134.2 (440)
48.3 (30)	201.3 (660)
64.4 (40)	268.3 (880)
80.5 (50)	335.4 (1100)
96.0 (60)	400.0 (1312)
112.7 (70)	469.6 (1540)
128.8 (80)	536.7 (1761)
144.8 (90)	603.3 (1979)
160.9 (100)	670.4 (2200)
177.0 (110)	737.5 (2420)

Figure 6. Passive Crossing
Detectability Level vs. Warning Signal Level
280 m (919 ft) From Nathan K-5-LA

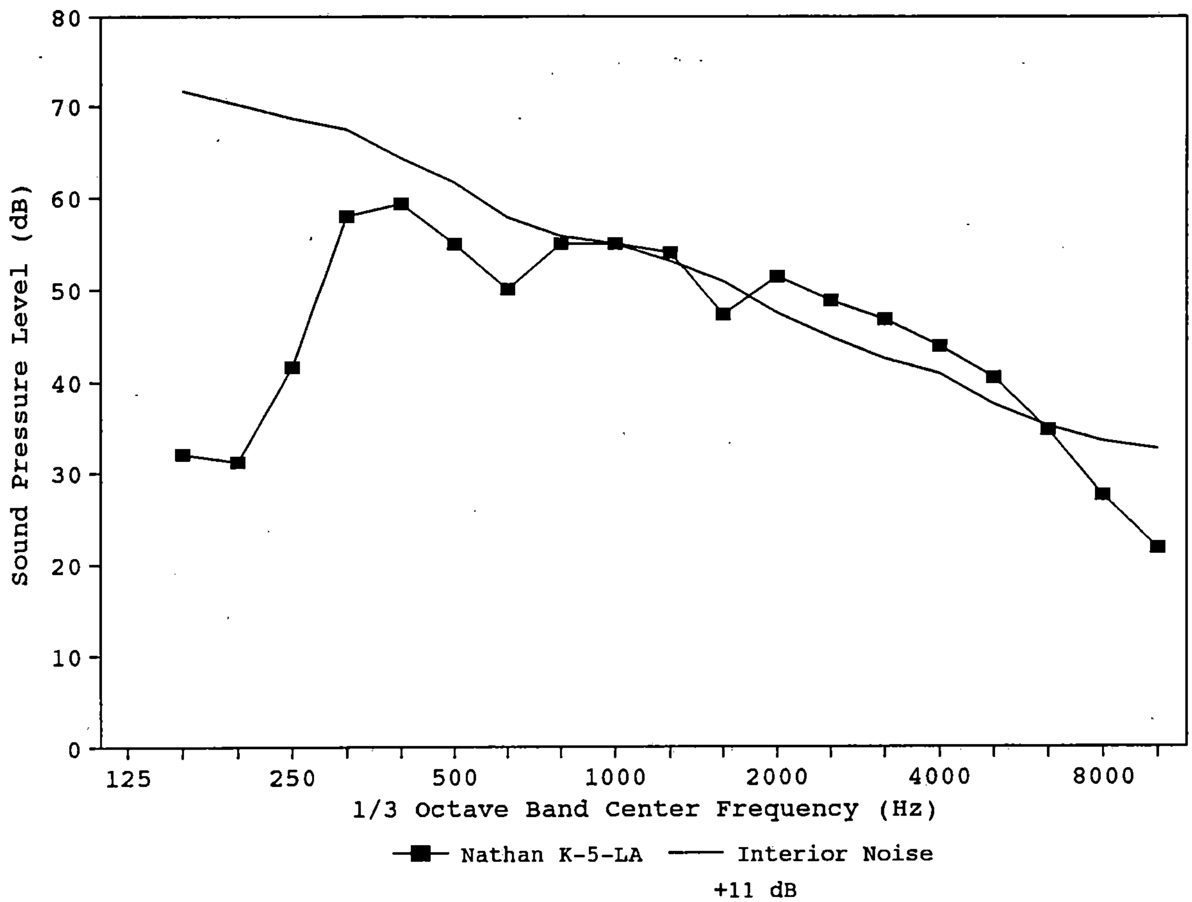


Figure 7. Passive Crossing
Detectability Level vs. Warning Signal Level
74 m (243 ft) From Leslie RSL-3L-RF and Leslie RS-3L

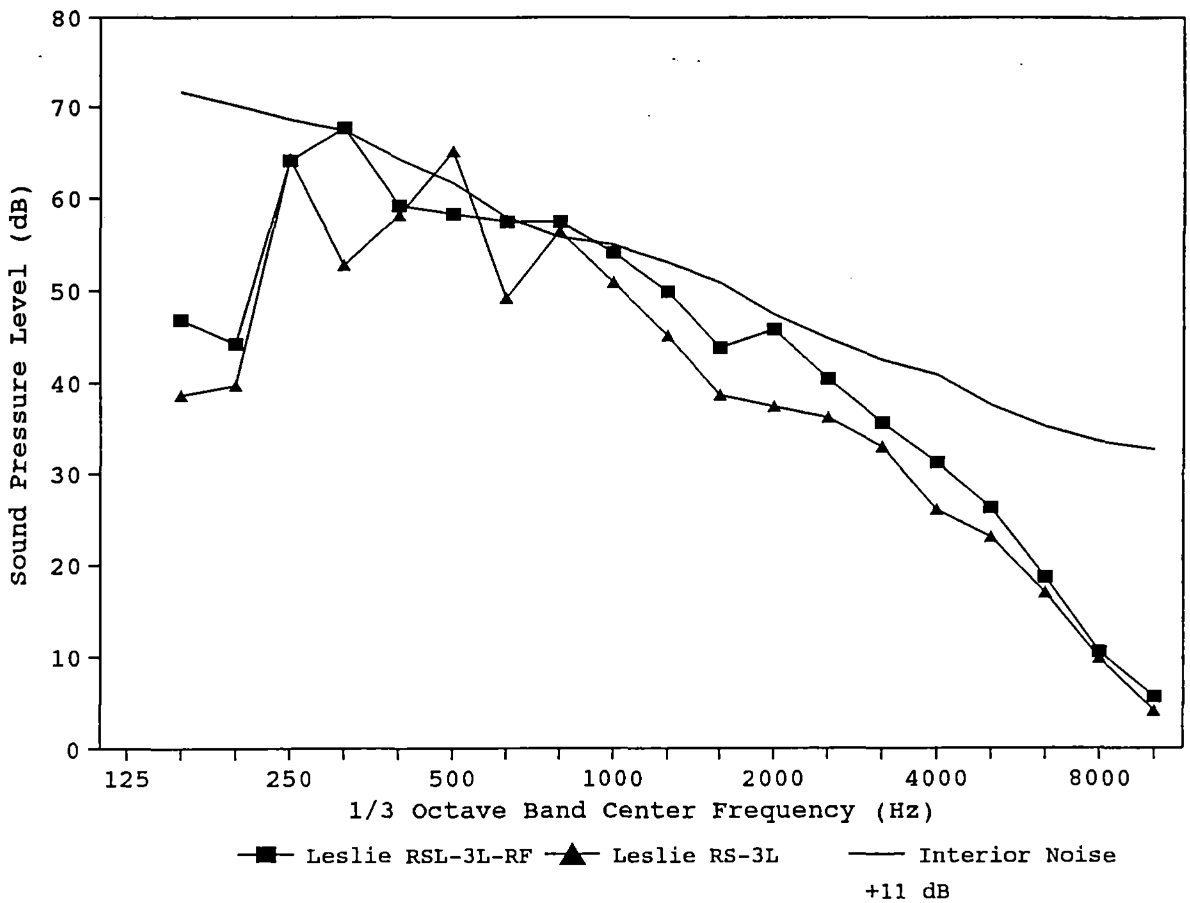


Figure 8. Active Crossing
Detectability Level vs. Warning Signal Level
492 m (1614 ft) From Nathan K-5-LA

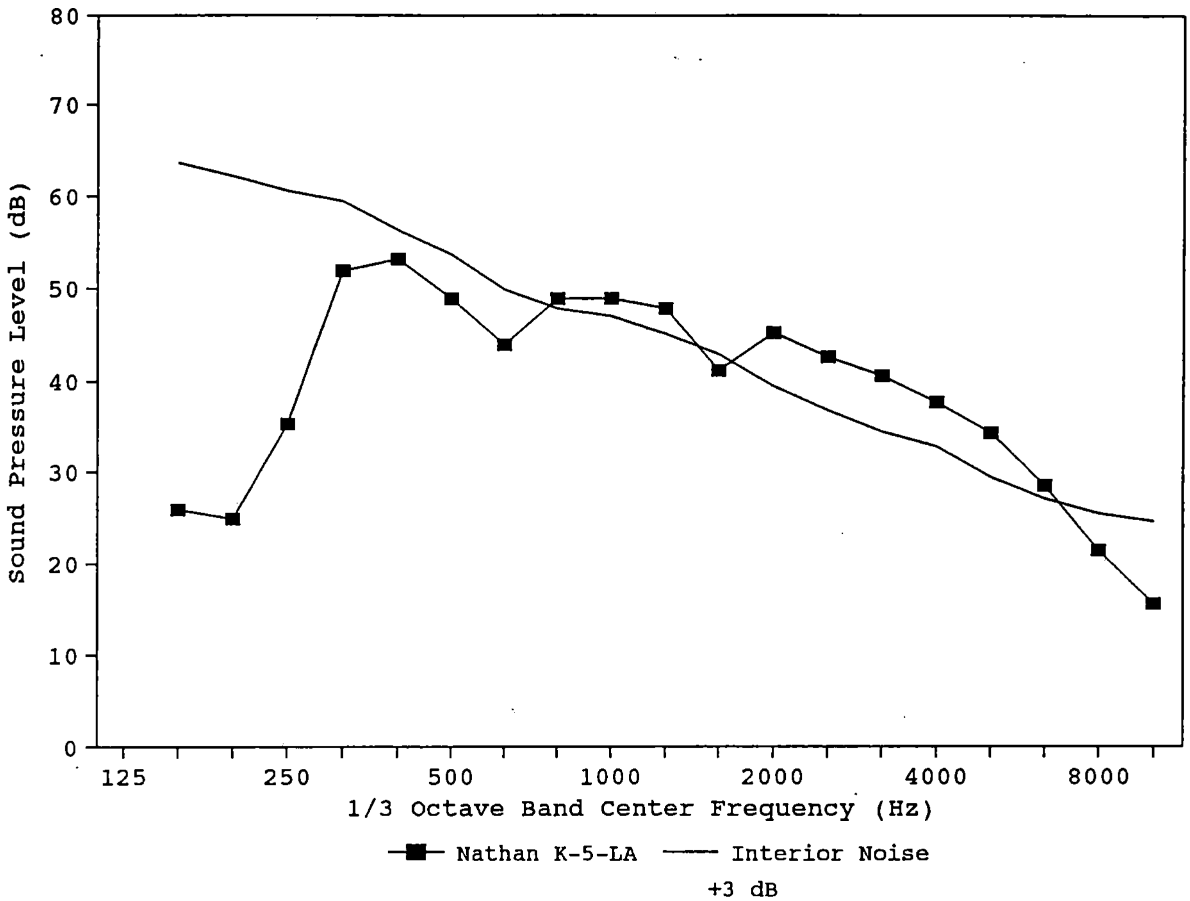


Figure 9. Active Crossing
Detectability Level vs. Warning Signal Level
134 m (440 ft) From Leslie RSL-3L-RF

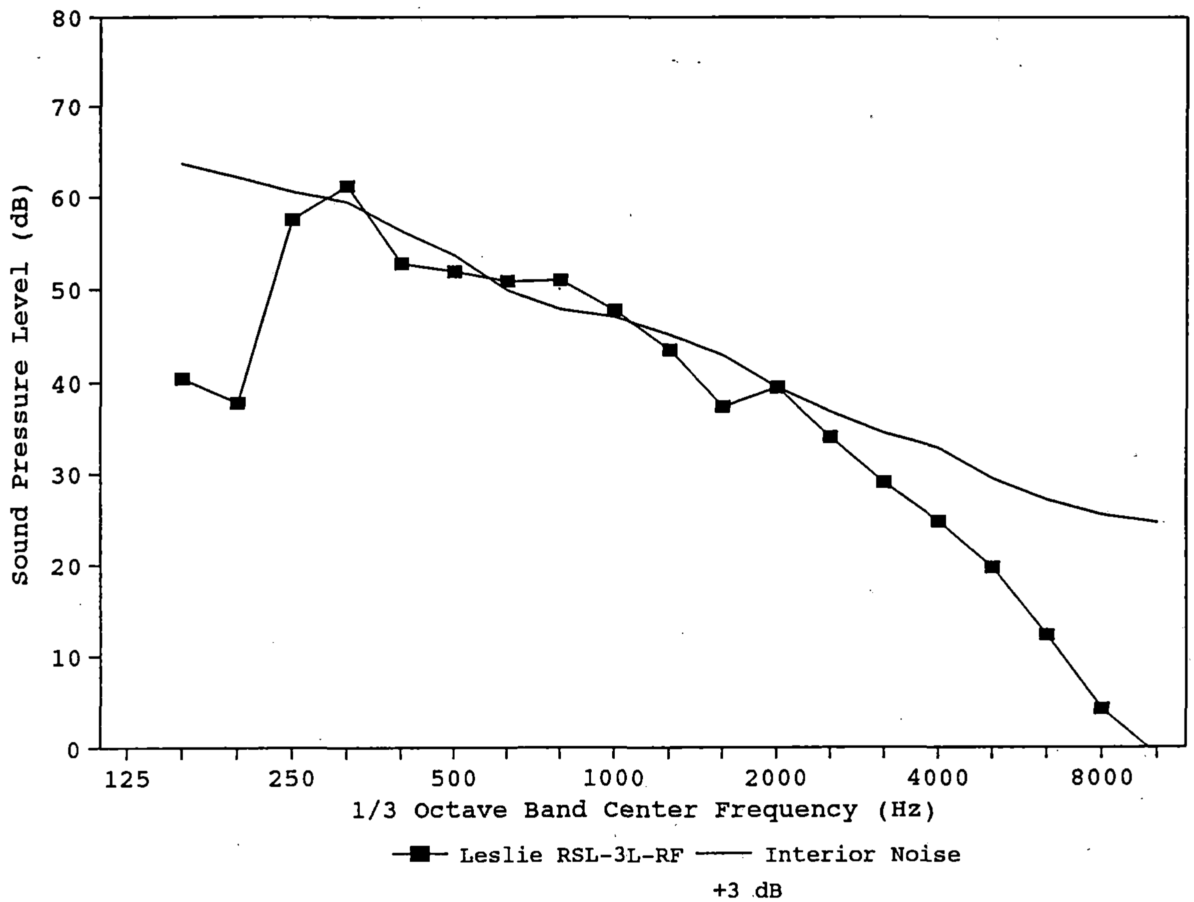


Figure 10. Active Crossing
Detectability Level vs. Warning Signal Level
89 m (292 ft) From Leslie RS-3L

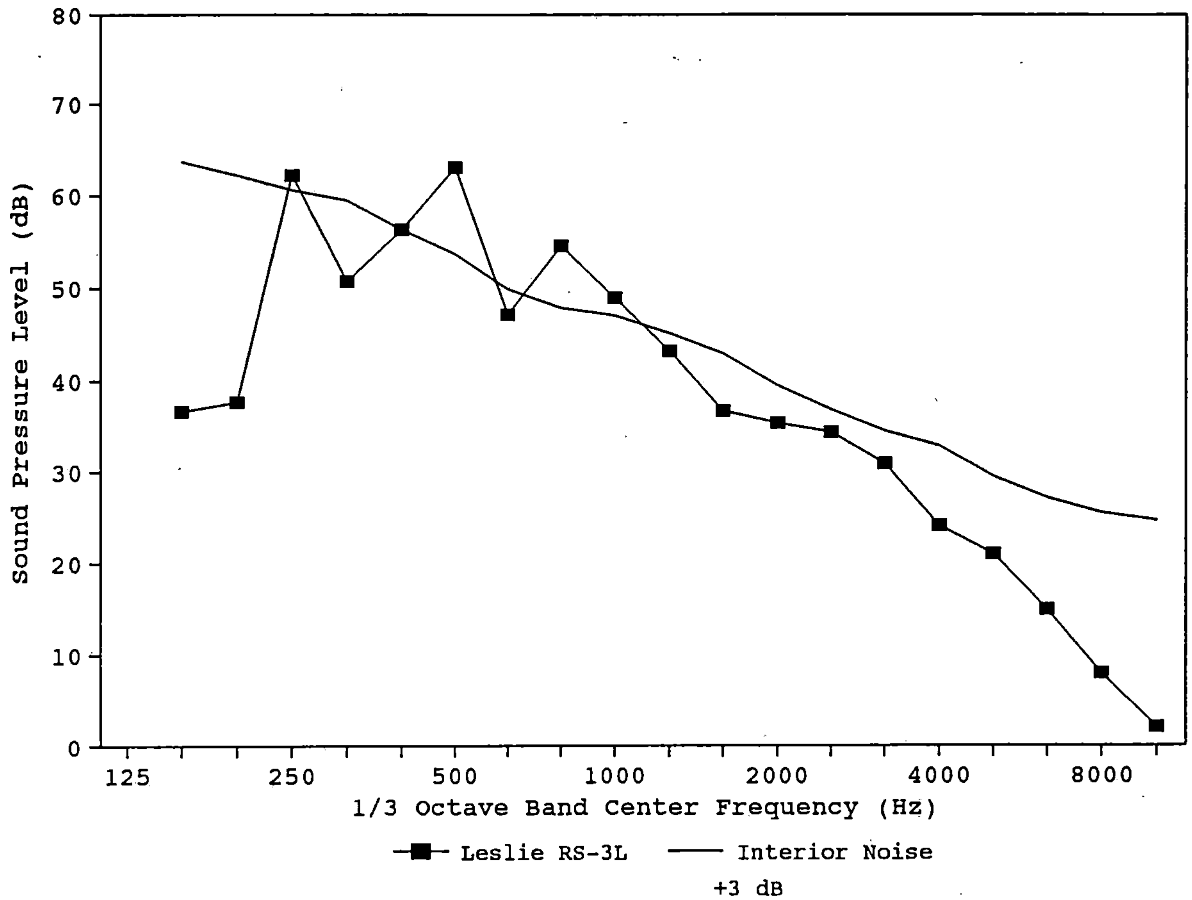
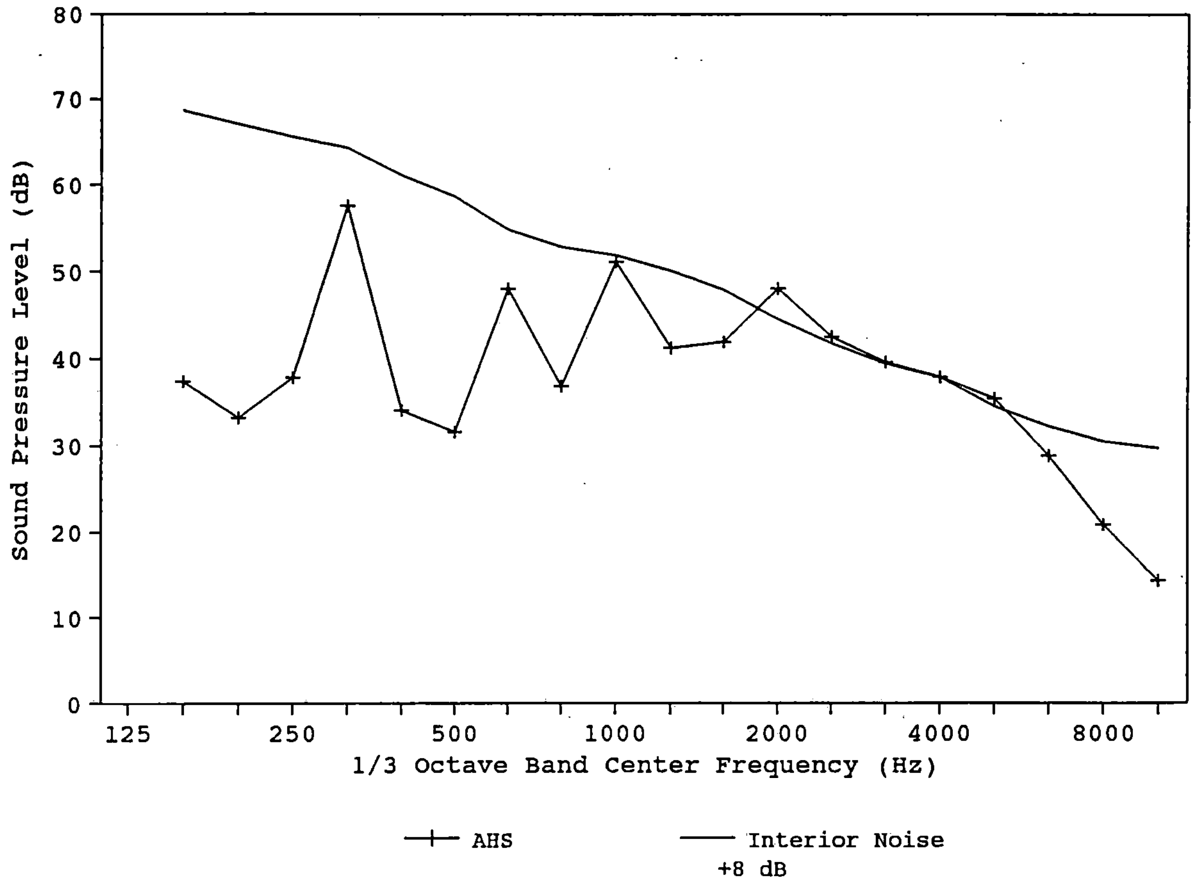


Figure 11. Active Crossing Equiped with Wayside Horn System
Detectability Level vs. Warning Signal Level
29 m (95 ft) From the AHS



6.0 NIGHTTIME RAILROAD HORN BANS

As stated in Section 1.0, this study was prompted by the results of a nighttime (10pm to 6am) railroad horn ban by the Florida East Coast Railway. The Florida situation provides two indications that the train horns were detected at active crossings. First, when the ban was in effect, the accident rate at impacted crossings had tripled; when horn use was resumed, the number of accidents returned to pre-ban levels[3].

Secondly, the increase in accidents could be partially explained by motorist confusion resulting from the use of horns during the day. Even when the whistle ban was in effect, the horn was being utilized during a good portion of the day. Consequently, the motorist may have been conditioned to expect the horn during the times of day when the ban was in effect. In fact, when the gates, lights, and bells were activated, but the whistle did not blow, the motorist may have incorrectly inferred that there was a false activation, or that the locomotive was too far away to be detected. At this point the motorist may have decided to continue around the gates, sometimes resulting in a collision.

