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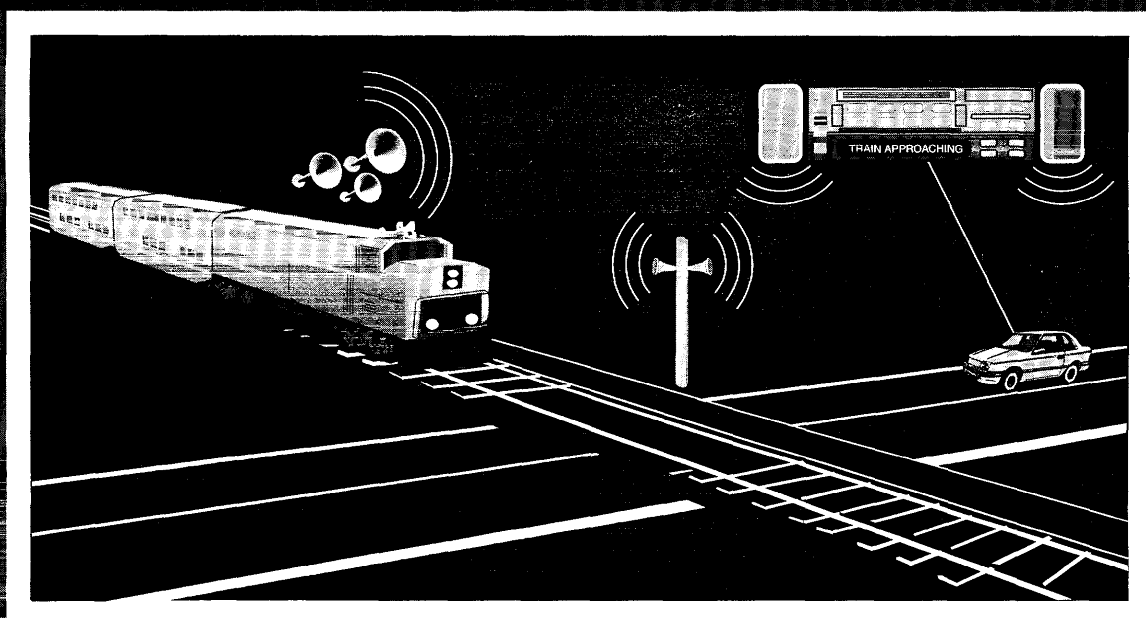

Safety of Highway-Railroad Grade Crossings

DOT/FRA/ORD-99/10
DOT-VNTSC-FRA-98-2

Final Report
January 1999

always expect a train

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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), Acoustics Facility, in support of the Federal Railroad Administration (FRA). This study evaluated the community noise impact, human detectability and effectiveness of railroad horn systems, both conventional and alternative, at highway-railroad grade crossings.

This study represents the combined effort of several authors whose expertise lies in two distinct areas. The sections of this report which focus on acoustics and acoustical measurements were written by Amanda S. Rapoza and Edward J. Rickley. The sections which focus on signal detection theory and horn effectiveness were written by Thomas G. Raslear.

The authors would like to thank the following individuals for their support: Claire Orth, Chief, FRA's Equipment and Operating Practices Research Division, and Garold Thomas, Program Manager, FRA's Office of Research and Development; Anya Carroll, Principal Investigator, Volpe Center's Highway-Railroad Grade Crossing Safety Research Program; John Hitz, Chief, Volpe Center's Accident Prevention Division; Jordan Multer, Volpe Center's Operator Performance and Safety Analysis Division; W. Douglass DeBoer, Railroad Safety Inspector, FRA's Office of Safety; and Hank Dickinson and Jerry Hall, 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.

METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in) = 2.5 centimeters (cm)
1 foot (ft) = 30 centimeters (cm)
1 yard (yd) = 0.9 meter (m)
1 mile (mi) = 1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2) = 6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2) = 0.09 square meter (m^2)
1 square yard (sq yd, yd^2) = 0.8 square meter (m^2)
1 square mile (sq mi, mi^2) = 2.6 square kilometers (km^2)
1 acre = 0.4 hectare (ha) = 4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz) = 28 grams (gm)
1 pound (lb) = .45 kilogram (kg)
1 short ton = 2,000 pounds (lb) = 0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp) = 5 milliliters (ml)
1 tablespoon (tbsp) = 15 milliliters (ml)
1 fluid ounce (fl oz) = 30 milliliters (ml)
1 cup (c) = 0.24 liter (l)
1 pint (pt) = 0.47 liter (l)
1 quart (qt) = 0.96 liter (l)
1 gallon (gal) = 3.8 liters (l)
1 cubic foot (cu ft, ft^3) = 0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3) = 0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

°C=5/9(°F - 32)