The above suggests that the motorist in Florida could almost always detect the railroad horns. This is not consistent with the conclusions in Section 5.2 for the Leslie RS-3L (used by the Florida East Coast Railway) when used at active crossings, even in low-speed encounters. However, the conclusions in Section 5.2 are based upon the assumption that the motor vehicle interior noise levels when the vehicle is stopped at the crossing are identical to those when the vehicle is traveling 48 km/hr (30 mph). If a motorist were completely stopped at a crossing, interior noise levels would likely be significantly lower (15-25 dB) than the levels that the conclusions in Section 5.2 were based upon. In addition, due to the mild climate, motorists in Florida may be much more likely to be driving with open windows, thus reducing the vehicle's insertion loss (and thereby increasing the signal level) 5 to 15 dB.

In order to resolve the above inconsistencies, a more detailed set of automotive insertion loss and interior noise data must be collected. These data would include insertion loss characteristics for motor vehicles with windows both opened and closed, and interior noise data for vehicles traveling at a variety of speeds, especially at idle. This would allow for a more accurate representation of the situations that may have been encountered in Florida during the whistle ban.

REFERENCES

1. Aurelis, J.P., and Korobow, The Visibility and Audibility of Trains Approaching Highway Railroad Grade Crossings, Report No. FRA-RP-71-2, May, 1971.

2. Eldred, K.M., and Sharp, B.H., Are Present Horns, Whistles, and Sirens Necessary for Communications?, Proceedings, International Conference on Transportation and the Environment, Washington D.C., May 31 - June 2, 1972.

3. Florida's Train Whistle Ban, U.S. Department of Transportation, Federal Railroad Administration, Office of Safety, July, 1990.

4. Keller, A., and Rickley, E., The Safety of Highway - Railroad Grade Crossings: Study of the Acoustic Characteristics of Railroad Horn Systems, Report No. DOT/FRA/ORD-93/25, June, 1993.

5. International Organization for Standardization, Acoustics - Attenuation of Sound Propagation Outdoors - Part 1: Method of Calculation of the Attenuation of Sound by Atmospheric Absorption, Draft International Standard ISO/DIS 9613-1, Geneva, 1990.

6. Peirce, Allan D., Acoustics: An Introduction to Its Physical Principles and Applications, Acoustical Society of America, Woodbury, NY, 1991.

7. Guide on Evaluation and Attenuation of Traffic Noise, American Association of State Highway and Transportation Officials, 1974.

8. Beranek, Leo L., Noise and Vibration Control, Institute of Noise Control Engineering, Washington, D.C., 1971.

9. Wilson, D., A Study of Sound Level of Train Horns Measured Inside Selected Vehicle Types, Unpublished Masters Thesis, University of Tennessee, Knoxville, December, 1983.

10. Potter, R.C., Fidell, S.A., Myles, M.M., and Keast, D.N., Effectiveness of Audible Warning Devices on Emergency Vehicles, Report No. DOT-TSC-OST-77-38, August 1977.

11. Society of Automotive Engineers Recommended Practice J1477, Measurement of Interior Sound Levels of Light Vehicles, Warrendale, PA, January, 1986.

12. American National Standards Institute, Methods for Determination of Insertion Loss of Outdoor Noise Barriers, ANSI S12.8-1987, New York, NY: Acoustical Society of America, Standards Secretariat, August, 1987.

13. Car and Driver, September 1992, February 1993, and April 1993.

14. Road and Track, March 1993.

15. Engineering Dynamics, Unpublished Data, September, 1990.

16. Thomas Raslear, personal communications.

17. Transportation and Traffic Engineering Handbook, Institute of Transportation Engineers, Second Edition, 1982.

18. Olsen, Paul L. and Sivak, Michael, "Perception-Response Time to Unexpected Roadway Hazards", Human Factors, 28, No. 1, 1986, p. 91-96.

19. The Standard Code of Operating Rules, Association of American Railroads, January 1986, Washington, D.C. 20001.

20. Russell, E., Narum, B., Amos, C., and Scherzinger, J., Compilation of States' Laws and Regulations on Matters Affecting Rail-Highway Crossings, U.S. Department of Transportation, Federal Railroad Administration and Federal Highway Administration, Report No. FHWA-TS-83-203, U.S. Government Printing Office, Washington, D.C., April, 1983.

APPENDIX A

DATA ACQUISITION EQUIPMENT

This Appendix contains detailed descriptions of the acoustic data acquisition systems and calibration procedures used during field measurements in this study.

Digital Recording System (PCM Type)

The PCM type digital recording system consisted of the following components: 1.) A General Radio Model 1962-9610 random incidence electret microphone, fitted with a Brüel & Kjær (B&K) model UA0237 (7.6 cm diameter) windscreen. 2.) A General Radio Model 1560-P42 preamplifier. 3.) A stepped gain amplifier. 4.) A Sony Model PCM-F1 Digital Audio Processor (PCM-F1). 5.) A JVC Model BR-6200U video cassette recorder. 6.) An annotation microphone. The microphone/preamplifier assembly was mounted on a tripod and oriented for grazing incidence. A 1.52 m cable connected the microphone/preamplifier assembly to the recording instrumentation.

The signal from the microphone was split into two channels, each was low-pass filtered (22kHz anti-alias filter), digitized at a rate of 44.056 kHz and recorded on two video channels with a 10 dB gain offset between channels. Additional recording gains were provided, using the stepped-gain amplifier, and fine tuned (prior to system calibration), using the PCM-F1 variable gain adjustment. Recording gains were adjusted so that the bast possible signal-to-noise ratio would be achieved, while allowing enough 'head room' to comply with applicable distortion avoidance requirements. Voice annotation was recorded on audio channel 1.

Digital Recording Systems (DAT Type)

The DAT type digital recording system consisted of the following components: 1.) A General Radio Model 1962-9610 random incidence electret microphone, fitted with a Brüel & Kjær Model UA0237 (7.6 cm diameter) windscreen. 2.) A General Radio Model 1560-P42 preamplifier. 3.) A stepped gain amplifier. 4.) A Sony Model TCD-D10 ProII digital audio tapecorder. 5.) An annotation microphone. The microphone/preamplifier assembly was mounted on a tripod at a height of 1.2 meters above ground, and oriented for grazing incidence. A 61 m cable connected the microphone/preamplifier assembly to the recording instrumentation.

The signal from the microphone was low-pass filtered (24 kHz anti-alias filter), digitized at a rate of 48 kHz and recorded on one channel. Additional recording gains were provided using the stepped-gain amplifier, and fine tuned (prior to system calibration) using the DAT's variable gain adjustment. Recording gains were provided so that the best possible signal-to-noise ratio would be achieved, while allowing enough "head room" to comply with applicable distortion avoidance requirements. Voice annotation was recorded on the other channel.

Sound Level Meter System

The sound level meter system consisted of the following components: 1.) A General Radio Model 1962-9610 random incidence electret microphone, fitted with a Brüel & Kjær Model UA0237 (7.6 cm diameter) windscreen. 2.) A Larson-Davis Model 827-0V preamplifier. 3.) A Larson-Davis Model 820 Type I Precision Integrating Sound Level Meter/Environmental Noise Analyzer (LD820) conforming to ANSI S1.4-1971 requirements. The microphone/preamplifier assembly was mounted on a tripod at a height of 1.2 meters above ground level and oriented for grazing incidence. A 15.25 m cable connected the microphone/preamplifier assembly to the sound level meter.

The LD820 was operated in the "slow" sound level meter response mode, and was programmed to internally A-weight and store the acoustic level time history, one data record every 1/8 second over the entire period of data acquisition. The data stored in the LD820, including calibration data, were downloaded into an AST Premium Exec Model 386SX/20 portable notebook computer after each test and subsequently stored on floppy diskette for off-line analysis.

Artificial Source

An artificial source consisting of a horn speaker system was deployed to broadcast pink noise during insertion loss measurements. Seven octave bands of pink noise were recorded and reproduced on a Sony Model TCD-5M cassette deck. The signal was amplified with a McIntosh Model 275 power amplifier and broadcast with a University Sound horn speaker Model GH and driver Model ID-60. The cone of the horn was positioned 1.2 m above ground, 7.62 m from the data acquisition system.

The output, 1.2 m from the cone of the speaker, was monitored and stored using a Sound Level Meter System. Prior to each broadcast the gain of the speaker system was set to produce a level of 114.0 dB at 1 kHz. The sound level meter was used to obtain a measure of the stability of the signal output and the near field frequency response of the speaker. It was set to measure with fast response characteristics, and was programmed to internally A-weight and store the acoustic level time history, one data record every 1/2 second.

System Calibration

Calibration of both the digital recording system and the sound level meter system was performed using a General Radio Model 1562-A sound level calibrator with an output sound pressure level of 114 dB (re: 20 μPa) at 1000 Hz at the beginning of the test day and at regular intervals throughout the day. The microphones and calibrators are calibrated annually and checked prior to field measurements at the Volpe Center. Pink noise from a Cetec Ivie IE-20B random noise generator was recorded on the system at the beginning of each test day and used for off-line frequency response adjustments.

APPENDIX B

THE ACOUSTIC CHARACTERISTICS OF RAILROAD HORN SYSTEMS MOUNTED ON IN-SERVICE LOCOMOTIVES

This Appendix contains a plan view of each measurement site (Figures B-1 through B-6), information on the site conditions, locomotive operating conditions, and the levels attained throughout the signaling cycle (Tables B-1 through B-12), the frequency spectrum at A_{max} for each signaling cycle (Figures B-7 through B-12), and the spectral and A-weighted time history for each signaling cycle (Figures B-13 through B-24).

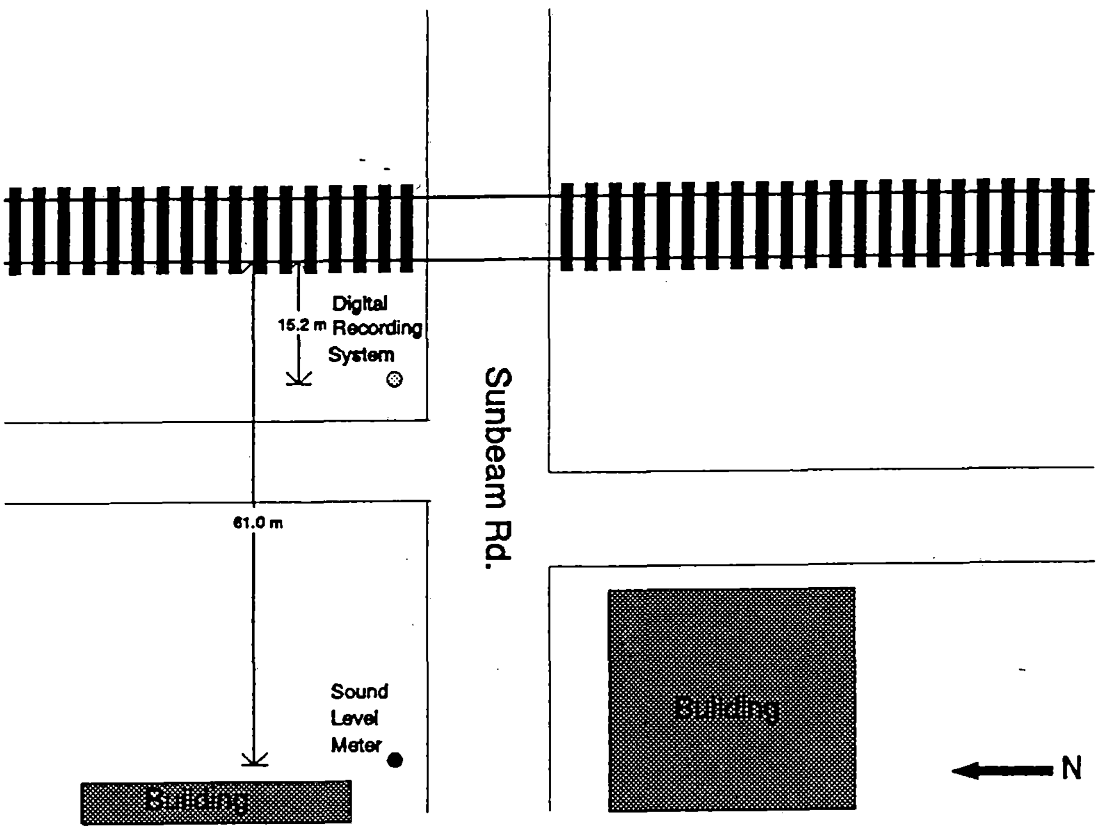


Figure B-1. Plan View (Not to Scale)
Sunbeam Road, Jacksonville, FL

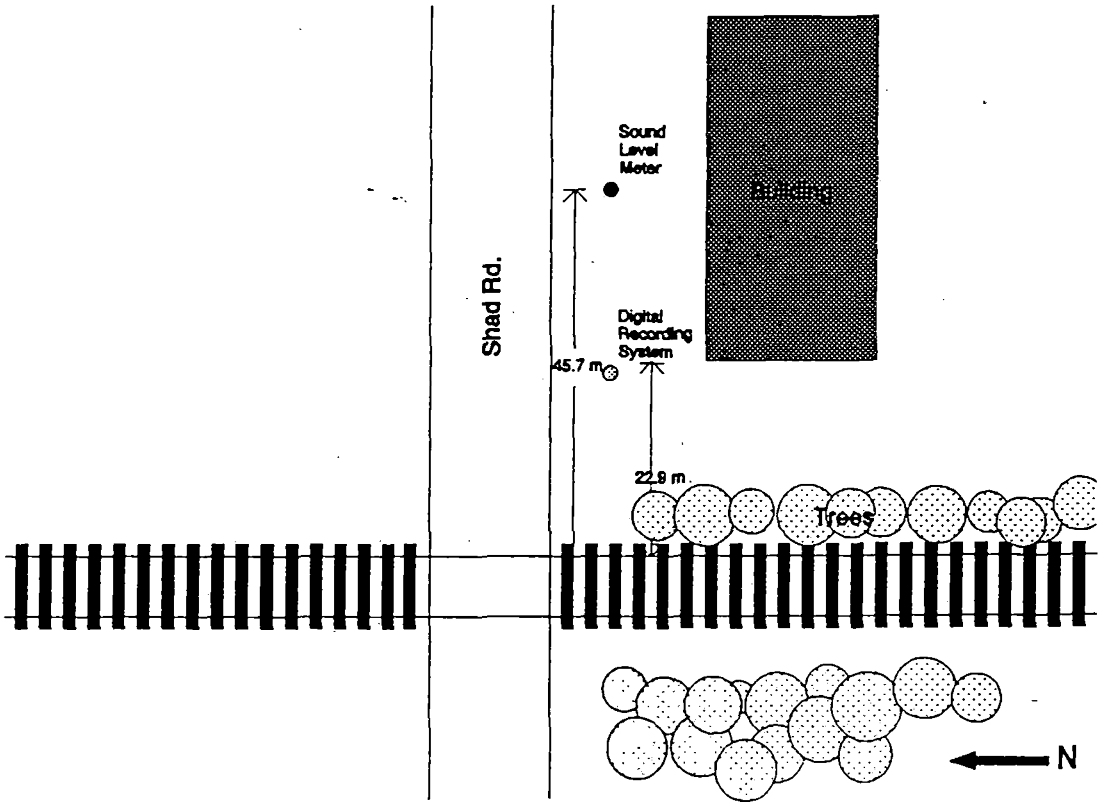


Figure B-2. Plan View (Not to Scale)
Shad Road, Jacksonville, FL

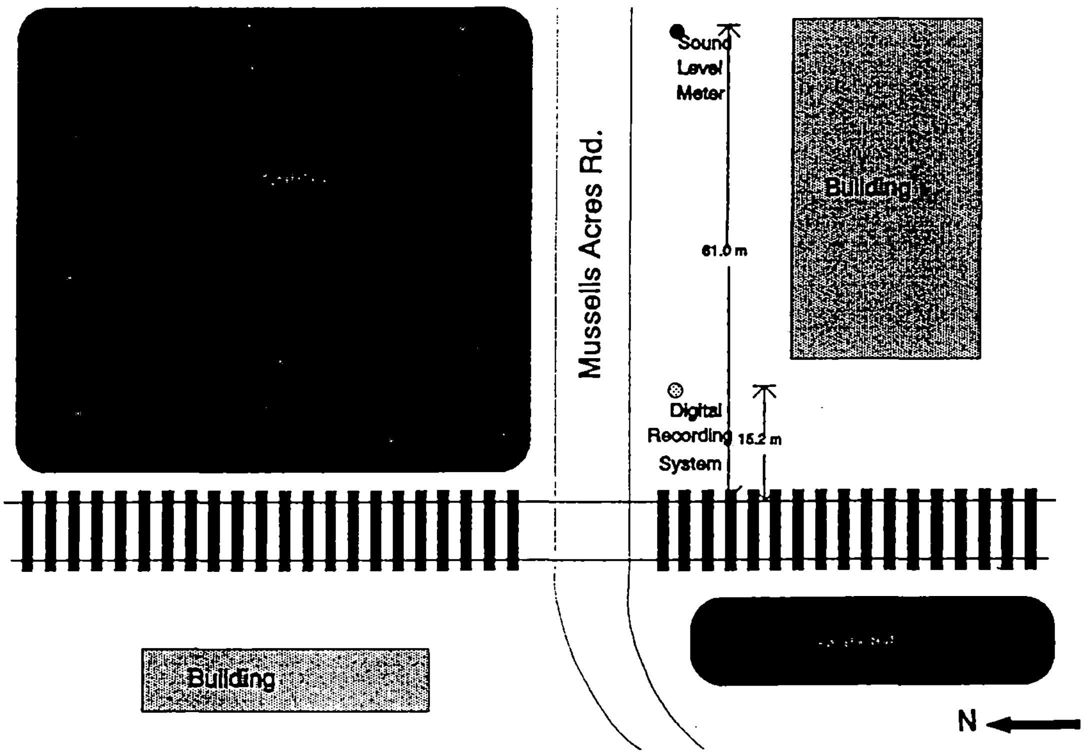


Figure B-3. Plan View (Not to Scale)
Mussells Acres Road, Jacksonville, FL

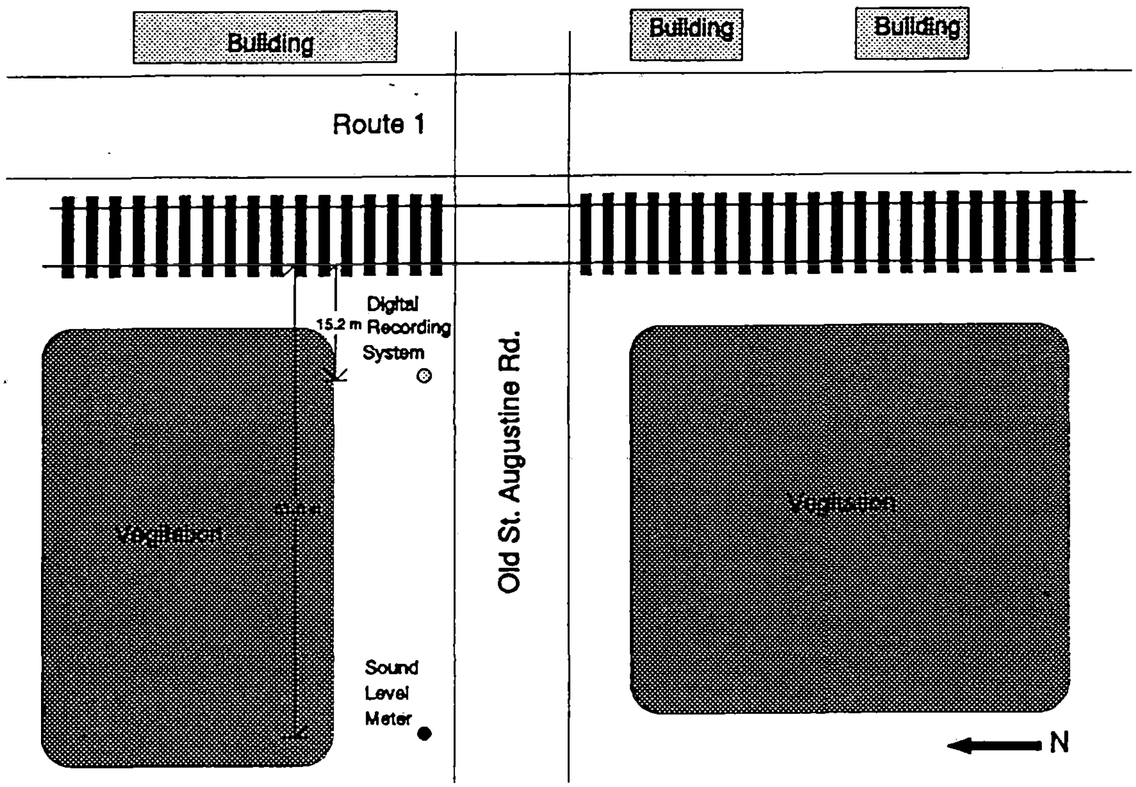


Figure B-4. Plan View (Not to Scale)
Old St. Augustine Rd., Jacksonville, FL

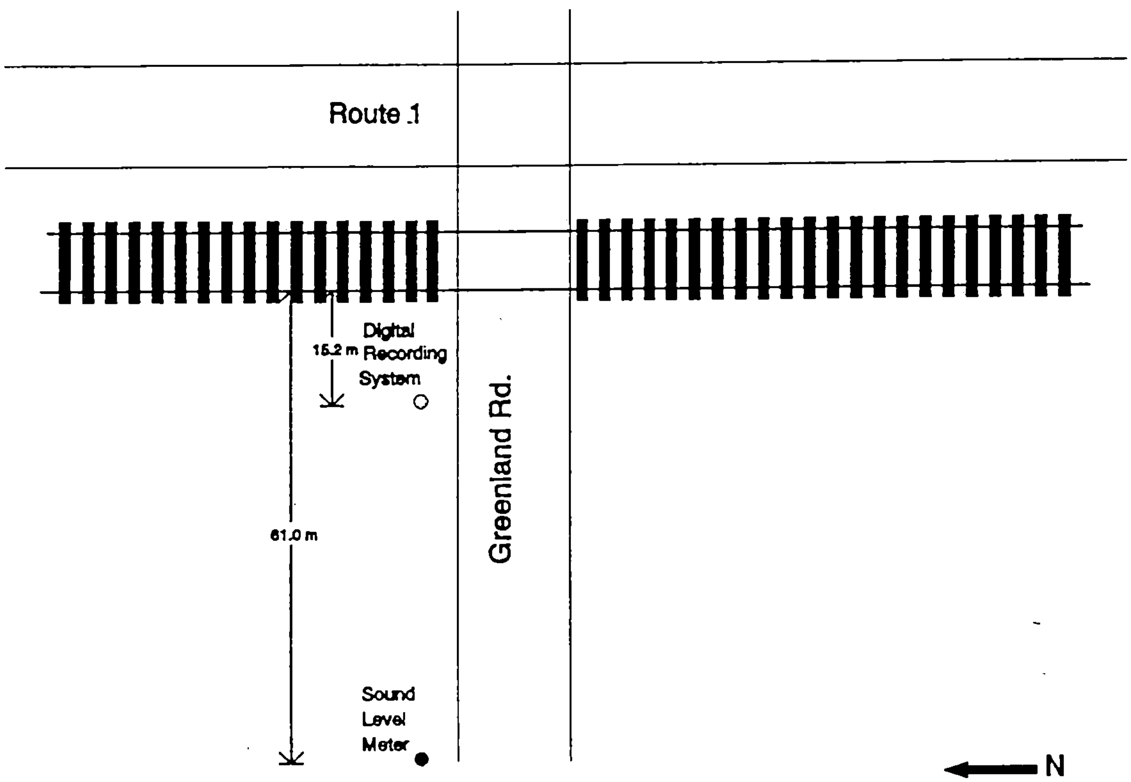


Figure B-5. Plan View (Not to Scale)
Greenland Road, Jacksonville, FL

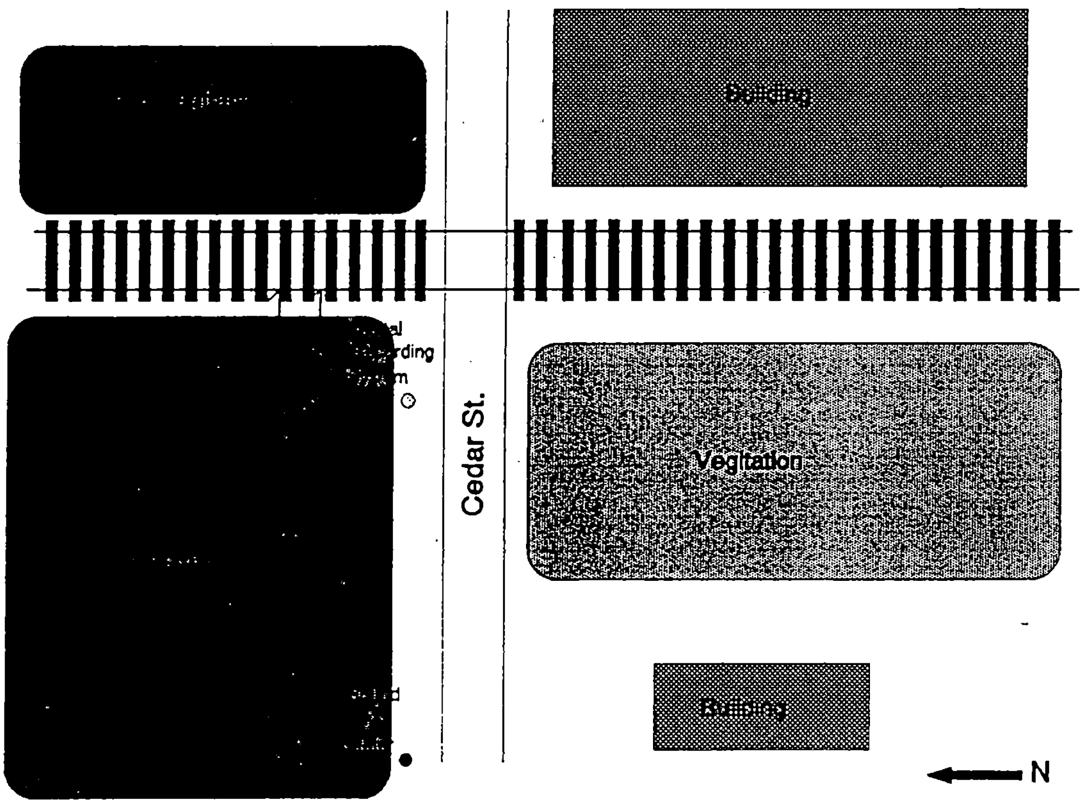


Figure B-6. Plan View (Not to Scale)
Cedar Street, Jacksonville, FL

Table B-1. Summary of Warning Signal Levels and Site Conditions
Sunbeam Road - Train 1

Date:	07/08/92
Time:	06:59
Train Speed:	41.84 km/hr
Direction of Travel:	North
Speed Limit on Road:	72.42 km/hr
Type of Road:	Paved - Three lane
Temperature:	25.55 °C
Relative Humidity:	88%
Required Warning Distance*:	148.4 m
Source:	No air pressure regulator. Rated at 114 dBA at 30.5 m.

Microphone Location: 15.25 m east of tracks				
Signal Component	SEL (dBA)	L_{max} (dBA)	Duration (sec)	Distance from mic to Locomotive (m)
1.) Long		91.94	4.75	135
2.) Long		98.69	3.75	80
3.) Short		99.73	1.38	75
4.) Long		112.14	5.00	20
Combined	114.43	112.14	14.88	

Microphone Location: 61.0 m east of tracks				
Signal Component	SEL (dBA)	L_{max} (dBA)	Duration (sec)	Distance from mic to locomotive (m)
1.) Long		89.10	4.75	147
2.) Long		97.00	4.00	99
3.) Short		95.50	1.50	79
4.) Long		101.30	5.38	62
Combined	107.20	101.30	15.63	

Table B-2. Summary of Warning Signal Levels and Site Conditions
Sunbeam Road - Train 2

Date:	07/08/92
Time:	07:46
Train Speed:	56.33 km/hr
Direction of Travel:	North
Speed Limit on Road:	72.42 km/hr
Type of Road:	Paved - Three lane
Temperature:	27.78 °C
Relative Humidity:	84%
Required Warning Distance*:	162.8 m
Source:	Rated at 104 dBA at 30.5 m.

Microphone Location: 15.25 m east of tracks				
Signal Component	SEL (dBA)	L_{max} (dBA)	Duration (sec)	Distance from mic to locomotive (m)
1.) Long		78.68	5.13	207
2.) Long		84.77	4.50	122
3.) Short		82.28	2.50	72
4.) Long		103.76	5.38	19
Combined	107.37	103.76	17.51	

Microphone Location: 61.0 m east of tracks				
Signal Component	SEL (dBA)	L_{max} (dBA)	Duration (sec)	Distance from mic to locomotive (m)
1.) Long		74.50	4.13	216
2.) Long		80.10	4.25	135
3.) Short		78.30	2.88	93
4.) Long		95.60	5.00	62
Combined	98.9	95.60	16.26	

Table B-3. Summary of Warning Signal Levels and Site Conditions
Shad Road - Train 3

Date:	07/08/92
Time:	08:31
Train Speed:	75.64 km/hr
Direction of Travel:	North
Speed Limit on Road:	72.42 km/hr
Type of Road:	Paved - Three lane
Temperature:	28.33 °C
Relative Humidity:	84%
Required Warning Distance*:	185.8 m
Source:	Rated at 104 dBA at 30.5 m.

Microphone Location: 22.86 m west of tracks				
Signal Component	SEL (dBA)	L_{max} (dBA)	Duration (sec)	Distance from mic to locomotive (m)
1.) Long		86.14	2.75	154
2.) Long		89.85	2.13	94
3.) Short		90.54	1.38	67
4.) Long		96.86	5.63	32
Combined	98.1	96.86	11.88	

Microphone Location: 45.72 m west of tracks				
Signal Component	SEL (dBA)	L_{max} (dBA)	Duration (sec)	Distance from mic to locomotive (m)
1.) Long		74.60	3.13	159
2.) Long		86.10	1.88	102
3.) Short		86.20	1.25	81
4.) Long		92.60	6.38	51
Combined	98.0	92.60	12.64	

Table B-4. Summary of Warning Signal Levels and Site Conditions
Shad Road - Train 4

Date:	07/08/92
Time:	10:50
Train Speed:	93.34 km/hr
Direction of Travel:	North
Speed Limit on Road:	72.42 km/hr
Type of Road:	Paved - Three lane
Temperature:	32.78 °C
Relative Humidity:	70%
Required Warning Distance*:	209.6 m
Source:	Rated at 104 dBA at 30.5 m.

Microphone Location: 22.86 m west of tracks				
Signal Component	SEL (dBA)	L_{max} (dBA)	Duration (sec)	Distance from mic to locomotive (m)
1.) Long		82.70	2.75	174
2.) Long		93.93	2.63	97
3.) Short		91.75	0.75	72
4.) Long		96.43	6.13	28
Combined	98.07	96.43	12.26	

Microphone Location: 45.72 m west of tracks				
Signal Component	SEL (dBA)	L_{max} (dBA)	Duration (sec)	Distance from mic to locomotive (m)
1.) Long		72.90	3.13	178
2.) Long		87.60	3.25	105
3.) Short		88.50	1.00	82
4.) Long		92.80	9.00	49
Combined	98.20	92.80	16.38	

Table B-5. Summary of Warning Signal Levels and Site Conditions
Mussells Acres Road - Train 5

Date:	07/08/92
Time:	12:51
Train Speed:	67.59 km/hr
Direction of Travel:	South
Speed Limit on Road:	40.23 km/hr
Type of Road:	Unpaved
Temperature:	33.89 °C
Relative Humidity:	64%
Required Warning Distance*:	116.5 m
Source:	Rated at 104 dBA at 30.5 m.

Microphone Location: 15.24 m west of tracks				
Signal Component	SEL (dBA)	L_{max} (dBA)	Duration (sec)	Distance from mic to locomotive (m)
1.) Long		89.25	2.63	149
2.) Long		96.60	2.38	86
3.) Short		97.67	1.38	70
4.) Long		103.90	5.00	23
Combined	104.98	103.90	11.39	

Microphone Location: 61.0 m west of tracks				
Signal Component	SEL (dBA)	L_{max} (dBA)	Duration (sec)	Distance from mic to locomotive (m)
1.) Long		83.80	2.63	160
2.) Long		89.60	2.63	104
3.) Short		89.40	1.38	96
4.) Long		90.90	6.00	63
Combined	98.40	90.90	12.64	

Table B-6. Summary of Warning Signal Levels and Site Conditions Mussells Acres Road - Train 6

Date:	07/08/92
Time:	13:57
Train Speed:	69.20 km/hr
Direction of Travel:	South
Road Speed Limit:	40.23 km/hr
Road Type:	Unpaved
Temperature:	33.89 °C
Relative Humidity:	64%
Required Warning Distance*:	118.5 m
Source:	Rated at 104 dBA at 30.5 m.

Microphone Location: 15.24 m west of tracks				
Signal Component	SEL (dBA)	L_{max} (dBA)	Duration (sec)	Distance from mic to locomotive (m)
1.) Long		84.53	3.38	107
2.) Long		91.54	3.00	66
3.) Short		91.60	2.13	42
4.) Long		105.26	5.38	16
Combined	110.18	105.26	13.89	

Microphone Location: 61.0 m west

No data available

Table B-7. Summary of Warning Signal Levels and Site Conditions Old St. Augustine Road - Train 7

Date:	07/09/92
Time:	06:41
Train Speed:	42.28 km/hr
Direction of Travel:	South
Speed Limit on Road:	64.37 km/hr
Type of Road:	Paved - Two lane
Temperature:	24.44 °C
Relative Humidity:	86%
Required Warning Distance*:	136.1 m
Source:	No air pressure regulator. Rated at 114 dBA at 30.5 m.

Microphone Location: 15.24 m west of tracks				
Signal Component	SEL (dBA)	L_{max} (dBA)	Duration (sec)	Distance from mic to locomotive (m)
1.) Long		95.26	4.38	192
2.) Long		104.00	3.63	96
3.) Short		105.60	2.25	69
4.) Long		112.02	5.38	26
Combined	115.14	112.02	17.75	

Microphone Location: 61.0 m west of tracks				
Signal Component	SEL (dBA)	L_{max} (dBA)	Duration (sec)	Distance from mic to locomotive (m)
1.) Long		84.10	5.13	201
2.) Long		94.60	3.83	112
3.) Short		95.90	2.38	91
4.) Long		98.00	6.75	64
Combined	106.10	98.00	12.64	

Table B-8. Summary of Warning Signal Levels and Site Conditions Old St. Augustine Road - Train 8

Date:	07/09/92
Time:	06:46
Train Speed:	28.97 km/hr
Direction of Travel:	North
Speed Limit on Road:	64.37 km\hr
Type of Road:	Paved - Two lane
Temperature:	24.44 °C
Relative Humidity:	86%
Required Warning Distance*:	119.4 m
Source:	Rated at 104 dBA at 30.5 m.

Microphone Location: 15.24 m west of tracks				
Signal Component	SEL (dBA)	L_{max} (dBA)	Duration (sec)	Distance from mic to locomotive (m)
1.) Long		89.08	4.25	121
2.) Long		94.10	3.13	74
3.) Short		92.79	2.50	55
4.) Long		107.19	5.00	24
Combined	109.44	107.19	16.50	

Microphone Location: 61.0 m west of tracks				
Signal Component	SEL (dBA)	L_{max} (dBA)	Duration (sec)	Distance from mic to locomotive (m)
1.) Long		88.80	4.00	134
2.) Long		91.70	3.50	95
3.) Short		91.70	2.63	81
4.) Long		95.30	5.75	66
Combined	102.10	95.30	17.63	

Table B-8. Summary of Warning Signal Levels and Site Conditions
Old St. Augustine Road - Train 8

Date:	07/09/92
Time:	06:46
Train Speed:	28.97 km/hr
Direction of Travel:	North
Speed Limit on Road:	64.37 km\hr
Type of Road:	Paved - Two lane
Temperature:	24.44 °C
Relative Humidity:	86%
Required Warning Distance*:	119.4 m
Source:	Rated at 104 dBA at 30.5 m.

Microphone Location: 15.24 m west of tracks				
Signal Component	SEL (dBA)	L_{max} (dBA)	Duration (sec)	Distance from mic to locomotive (m)
1.) Long		89.08	4.25	121
2.) Long		94.10	3.13	74
3.) Short		92.79	2.50	55
4.) Long		107.19	5.00	24
Combined	109.44	107.19	16.50	

Microphone Location: 61.0 m west of tracks				
Signal Component	SEL (dBA)	L_{max} (dBA)	Duration (sec)	Distance from mic to locomotive (m)
1.) Long		88.80	4.00	134
2.) Long		91.70	3.50	95
3.) Short		91.70	2.63	81
4.) Long		95.30	5.75	66
Combined	102.10	95.30	17.63	

Table B-9. Summary of Warning Signal Levels and Site Conditions
Greenland Road - Train 9

Date:	07/09/92
Time:	8:02
Train Speed:	9.66 km/hr
Direction of Travel:	North
Road Speed Limit:	72.42 km/hr
Road Type:	Paved - Two lane
Temperature:	26.11 °C
Relative Humidity:	92%
Required Warning Distance*:	129.6 m
Source:	Rated at 104 dBA at 30.5 m.

Microphone Location: 15.24 m west of tracks				
Signal Component	SEL (dBA)	L_{max} (dBA)	Duration (sec)	Distance from mic to locomotive (m)
1.) Long		98.07	3.13	40
2.) Long		101.89	3.25	91
3.) Short		98.86	3.25	21
4.) Long		107.02	6.88	16
Combined	109.79	107.02	18.38	

Microphone Location: 61.0 m west of tracks				
Signal Component	SEL (dBA)	L_{max} (dBA)	Duration (sec)	Distance from mic to locomotive (m)
1.) Long		91.00	3.50	71
2.) Long		94.10	3.50	65
3.) Short		89.50	3.75	63
4.) Long		93.90	6.88	20
Combined	102.5	93.90	19.50	

Table B-10. Summary of Warning Signal Levels and Site Conditions Greenland Road - Train 10

Date:	07/09/92
Time:	12:41
Train Speed:	94.95 km/hr
Direction of Travel:	North
Speed Limit on Road:	72.42 km/hr
Type of Road:	Paved - Two lane
Temperature:	34.44 °C
Relative Humidity:	66%
Required Warning Distance*:	211.9 m
Source:	Rated at 104 dBA at 30.5 m.

Microphone Location: 15.24 m west of tracks				
Signal Component	SEL (dBA)	L_{max} (dBA)	Duration (sec)	Distance from mic to locomotive (m)
1.) Long		70.85	6.75	210
2.) Long		75.74	5.75	112
3.) Short		86.29	1.13	67
4.) Long		102.73	4.88	38
Combined	107.74	102.73	19.50	

Microphone Location: 61.0 m west of tracks				
Signal Component	SEL (dBA)	L_{max} (dBA)	Duration (sec)	Distance from mic to locomotive (m)
1.) Long		71.90	7.25	219
2.) Long		71.50	4.63	127
3.) Short		82.40	2.25	89
4.) Long		90.80	6.38	70
Combined	95.50	90.80	24.63	

Table B-11. Summary of Warning Signal Levels and Site Conditions
Cedar Street - Train 11

Date:	07/09/92
Time:	10:33
Train Speed:	70.81 km/hr
Direction of Travel:	North
Speed Limit on Road:	40.23 km/hr
Type of Road:	Unpaved
Temperature:	34.44 °C
Relative Humidity:	62%
Required Warning Distance*:	121 m
Source:	Rated at 104 dBA at 30.5 m.

Microphone Location: 15.24 m west of tracks				
Signal Component	SEL (dBA)	L_{max} (dBA)	Duration (sec)	Distance from mic to locomotive (m)
1.) Long		67.54	6.25	238
2.) Long		83.84	5.50	99
3.) Short		86.29	1.38	62
4.) Long		99.66	5.13	28
Combined	102.83	99.66	18.25	

Microphone Location: 61.0 m west of tracks				
Signal Component	SEL (dBA)	L_{max} (dBA)	Duration (sec)	Distance from mic to locomotive (m)
1.) Long		64.80	9.00	245
2.) Long		77.10	3.38	116
3.) Short		78.80	1.75	86
4.) Long		88.00	6.88	65
Combined	93.50	88.00	23.50	

Table B-12. Summary of Warning Signal Levels and Site Conditions
Cedar Street - Train 12

Date:	07/09/92
Time:	11:01
Train Speed:	96.56 km/hr
Direction of Travel:	North
Speed Limit on Road:	40.23 km/hr
Type of Road:	Unpaved
Temperature:	33.89 °C
Relative Humidity:	66%
Required Warning Distance*:	154.9 m
Source:	Rated at 104 dBA at 30.5 m.

Microphone Location: 15.24 m west of tracks				
Signal Component	SEL (dBA)	L_{max} (dBA)	Duration (sec)	Distance from mic to locomotive (m)
1.) Long		71.93	3.50	271
2.) Long		83.92	4.38	147
3.) Short		88.30	1.25	101
4.) Long		101.93	6.50	39
Combined	105.13	101.93	15.63	

Microphone Location: 61.0 m west of tracks				
Signal Component	SEL (dBA)	L_{max} (dBA)	Duration (sec)	Distance from mic to locomotive (m)
1.) Long		69.90	3.50	277
2.) Long		76.10	4.25	159
3.) Short		79.90	1.38	117
4.) Long		89.70	8.63	71
Combined	96.4	89.70	17.75	