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm) = 0.04 inch (in)
1 centimeter (cm) = 0.4 inch (in)
1 meter (m) = 3.3 feet (ft)
1 meter (m) = 1.1 yards (yd)
1 kilometer (km) = 0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2) = 0.16 square inch (sq in, in^2)
1 square meter (m^2) = 1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2) = 0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2) = 1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm) = 0.036 ounce (oz)
1 kilogram (kg) = 2.2 pounds (lb)
1 tonne (t) = 1,000 kilograms (kg) = 1.1 short tons

VOLUME (APPROXIMATE)

1 milliliter (ml) = 0.03 fluid ounce (fl oz)
1 liter (l) = 2.1 pints (pt)
1 liter (l) = 1.06 quarts (qt)
1 liter (l) = 0.26 gallon (gal)
1 cubic meter (m^3) = 36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3) = 1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

°F=9/5(°C) + 32

QUICK INCH-CENTIMETER LENGTH CONVERSION

INCHES	0			1			2			3			4			5

CENTIMETERS	0	1	2	3	4	5	6	7	8	9	10	11	12	13

QUICK FAHRENHEIT-CELSIUS TEMPERATURE CONVERSION

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50. SD Catalog No. C1310286.

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EXECUTIVE SUMMARY

The U.S. Department of Transportation, Research and Special Programs Administration, Volpe National Transportation Systems Center (Volpe Center), Acoustics Facility, in support of the Federal Railroad Administration (FRA), 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 devices (e.g., horns, alerting lights, and reflectorization) and the use of track system devices (e.g., signs, signals and lighting systems). As part of this research, the current effort reported here evaluates the detectability 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 speaks directly to the findings in a July 1990 report by the FRA which summarized the effects of a nighttime (10 pm to 6 am) railroad horn ban enacted by a number of communities at grade crossings, equipped with active signaling systems, along the Florida East Coast Railway Corridor [3]. This report found that horns reduced accidents by 69 percent. The model developed in this study shows consistency with these findings. It predicts that horns should reduce accidents by 69 percent for the conditions present in Florida East Coast Railway Corridor. A National study of horn bans found that, at grade crossings with horn bans, there were an average of 38 percent fewer accidents after the horn bans had been canceled [4]. In individual case studies, accident reduction rates as high as 53 percent and 59 percent were observed. For the mix of passive and active devices and horn types represented in the National study, the model predicted that horns should reduce accidents by 5 1 percent. The observed decrease is within one standard deviation of the predicted decrease based on the range of variability of conditions in the National study.

Since the majority of highway-railroad grade crossing accidents involve moving locomotives, acoustic data are presented for a conventional three-chime horn system on a moving locomotive. These data were obtained through wayside measurements of locomotives as they moved 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 sound attenuation effects of buildings and vegetation along the right-of-way on the warning signal strength. 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 200 ft (61 m) 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 dB(A). This sound level is characterized as "normally unacceptable" by the Department of Housing and Urban Development [9].

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 dB(A). Baseline interior noise levels were measured while the motor vehicles traveled at a constant speed of 30 mph (48 km/h), with windows closed, ventilation systems off, and radios off. Interior noise levels were found to be approximately 55-65 dB(A). 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 under baseline conditions.

The probability of detection of warning signal sound levels was 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 (Le., 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 motorist's expectation of encountering a train at that type of crossing. Tables E-l, E-2, and E-3 (following) summarize the results of the study in terms of the probability that a motorist will detect a warning signal for each scenario.

Table E-l. Passive Crossings

	Locomotive Speed (mph)									
	20	30	40	50	60	70	80	90	100	110
Nathan K-5-LA	>99%	>99%	>99%	>99%	>99%	>99%	>99%	>99%	>99%	99%
Leslie RSL-3L-RF	75%	55%	25%	≈0%	≈0%	≈0%	≈0%	≈0%	≈0%	≈0%
Leslie RS-3L	10%	≈0%	≈0%	≈0%	≈0%	≈0%	≈0%	≈0%	≈0%	≈0%

Note: motor vehicle speed = 30 mph

Table E-2. Active Crossings

	Locomotive Speed (mph)									
	20	30	40	50	60	70	80	90	100	110
Nathan K-5-LA	>99%	>99%	>99%	>99%	>99%	>99%	>99%	>99%	>99%	98%
Leslie RSL-3L-RF	98%	96%	93%	81%	60%	30%	5%	≈0%	≈0%	≈0%
Leslie RS-3L	96%	87%	60%	20%	≈0%	≈0%	≈0%	≈0%	≈0%	≈0%

Note: motor vehicle speed = 0 mph

Table E-3. Active Crossings Equipped with Wayside Horn Systems

	Motor Vehicle Speed (mph)						
	10	20	30	40	50	60	70
AHS	95%	71%	≈0%	≈0%	≈0%	≈0%	≈0%

Note: locomotive speed is not applicable

The warning signal duration is also addressed to determine if it can be changed to reduce the community noise impact. Historically, the signaling cycle is actuated 20 seconds before the locomotive reaches the crossing. It may be possible to actuate the signaling 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.