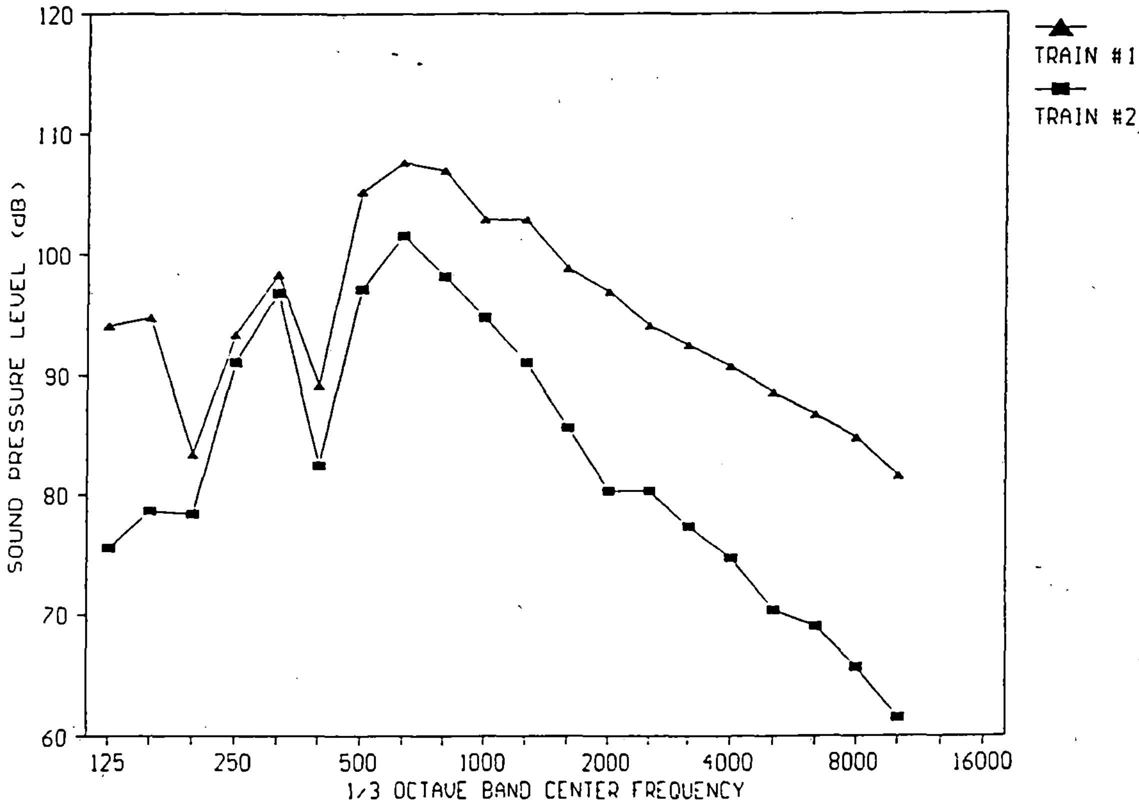


Figure B-7. Frequency Spectra at A_{max}
Sunbeam Road - Train 1 and Train 2

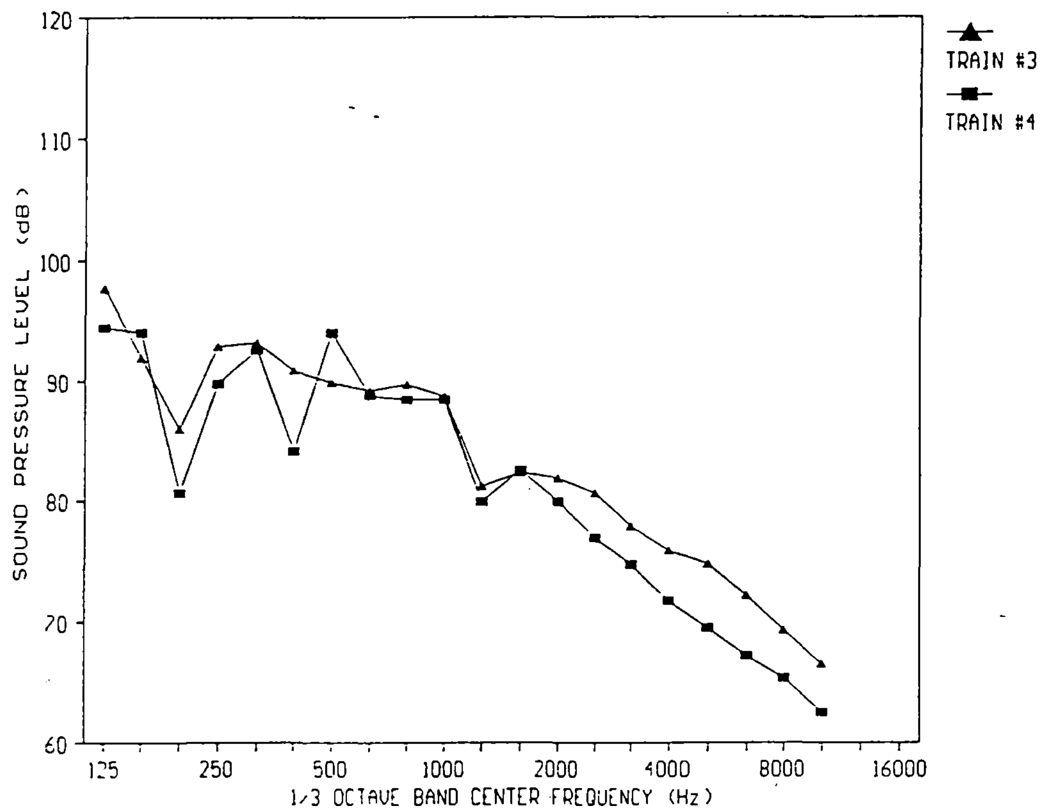


Figure B-8. Frequency Spectra at A_{max}
Shad Road - Train 3 and Train 4

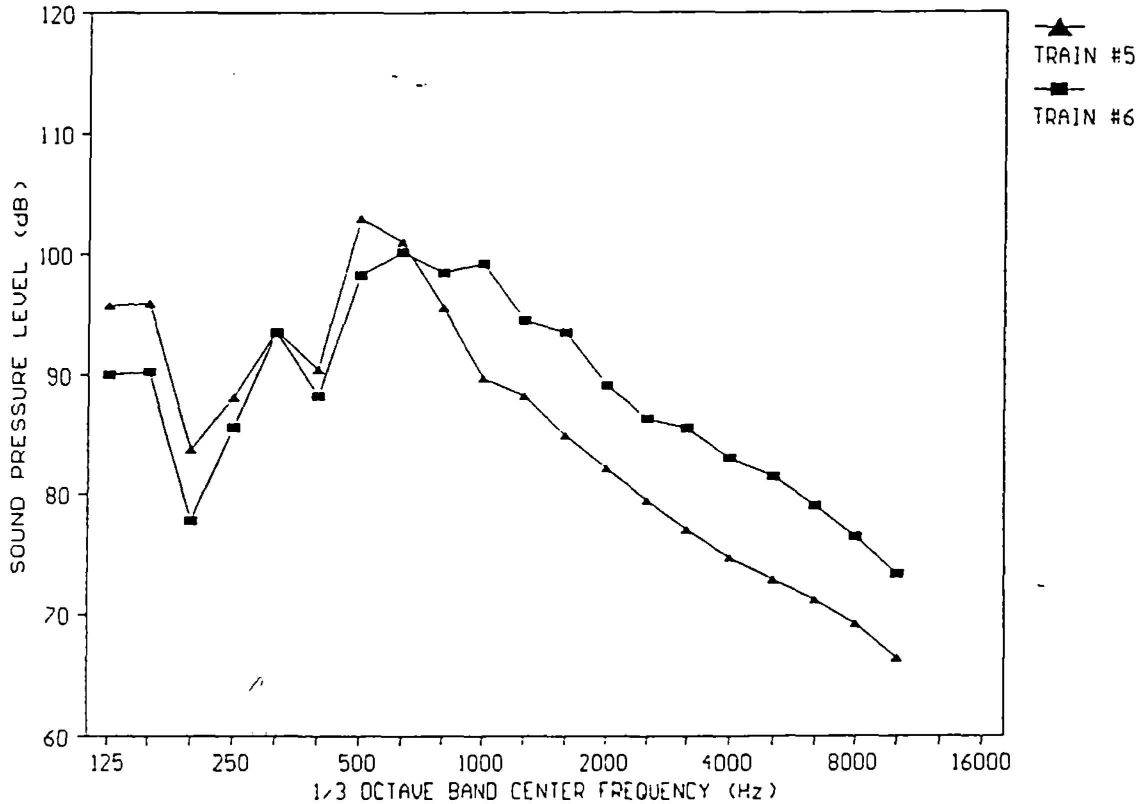


Figure B-9. Frequency Spectra at A_{max}
Mussells Acres Road - Train 5 and Train 6

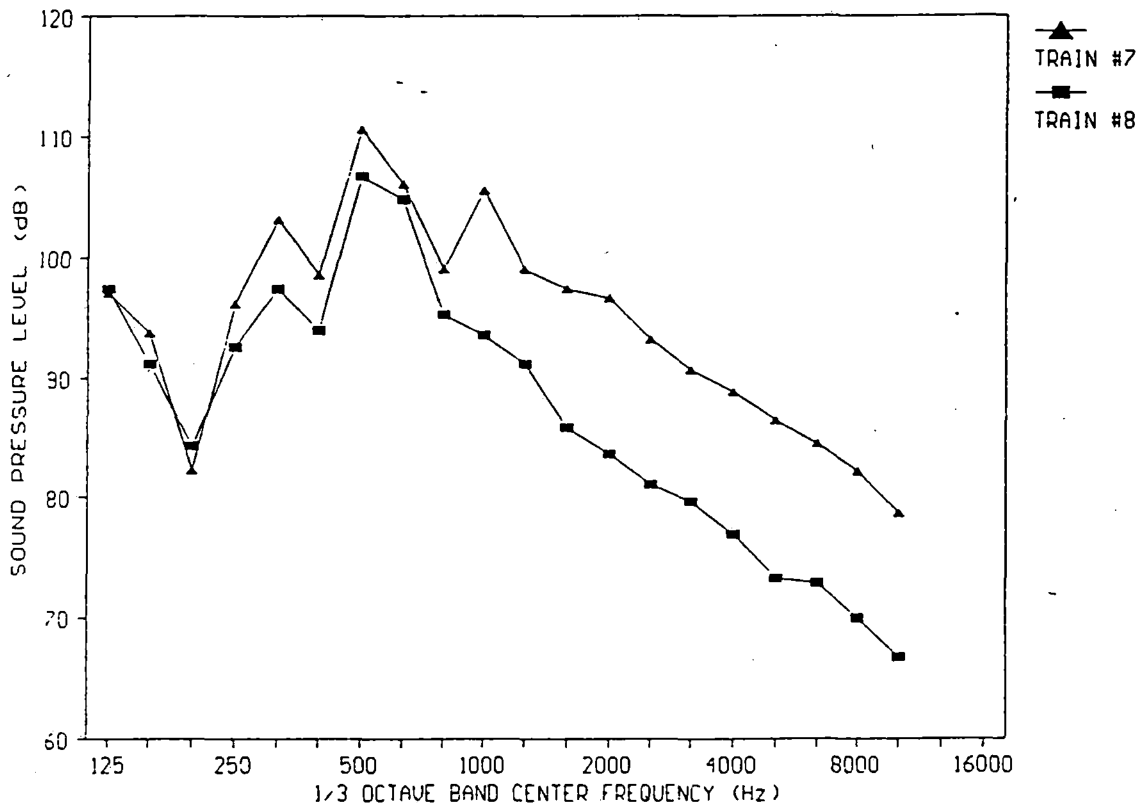


Figure B-10. Frequency Spectra at A_{max}
Old St. Augustine Road - Train 7 and Train 8

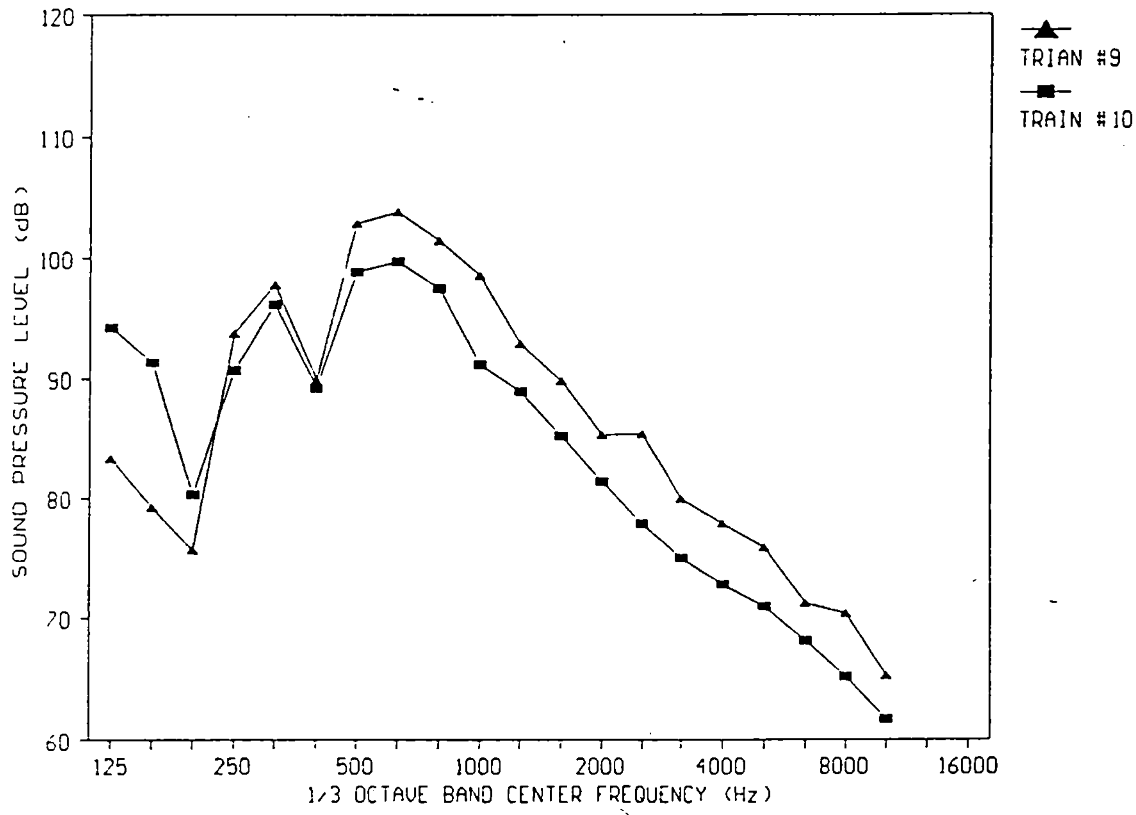


Figure B-11. Frequency Spectra at A_{max}
Greenland Road - Train 9 and Train 10

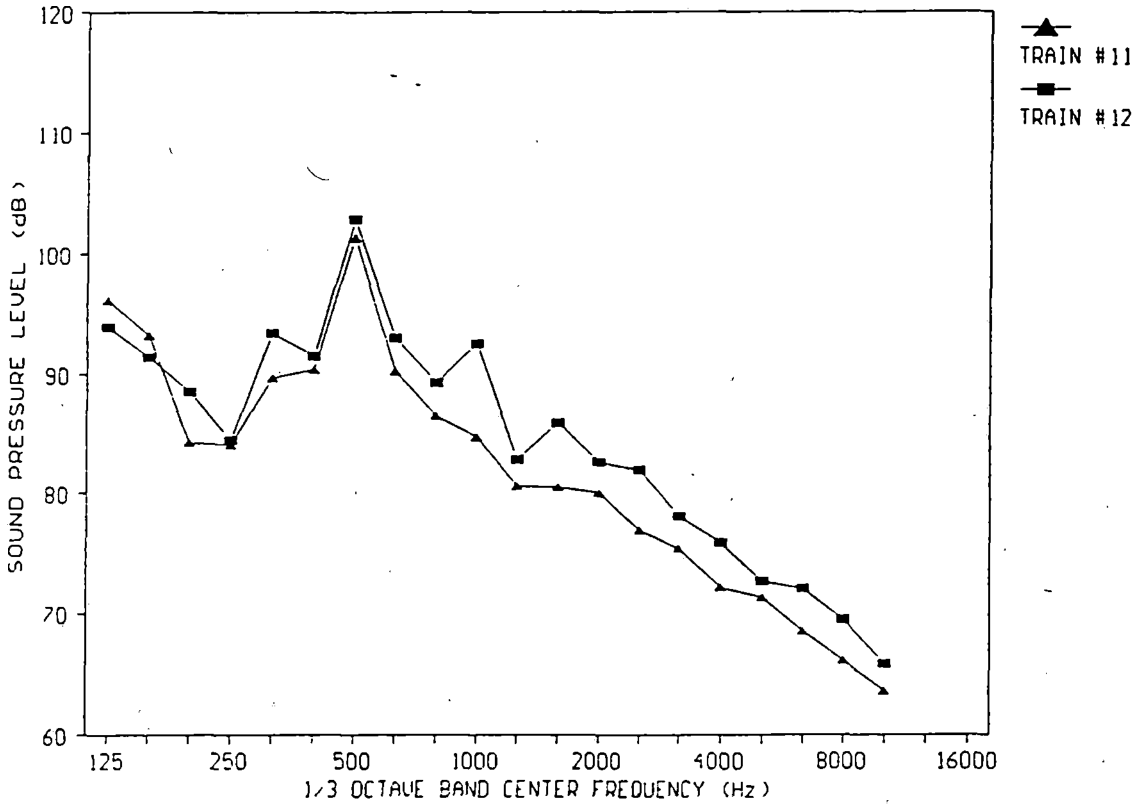
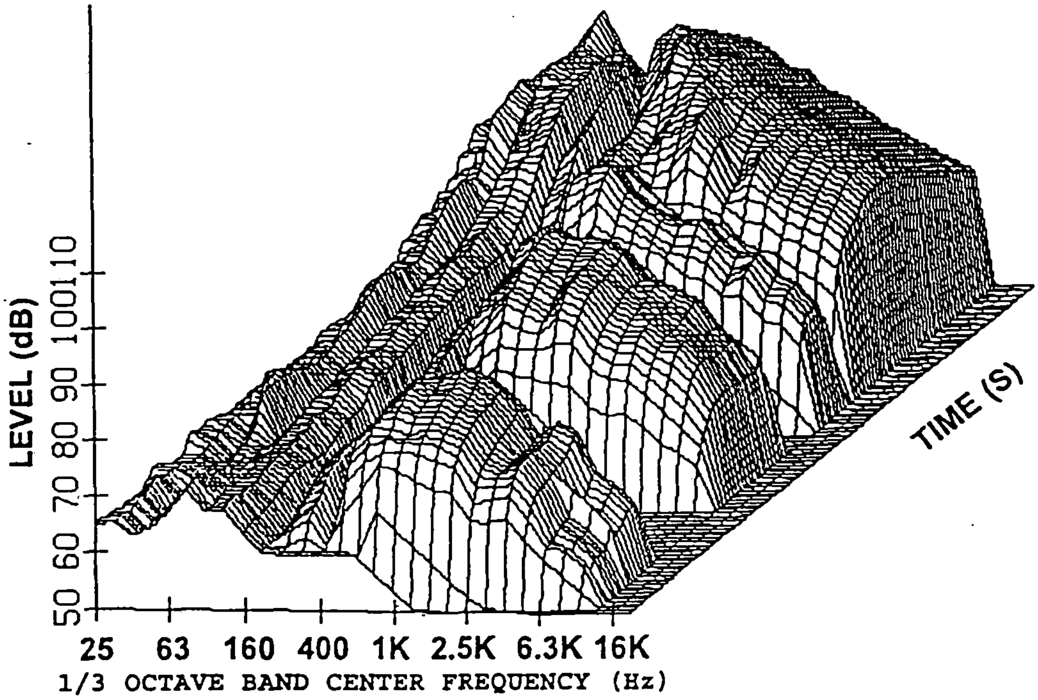


Figure B-12. Frequency Spectra at A_{max}
Cedar Street - Train 11 and Train 12



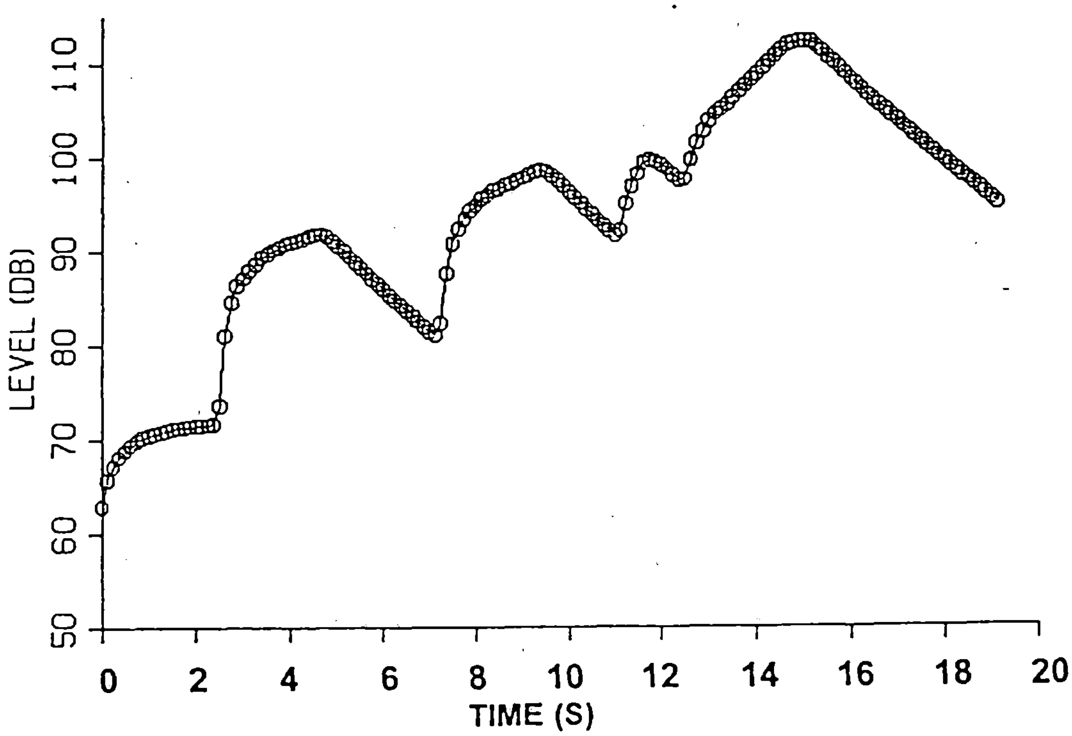
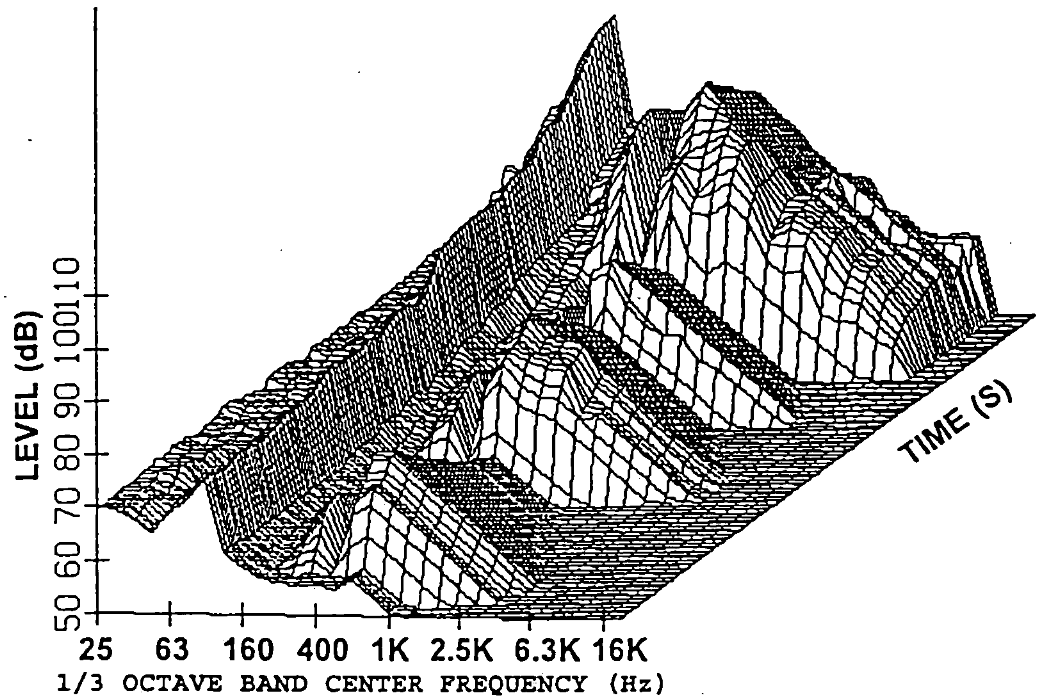


Figure B-13. Sunbeam Road - Train 1
A.) Spectral Time History
B.) A-Weighted Time History



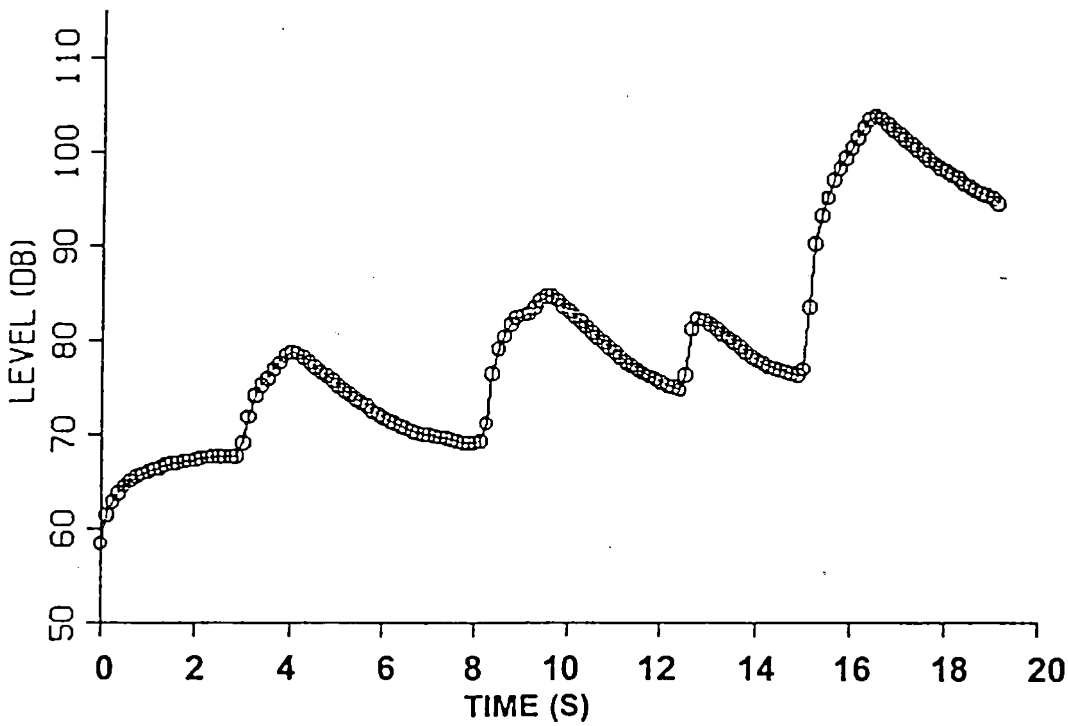
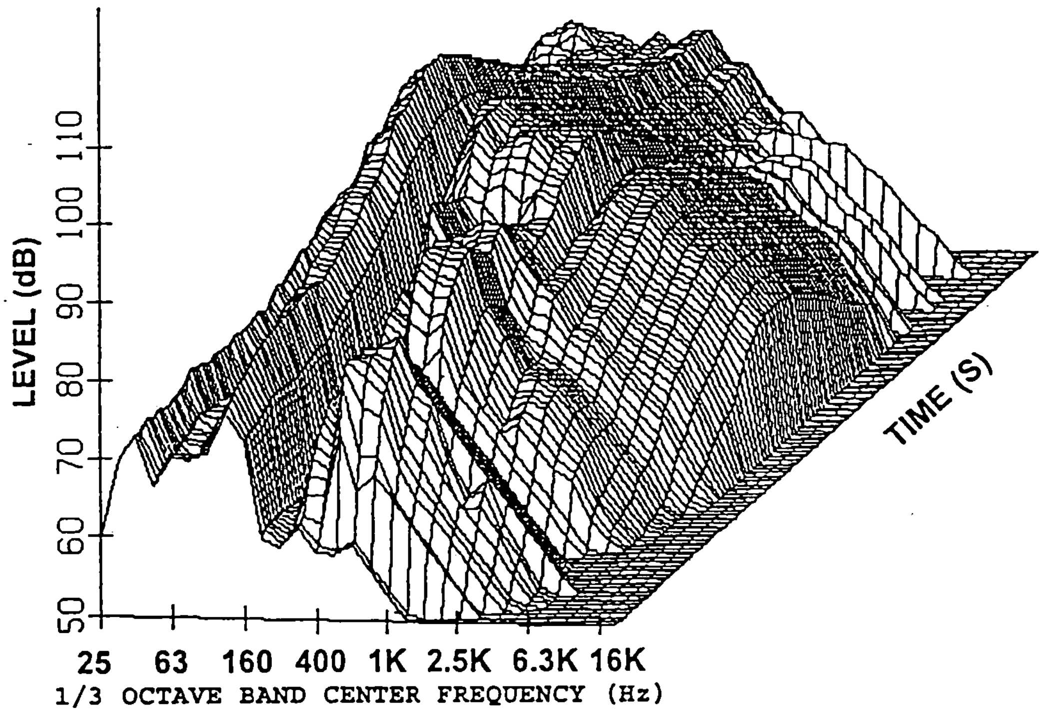


Figure B-14. Sunbeam Road - Train 2
A.) Spectral Time History
B.) A-Weighted Time History



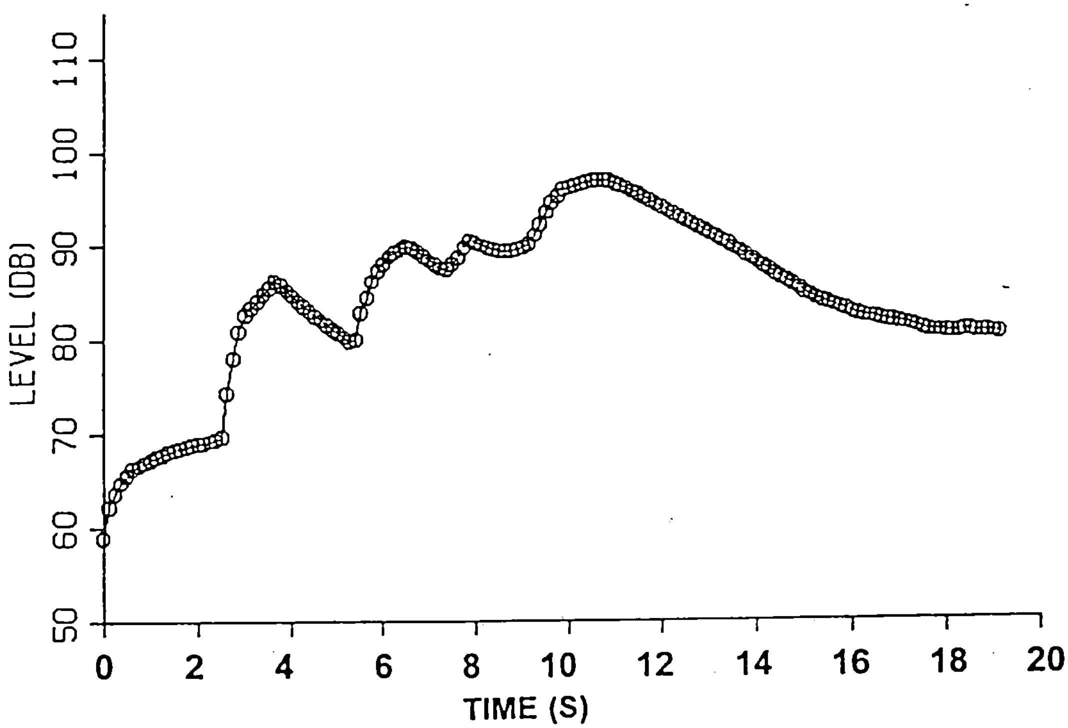


Figure B-15. Shad Road - Train 3
A.) Spectral Time History
B.) A-Weighted Time History

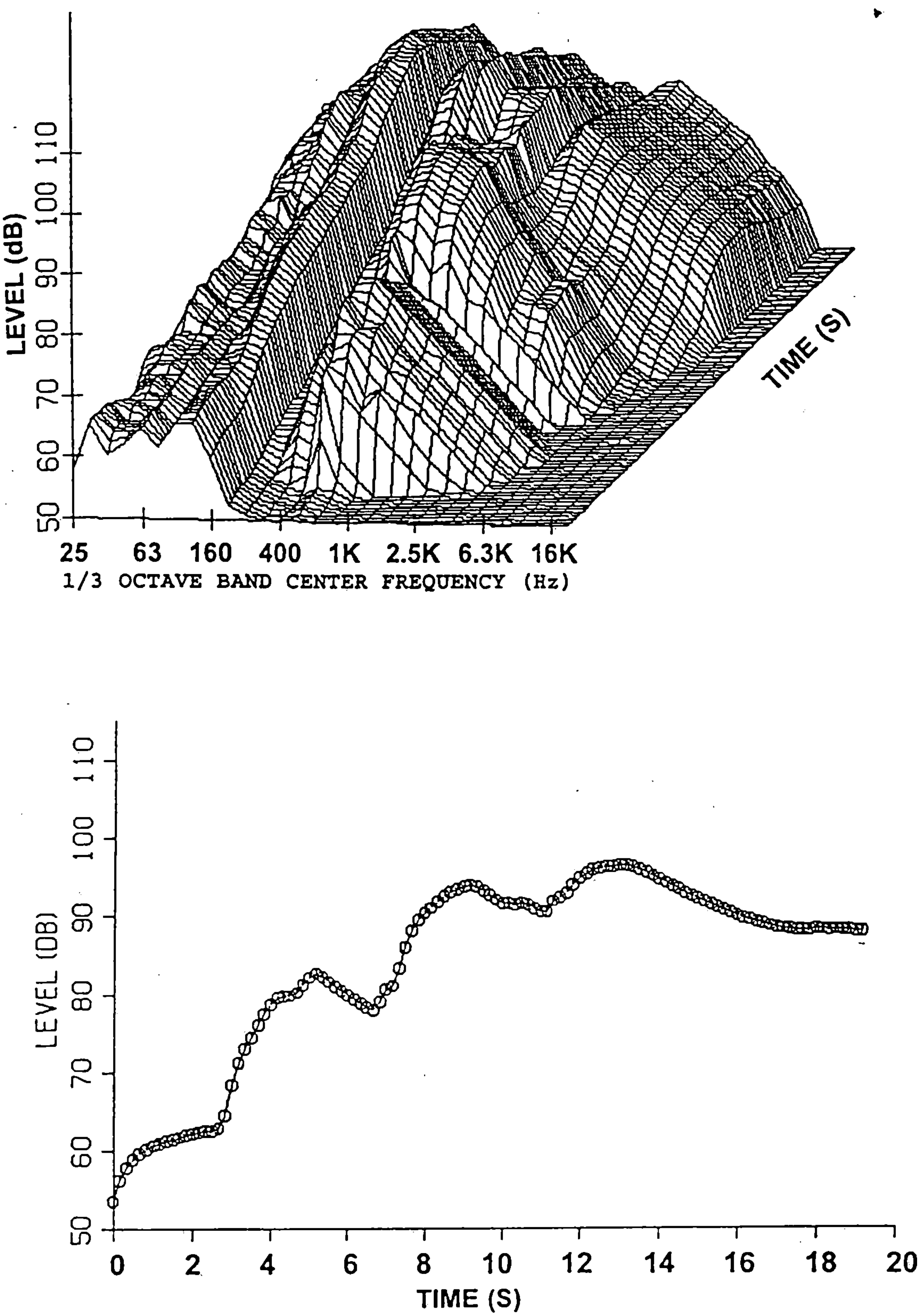
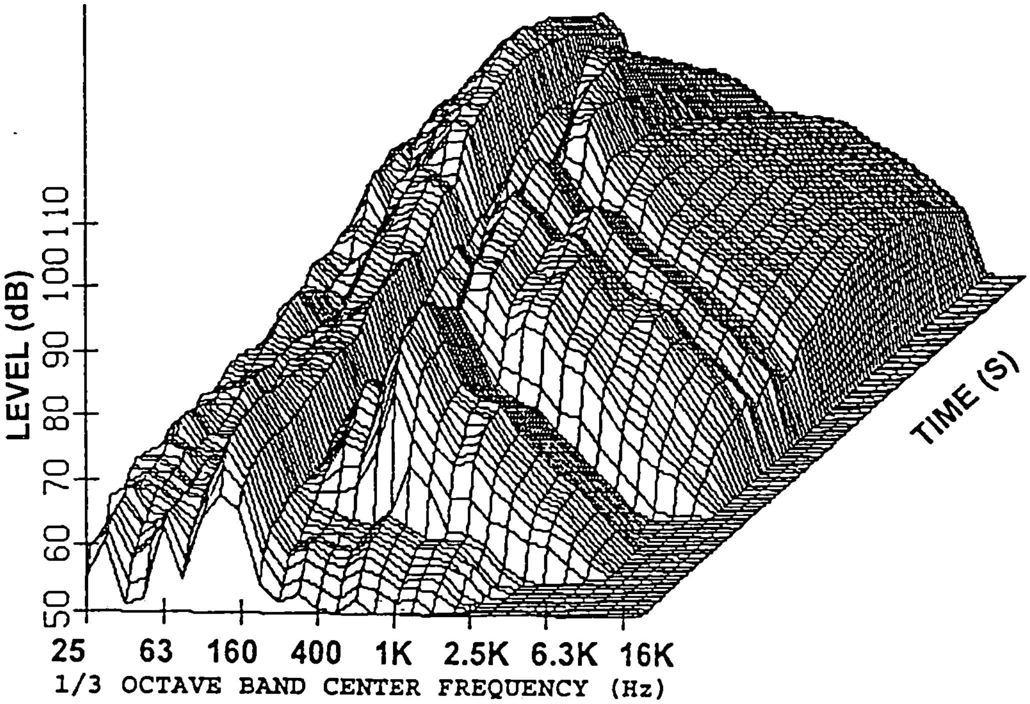


Figure B-16. Shad Road - Train 4
A.) Spectral Time History
B.) A-Weighted Time History



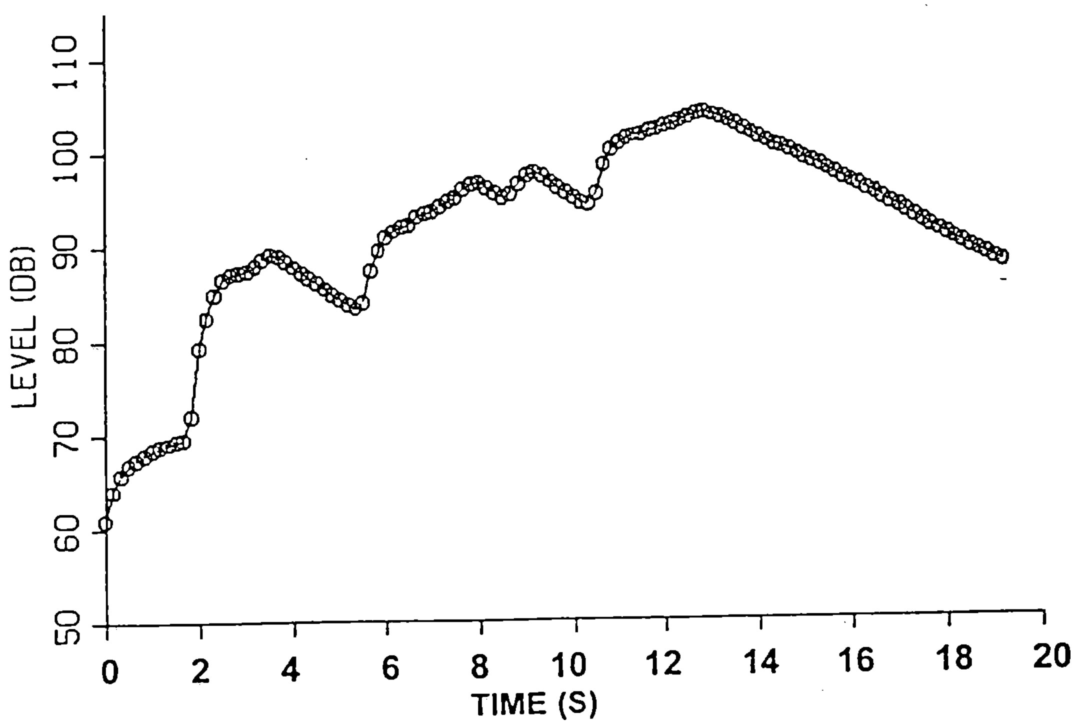
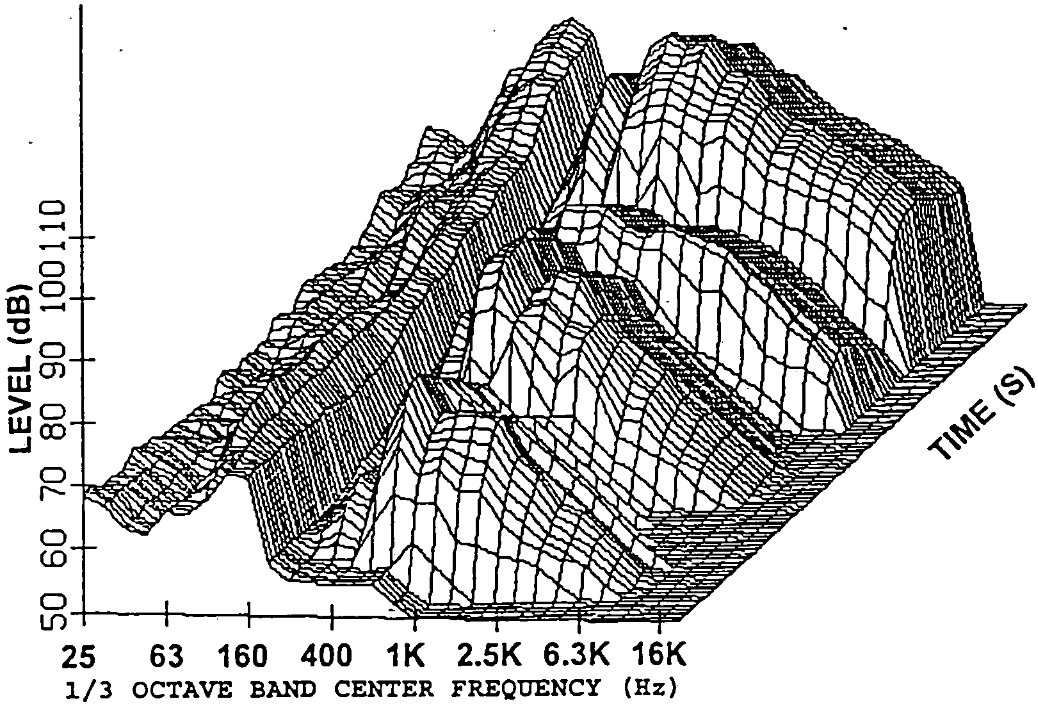


Figure B-17. Mussells Acres Road - Train 5
A.) Spectral Time History
B.) A-Weighted Time History



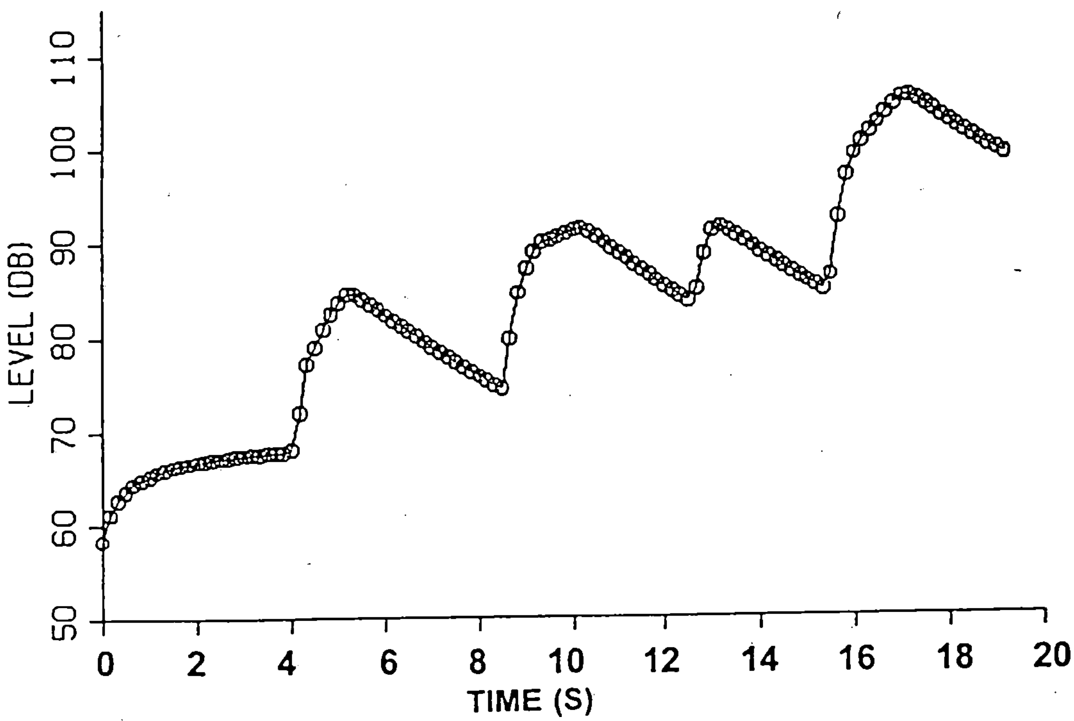
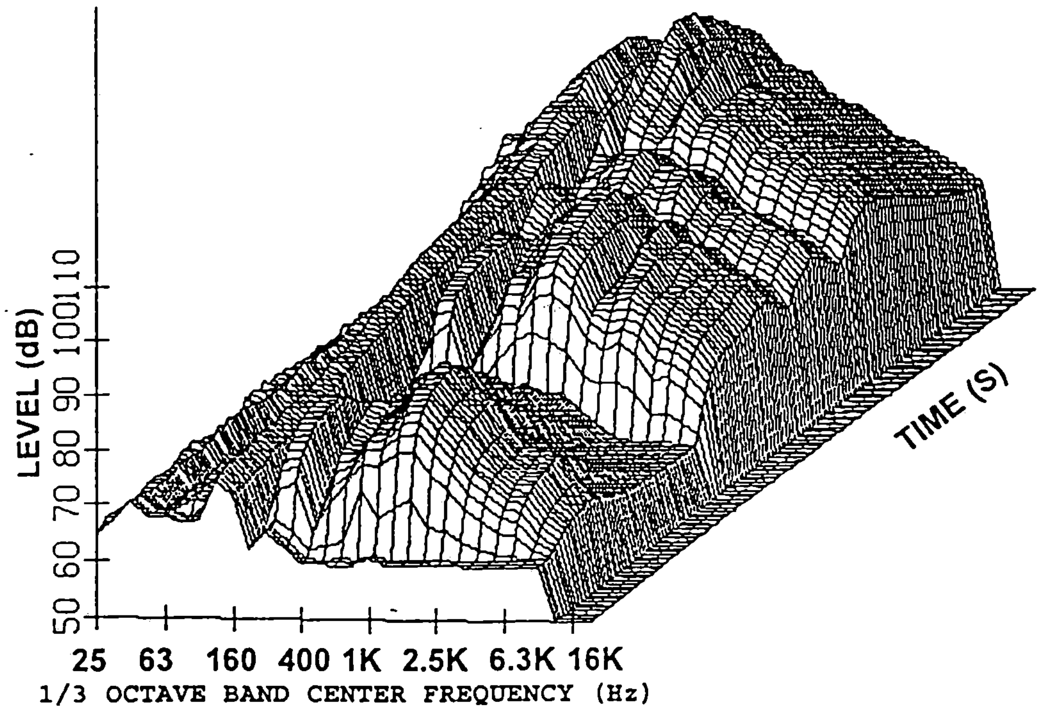


Figure B-18. Mussells Acres Road - Train 6
A.) Spectral Time History
B.) A-Weighted Time History



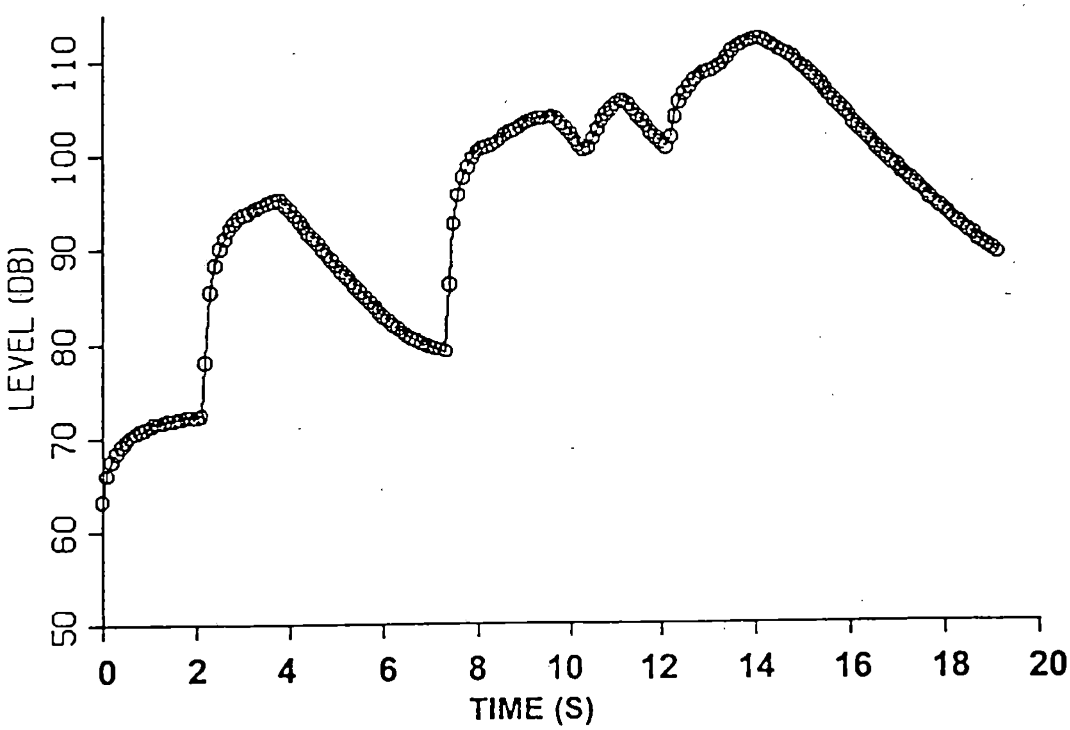
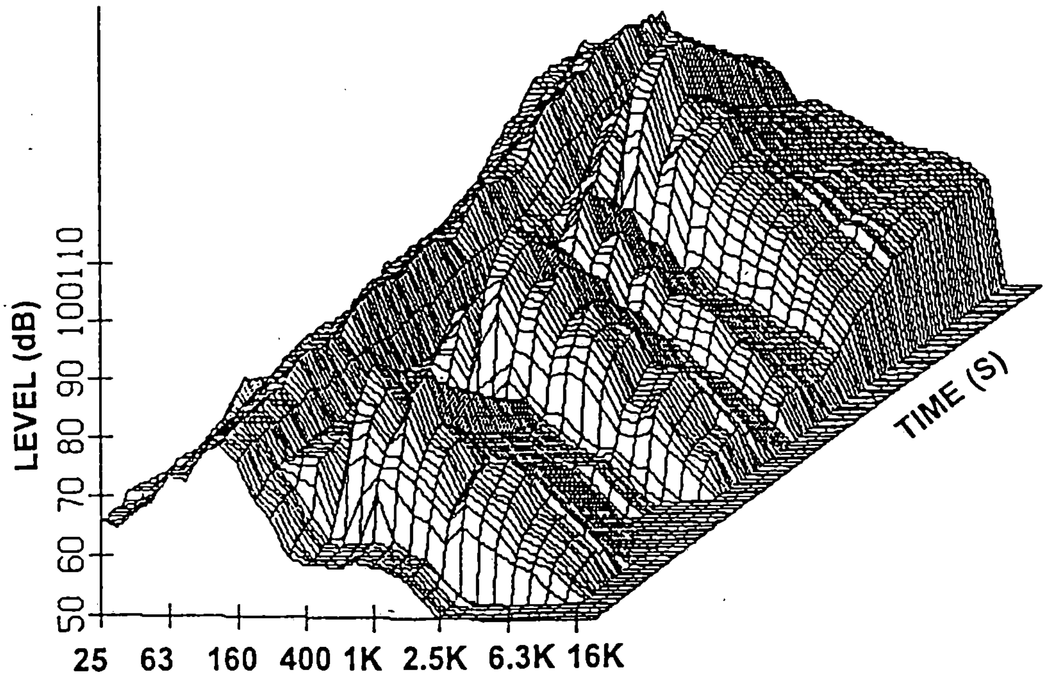


Figure B-19. Old St. Augustine Road - Train 7
A.) Spectral Time History
B.) A-Weighted Time History



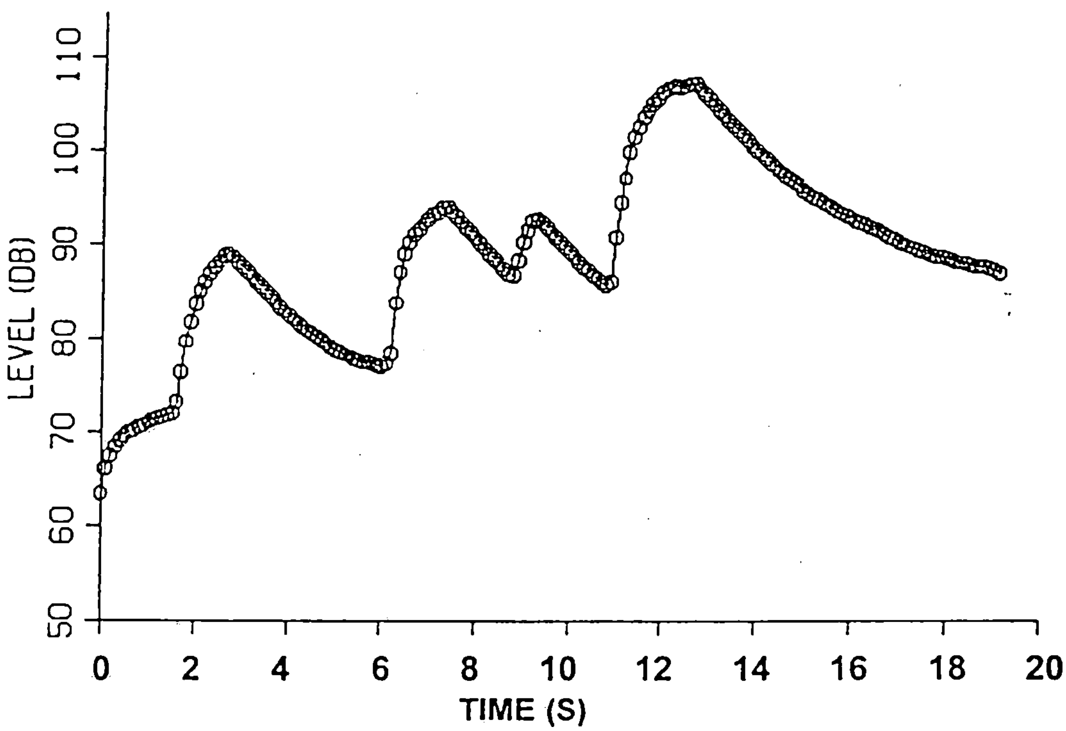
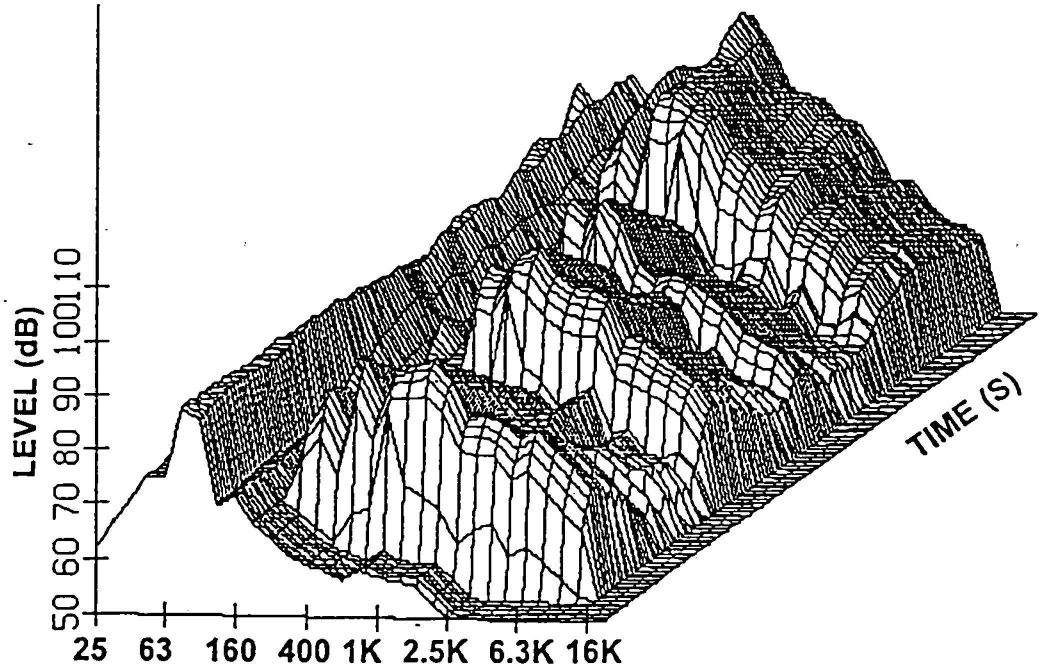


Figure B-20. Old St. Augustine Road - Train 8
A.) Spectral Time History
B.) A-Weighted Time History



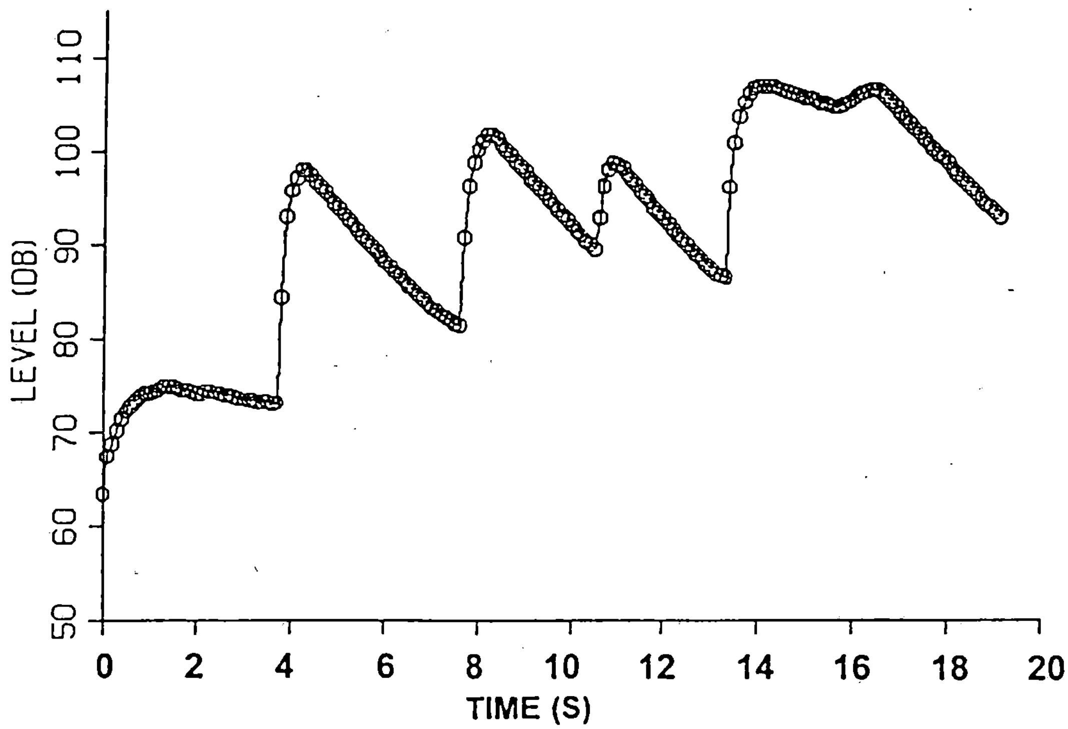
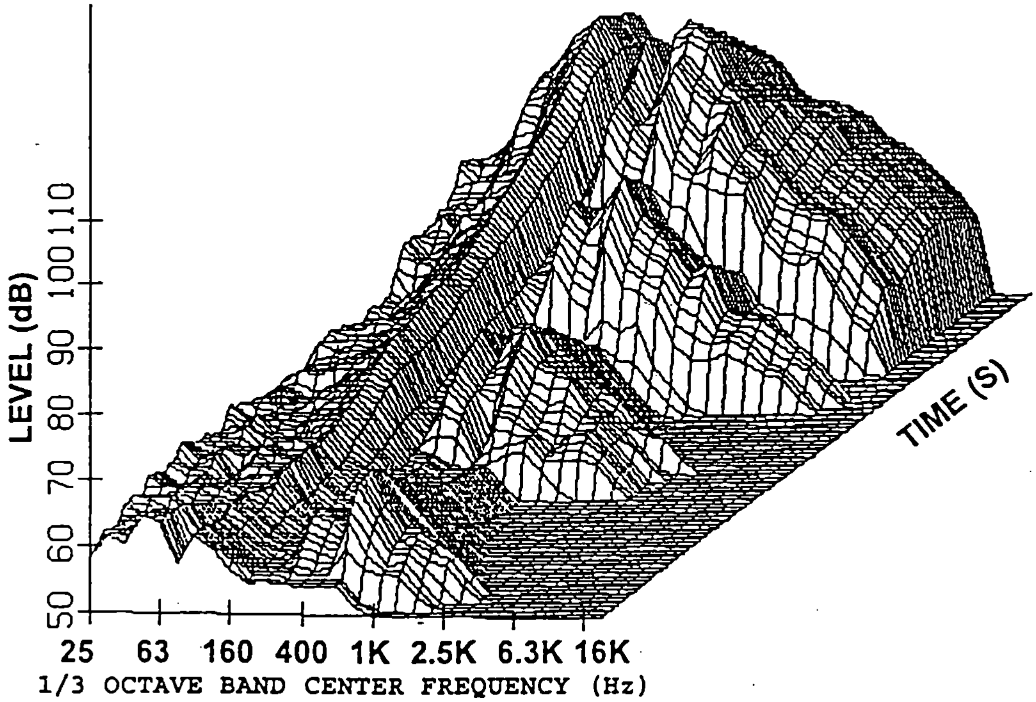


Figure B-21. Greenland Road - Train 9
A.) Spectral Time History
B.) A-Weighted Time History



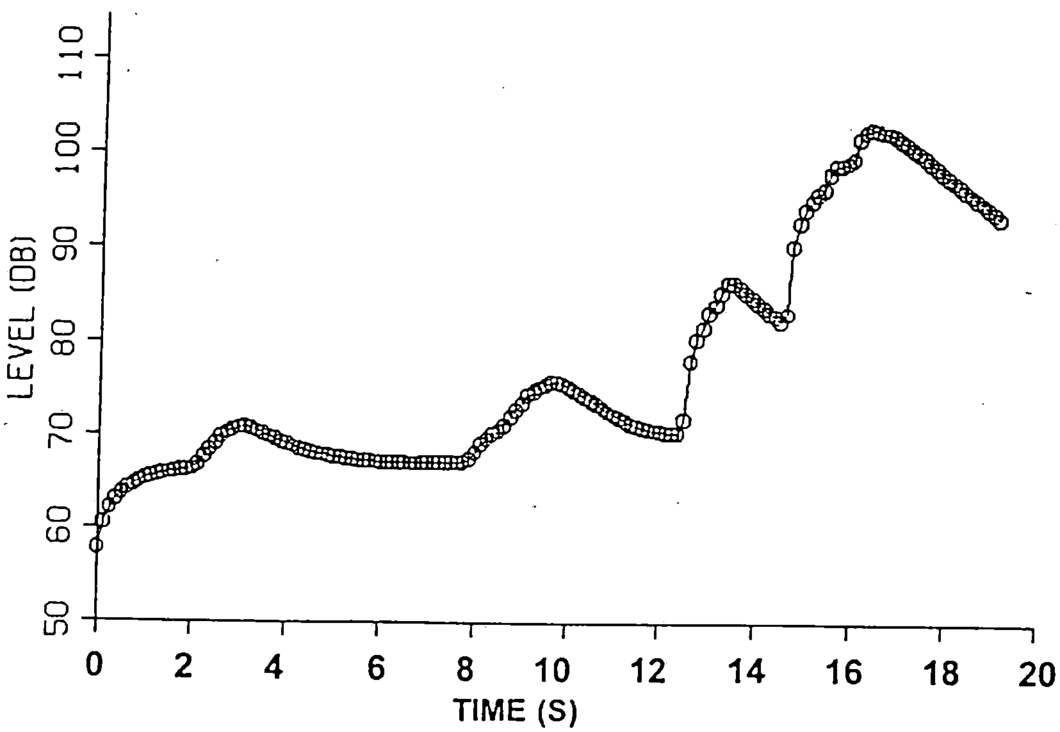
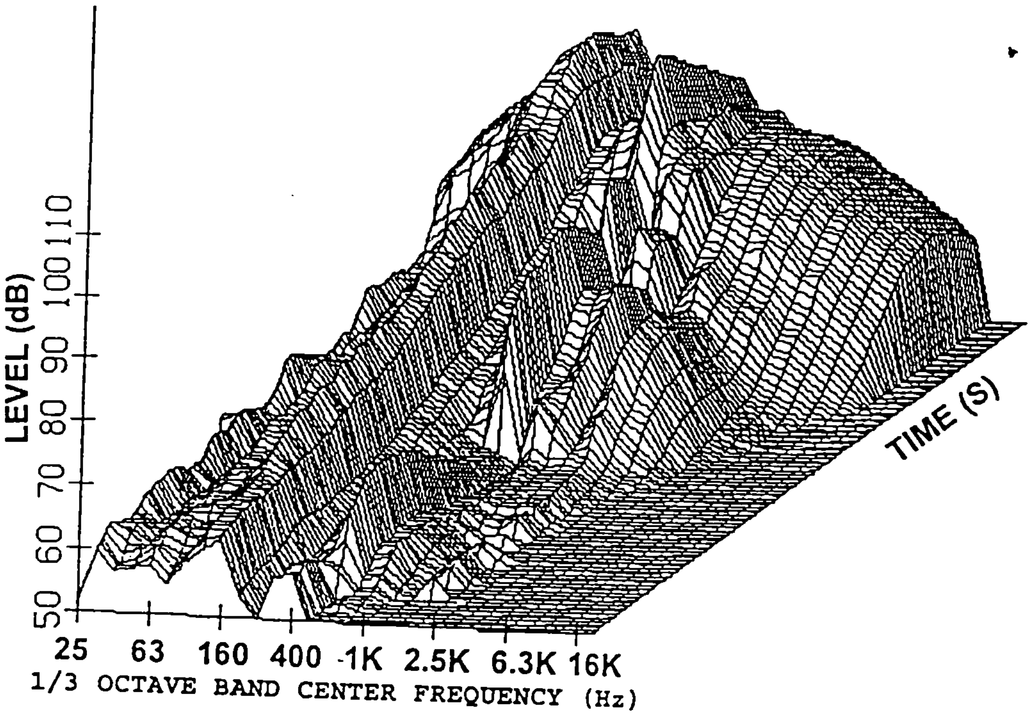


Figure B-22. Greenland Road - Train 10
A.) Spectral Time History
B.) A-Weighted Time History



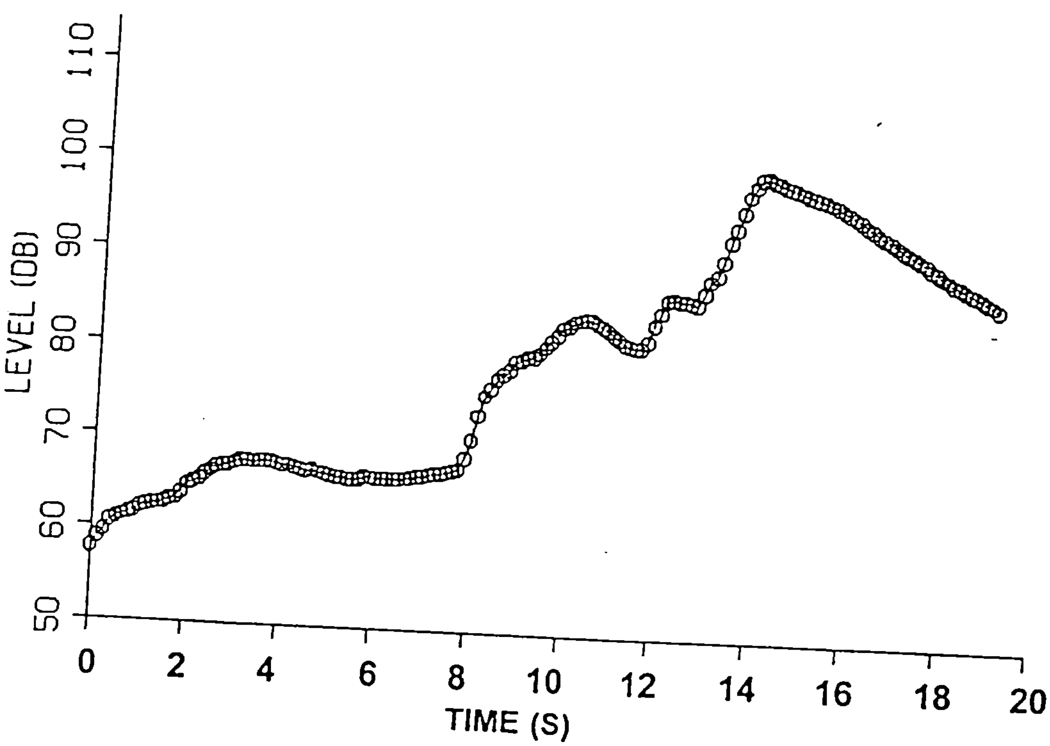


Figure B-23. Cedar St. - Train 11
A.) Spectral Time History
B.) A-Weighted Time History

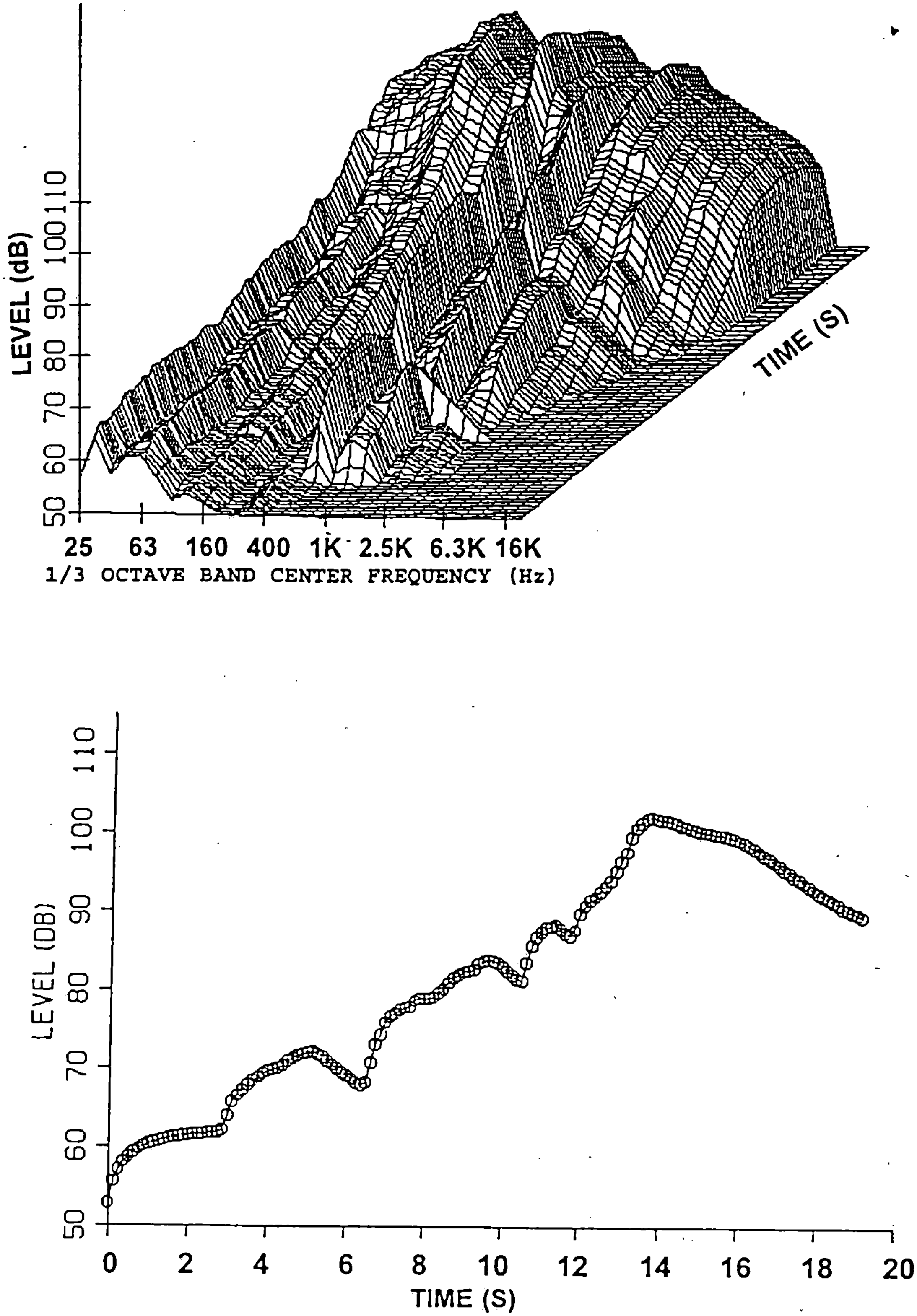


Figure B-24. Cedar St. - Train 12
A.) Spectral Time History
B.) A-Weighted Time History

APPENDIX C

THE ACOUSTIC CHARACTERISTICS OF AUTOMOBILES

This Appendix contains the average interior noise levels (Figures C-1 and C-2) and the insertion loss characteristics (Figures C-3 through C-11) for the seven motor vehicles tested.

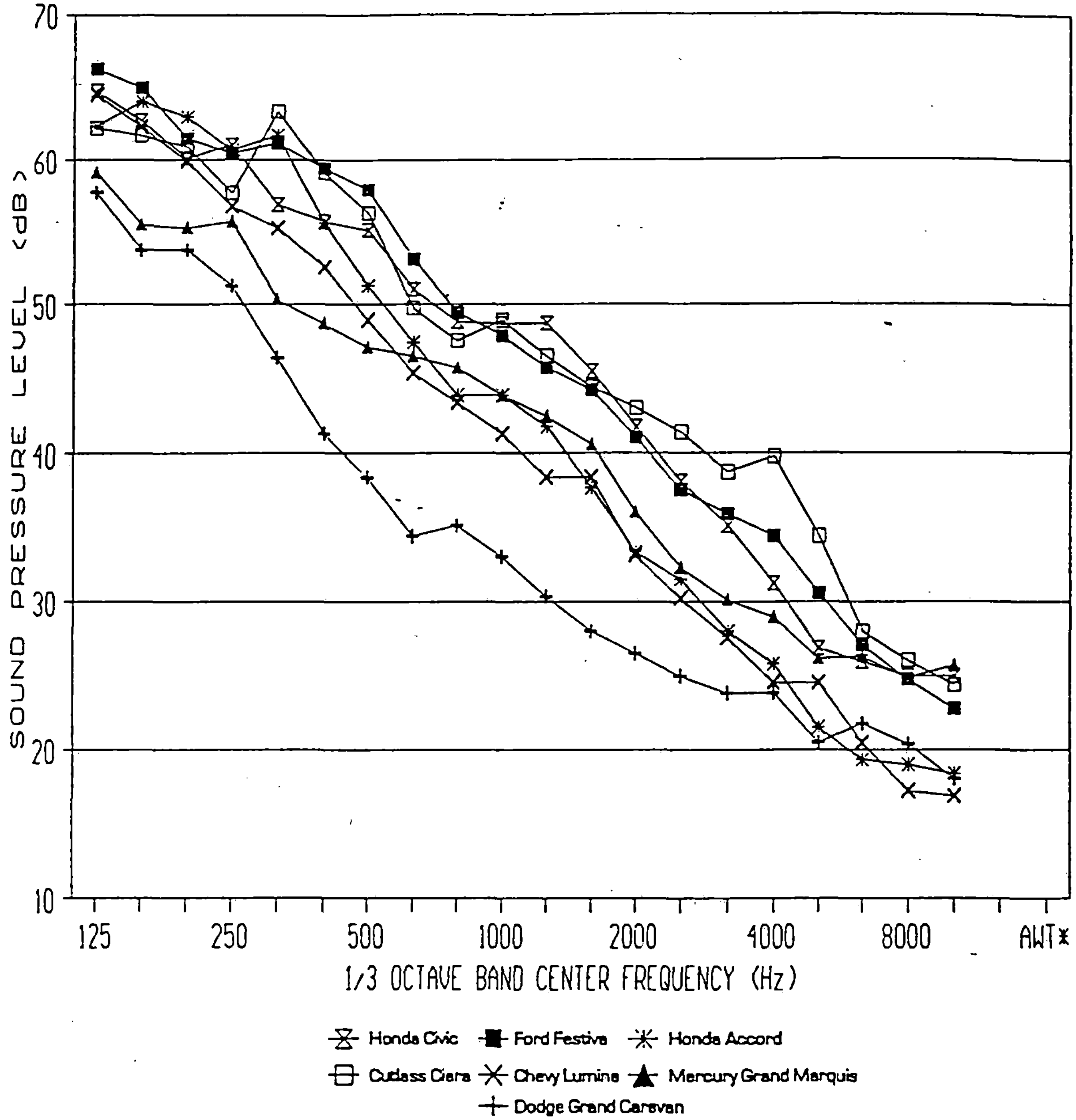


Figure C-1. Average Interior Noise Levels - 48.3 km/hr

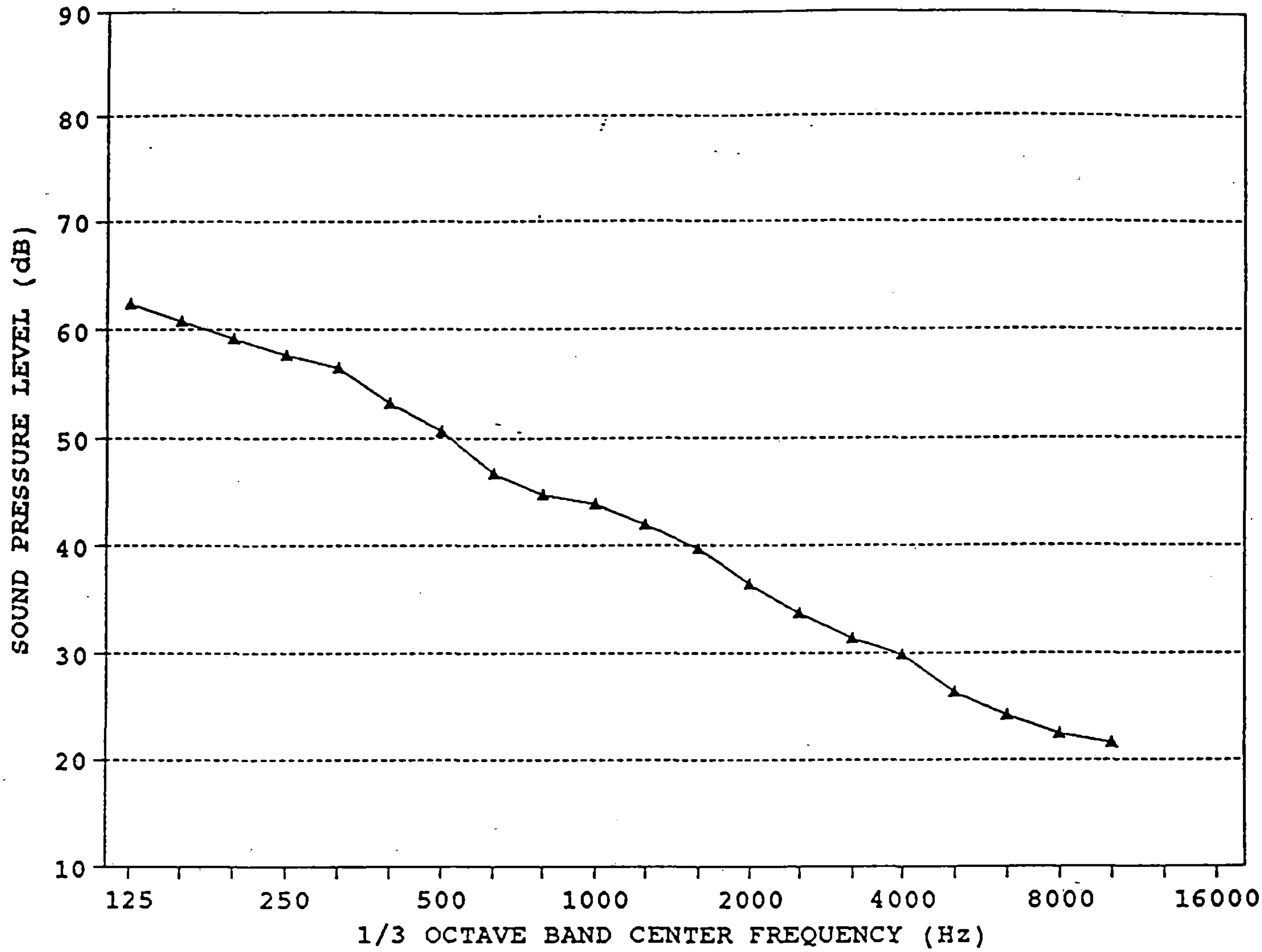


Figure C-2. Representative Interior Noise Level - 48.3 km/hr
(Average of Seven Vehicles Tested)

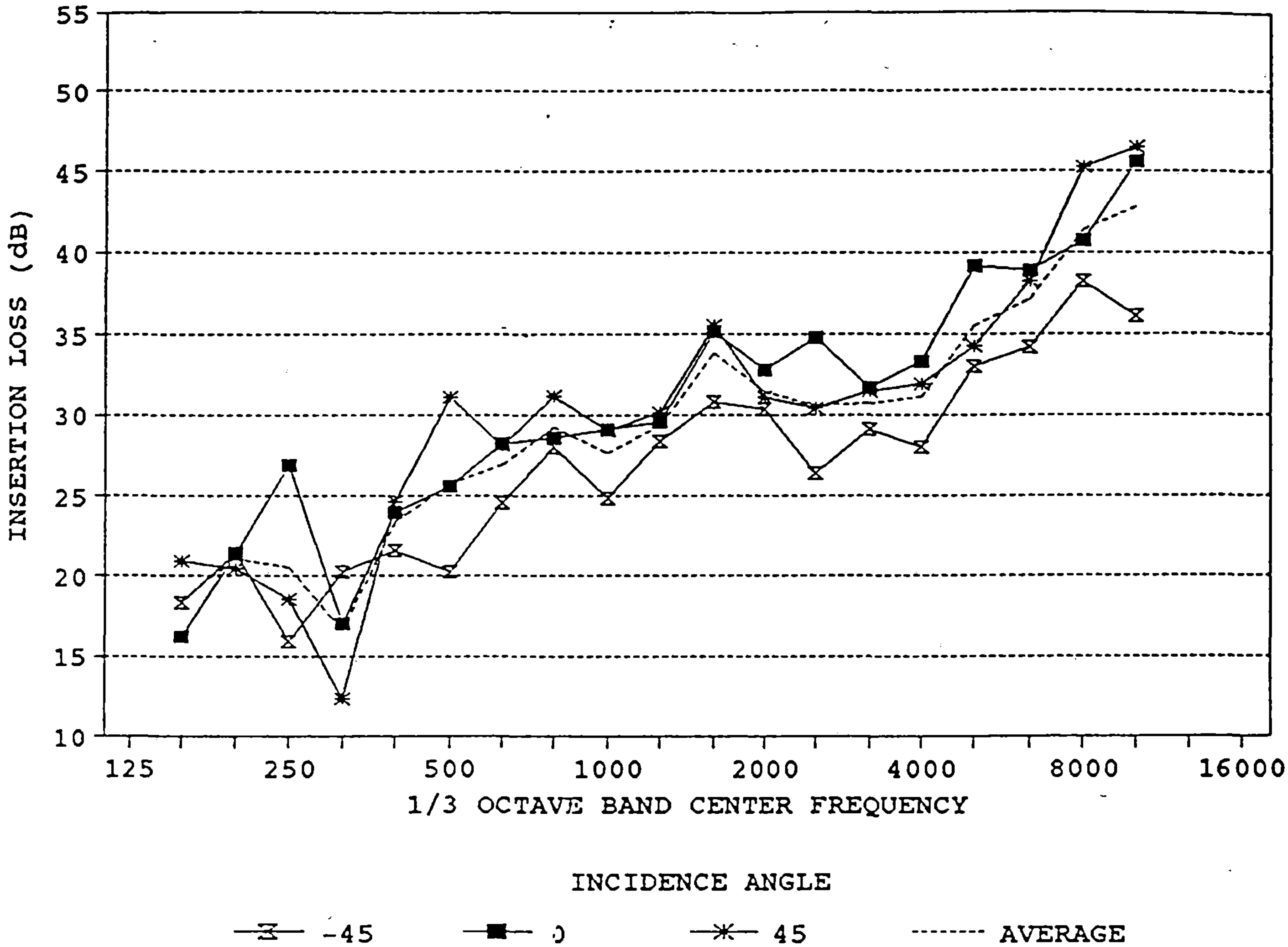


Figure C-3. Insertion Loss
1990 Honda Civic

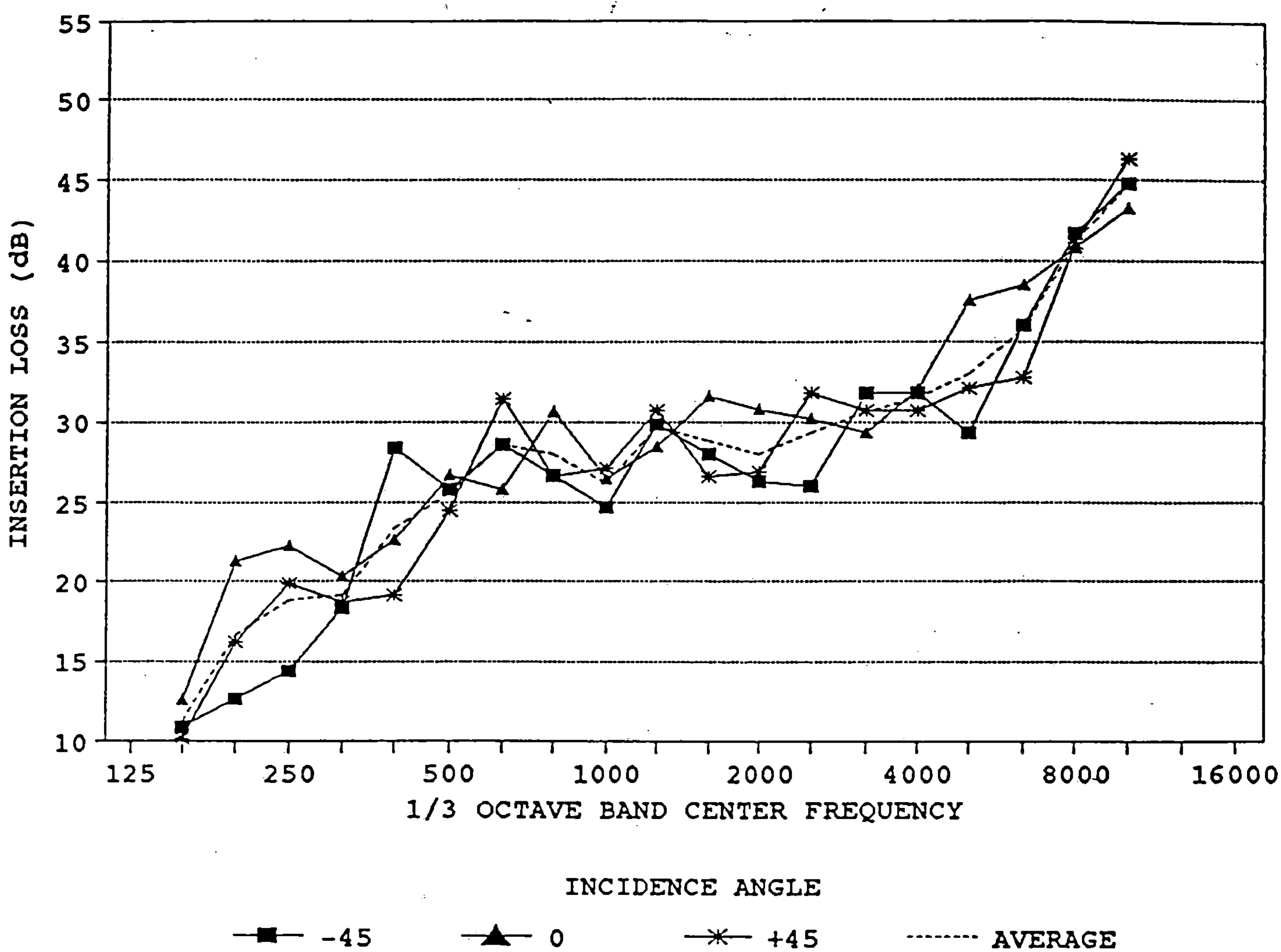


Figure C-4. Insertion Loss
1991 Ford Festiva

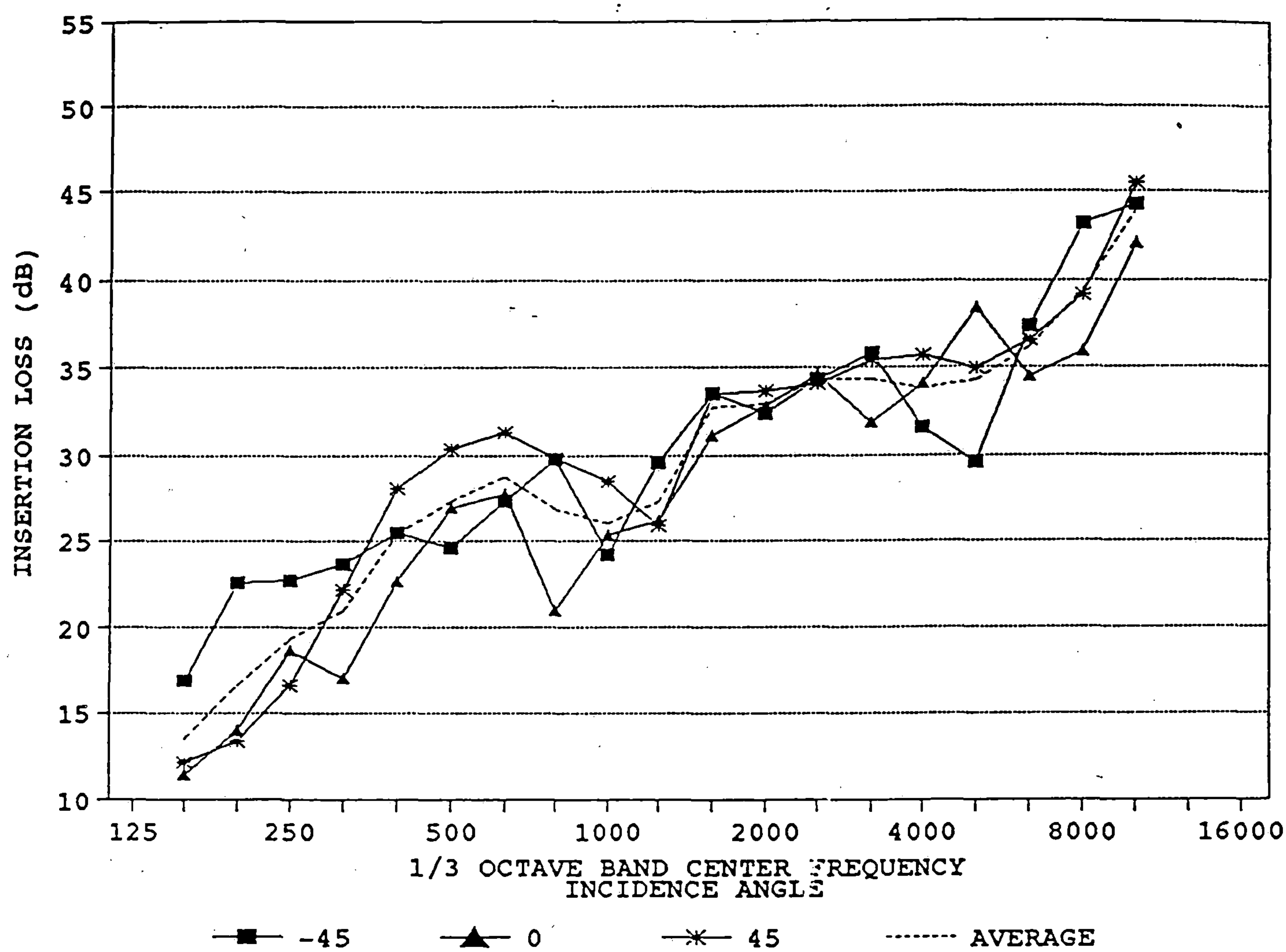


Figure C-5. Insertion Loss
1991 Honda Accord

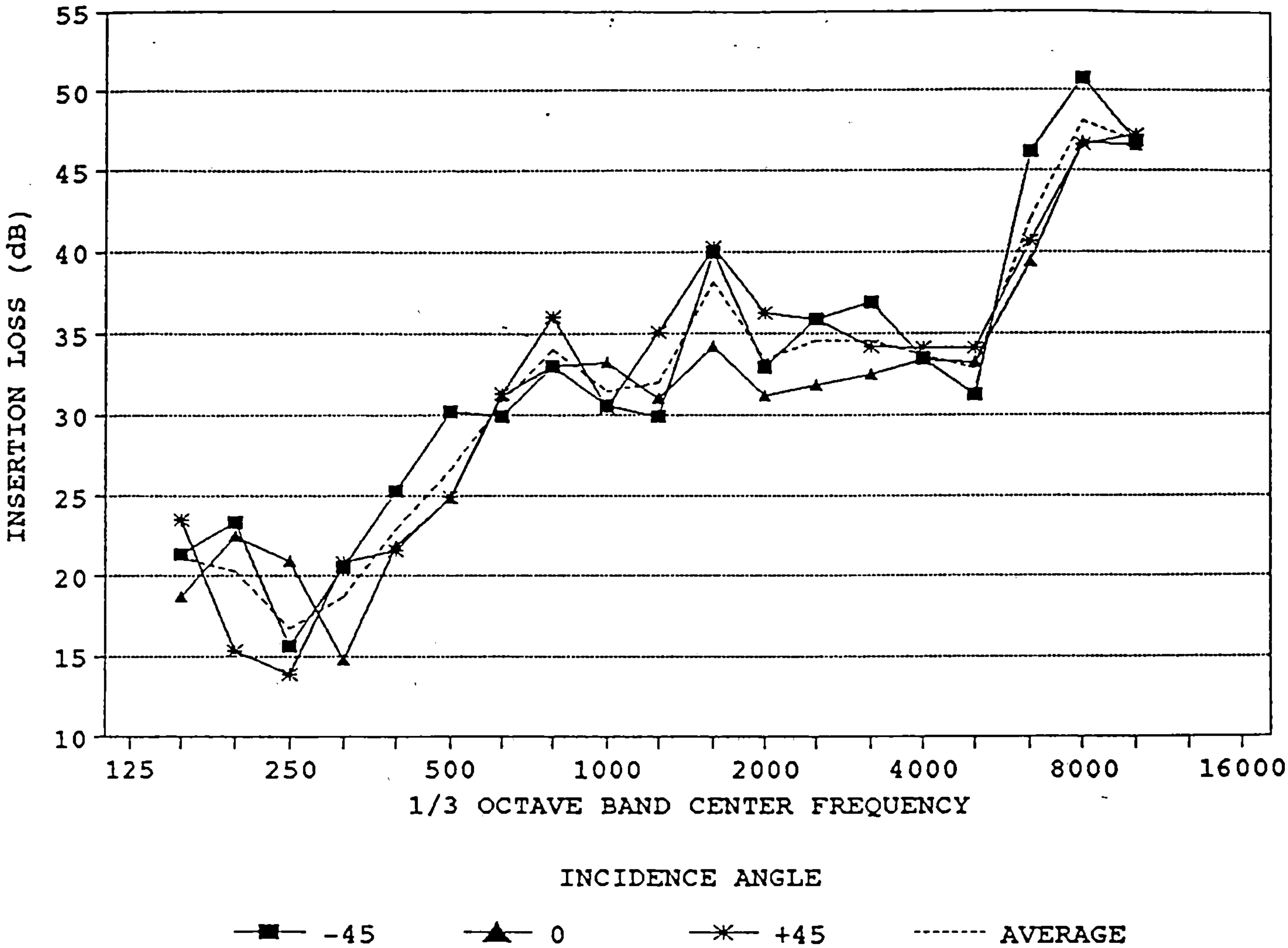


Figure C-6. Insertion Loss
1991 Cutlass Ciera

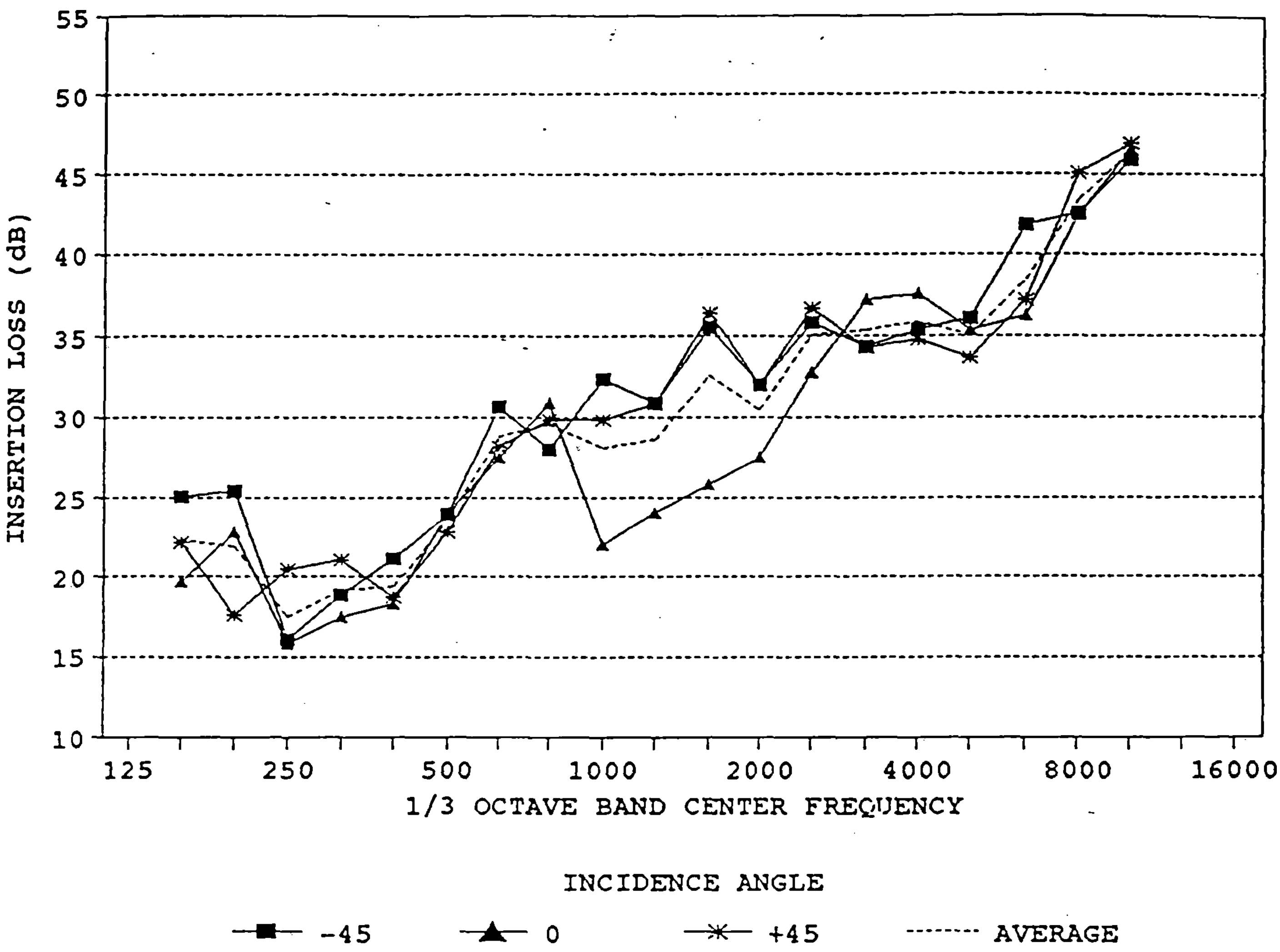


Figure C-7. Insertion Loss
1991 Chevrolet Lumina

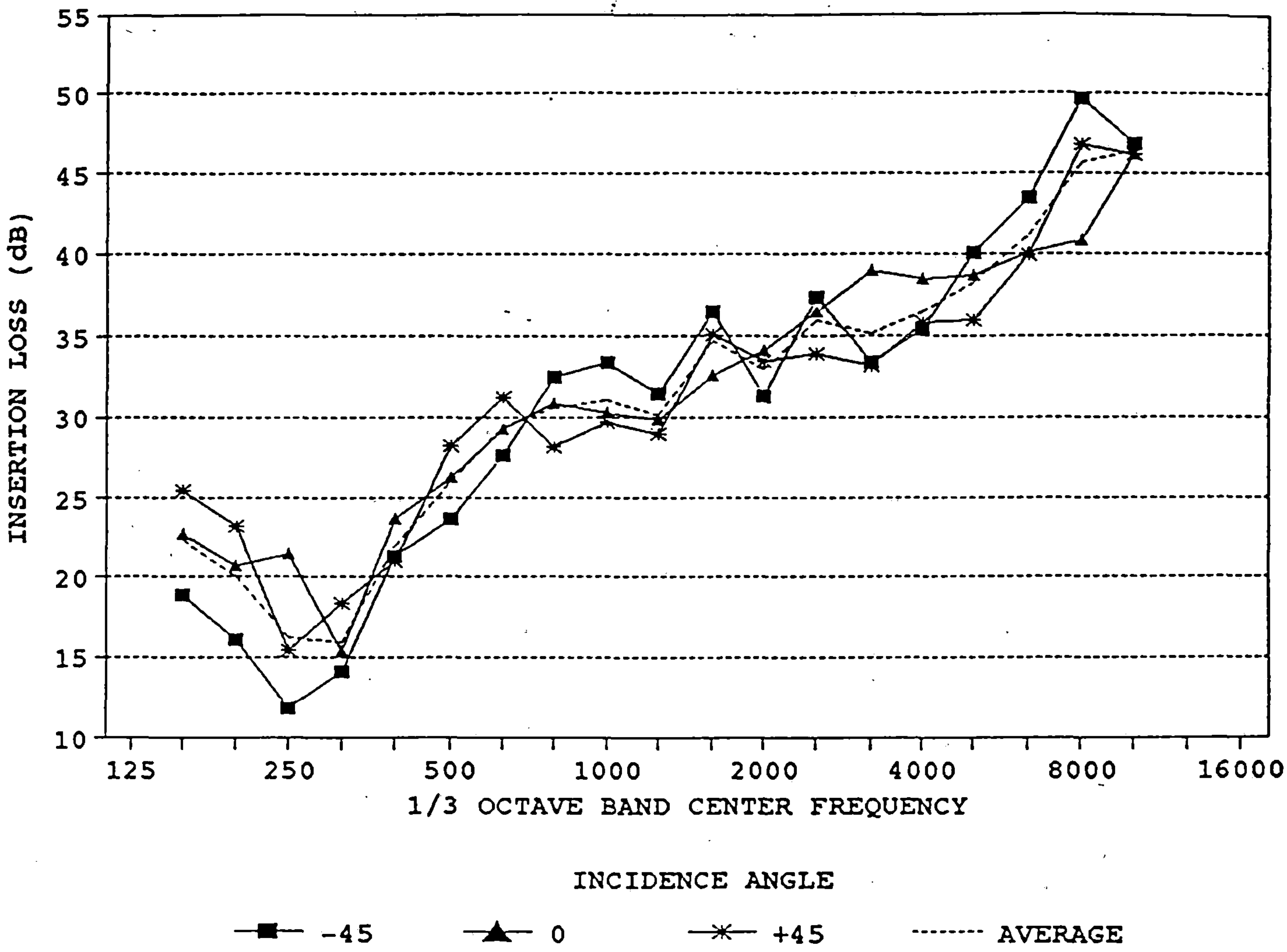


Figure C-8. Insertion Loss
1991 Mercury Grand Marquis

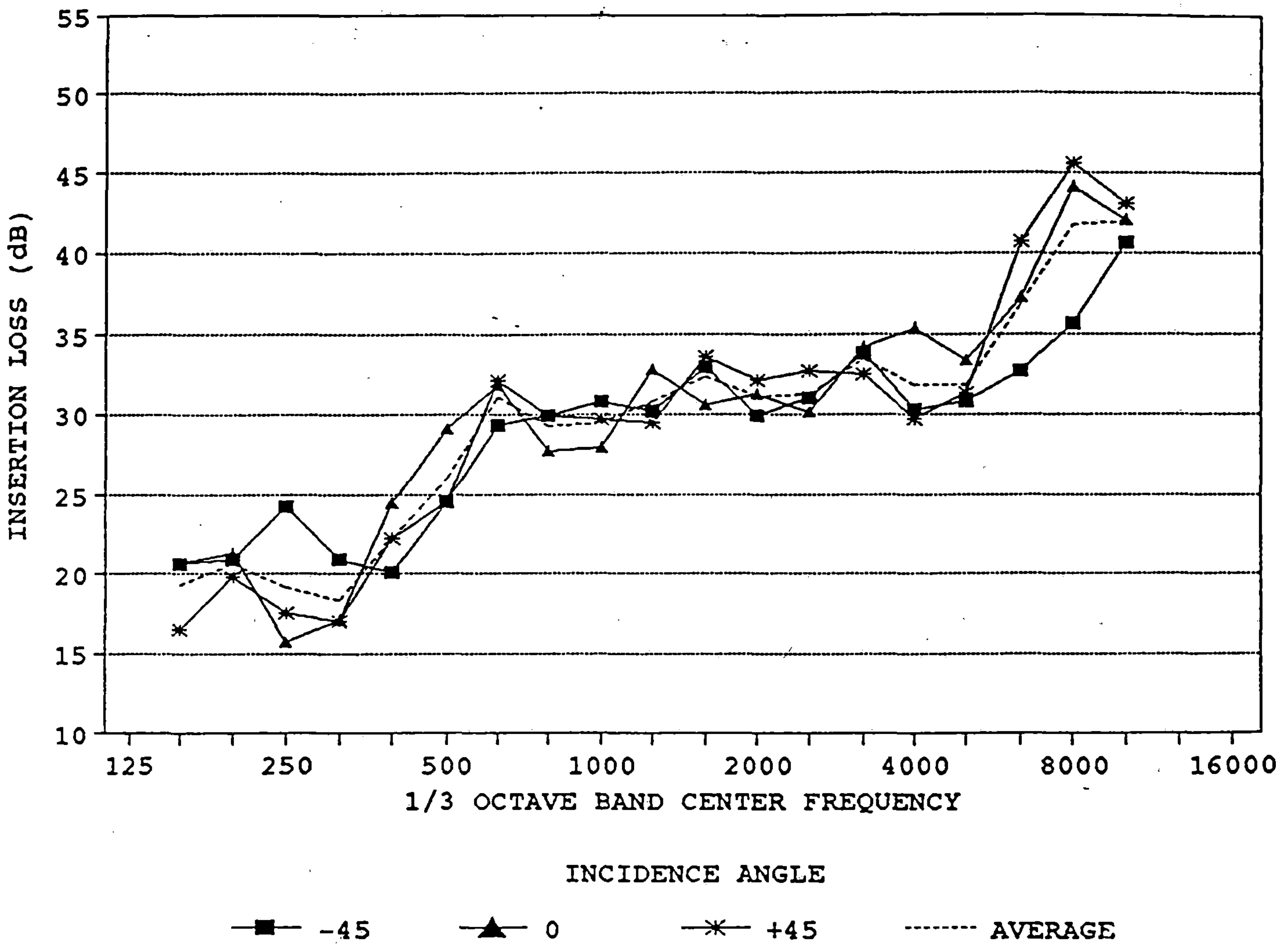


Figure C-9. Insertion Loss
1991 Dodge Grand Caravan

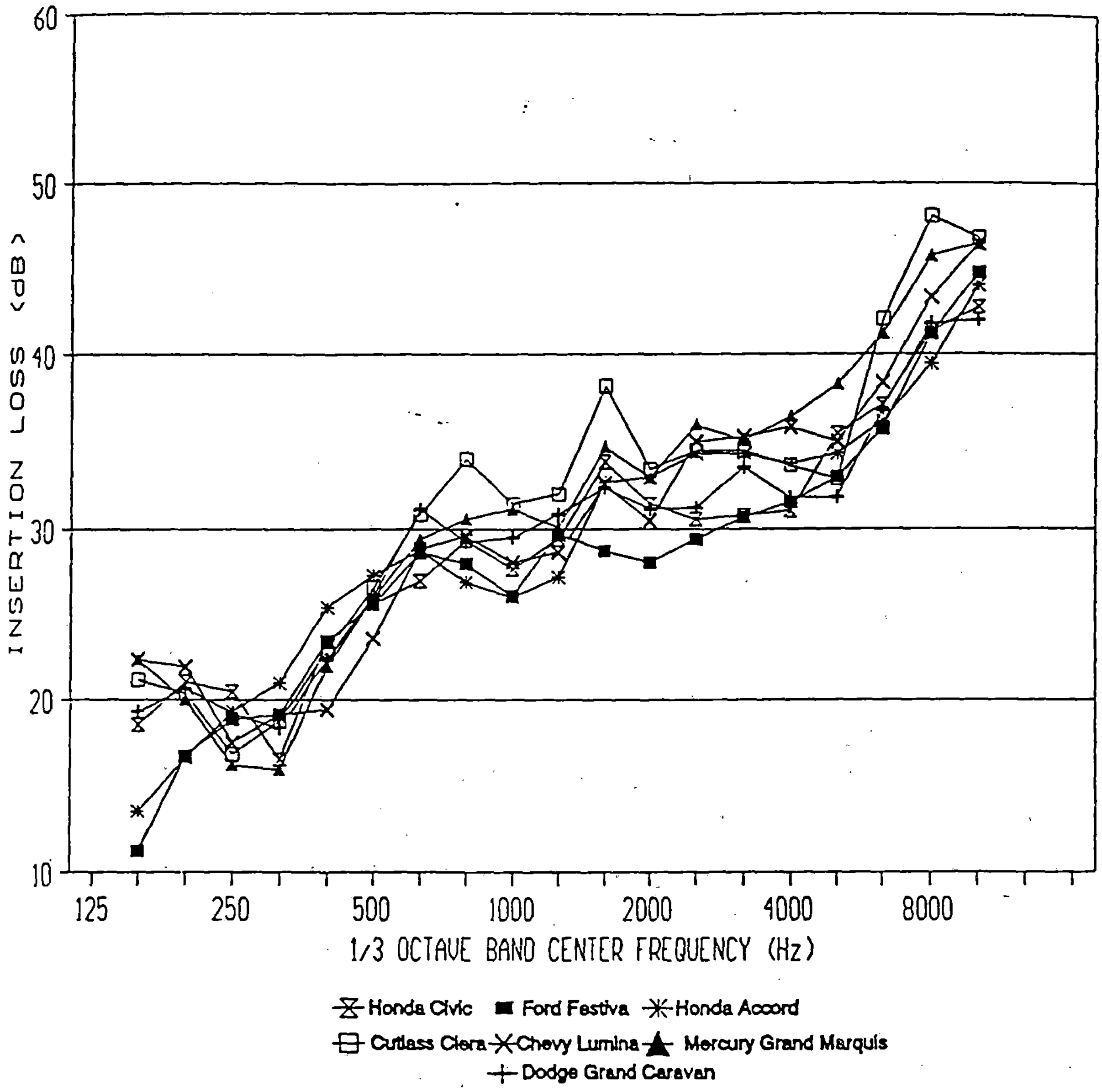


Figure C-10. Average Insertion Loss

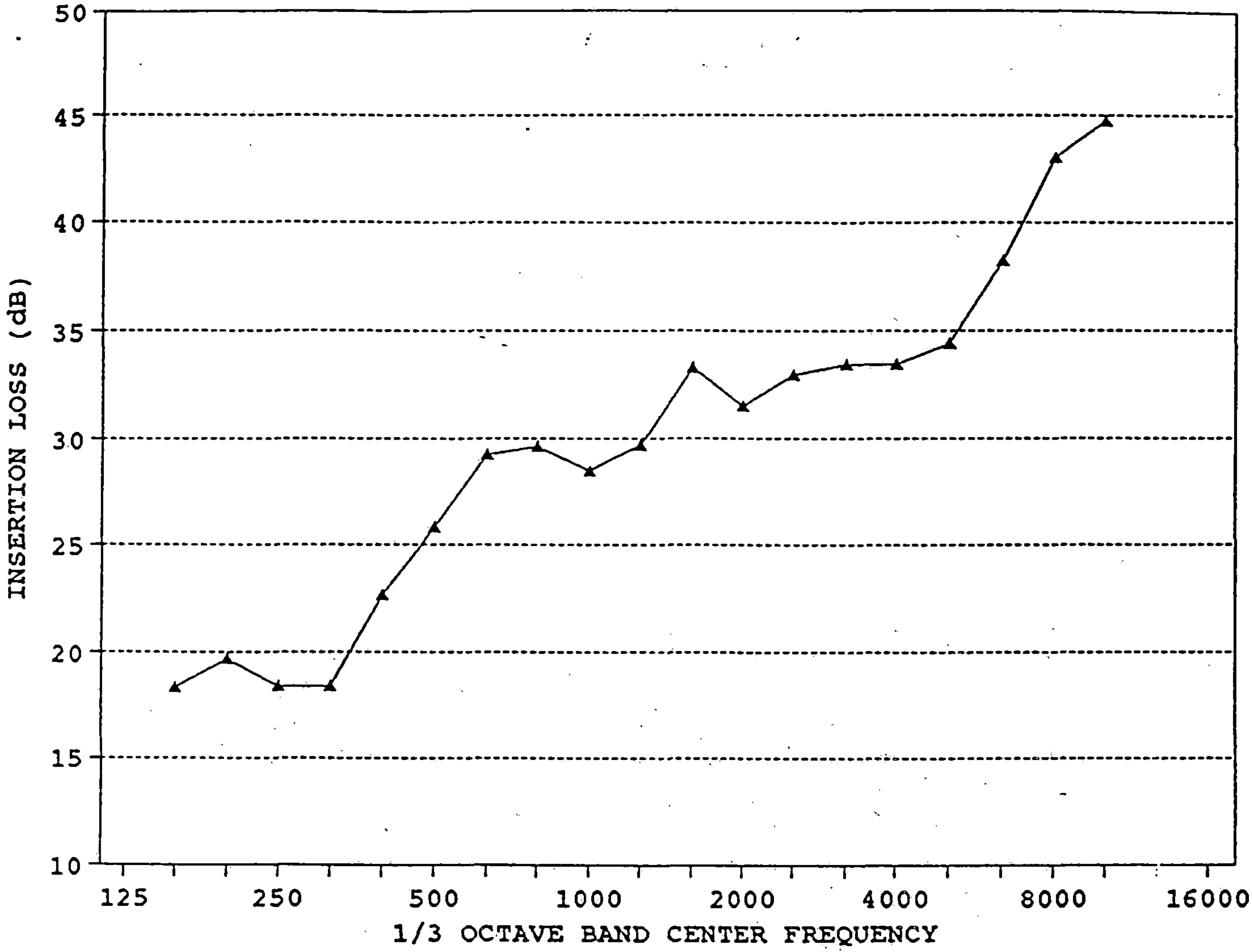


Figure C-11. Representative Insertion Loss (Average of Seven Vehicles Tested)

The Effectiveness of Railroad Horn Systems, The Safety of Highway-Railroad Grade Crossings, US DOT, FRA, AS Rapoza, EJ Rickley, 1995 - 08-Rail-Highway Grade Crossings