1. INTRODUCTION / BACKGROUND

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 Center's Acoustics Facility is conducting a study with the goal of optimizing the performance of railroad horn systems.

The primary objective of this report, the second in a series, was to determine the probability of detection of railroad horn systems for warning motorists of the impending arrival of a train at highway-railroad grade crossings. Additionally, the community noise impact of train horns was quantified.

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. Aurelius and Korobow reported in 197 1 that "horns are not a suitable primary warning in high-speed encounters" [1]. Eldred and Sharp reported in 1972 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" [2].

However, two recent report by the FRA contradict these conclusions. A 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 [3]. After six years of enforcement, a 195 percent increase in accidents was experienced by the Florida East Coast Railway during the hours that the ban was in effect, as compared to pre-ban accident levels during the same hours. In 199 1, when horn use was resumed, nighttime accidents at these crossings decreased by 69 percent. Then, in 1995, the FRA conducted a second study on railroad horn bans, this time summarizing experiences nationwide [4]. This study concluded that the experiences in Florida were not unique. In 12 case studies covering 8 states other than Florida, the accident rate declined by an average of 38 percent when the horn bans were canceled. Two of these case studies showed individual declines of 53 percent and 59 percent. These statistics indicate that, under certain conditions, motorists rely on the railroad horn as a warning. The findings described above regarding the effectiveness and detectability of train horns highlight the need for the current study.

The detectability of a railroad horn system depends upon: (1) its ability to direct its sound toward the approaching motorist; (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; and (3) the attentiveness of the motorist. Pertinent data were obtained through measurements of the acoustic characteristics (i.e., the interior noise levels and sound insulation of the passenger compartment) of 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 an earlier Volpe Center report, *Safety of Highway-Railroad Grade Crossings: Study of the Acoustic Characteristics of Railroad Horn Systems,* which details the acoustic characteristics of four selected types of railroad horn systems [5]. These horn systems are as follows: (1) the Nathan K-5-LA, a five-chime system with all horns facing forward; (2) the Leslie RSL-3L-RF, a three-chime system with two horns facing forward and one facing to the rear; (3) the Leslie RS-3L, a three-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.

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 cannot be increased further without causing an unacceptable impact on the surrounding communities, and potentially the locomotive occupants as well. In fact, many communities (such as those along Florida's east coast) have recently indicated that current horn systems create 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.

2. ACOUSTIC CHARACTERISTICS OF RAILROAD HORN SYSTEMS ON IN-SERVICE 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.

2.1 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 on July 8 and 9, 1992, in Jacksonville. 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 (i.e., short hood forward) was modified to include an air pressure regulator which fixed the sound level output at approximately 104 dB(A), 100 ft (30.5 m) to the front of the locomotive. The horn system mounted on the rear of the locomotive, rated by the manufacturer to have a sound level output of 114 dB(A), 100 ft (30.5 m) from the horn system, was not equipped with a regulator. Both types of horn systems (i.e., with and without the regulator) were measured in this study.

2.1.1 Data Acquisition Equipment

At each highway-railroad grade crossing, a digital audio tape recording system (DAT type) 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 seconds (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.

2.1.2 Test Sites/Microphone Locations

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

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

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

Figures B-l through B-6 in Appendix B 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 Figure B-2), the digital recording system was placed 50 ft (15 m) from the track and the sound level meter was placed 200 ft (61 m) from the track. The digital recording system at the Shad Road site was placed 75 ft (23 m) from the track and the sound level meter was placed 150 ft (46 m) from the track due to space restrictions. All crossings were equipped with an active signaling system consisting of flashing lights and gates.

2.1.3 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). 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.

2.1.4 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 dB(A), 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 (i.e., less that 10 dB above the ambient).

The data were then filtered into one-third octave band levels using a Brüel & Kjær Model 213 1 Digital Frequency Analyzer and stored in a Volpe Center computer in contiguous one-eighth 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_{ASmax})
  The maximum A-weighted sound level (measured in A-weighted decibels, dB(A)) 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_{ASmax}
  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 one-eighth second sound level records over the duration of the measured event.

- Sound exposure level (L_{AE})
  The energy summation of the A-weighted sound level over time with a reference duration of one second. The L_{AE} 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 downloaded 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_{ASmax}), A-weighted time histories, and the sound exposure level (L_{AE}) for each event.

2.2 ACOUSTIC DATA ANALYSIS

2.2.1 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 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 that 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 [6].

- 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 [7].

- Shielding from buildings has been shown to provide a reduction of 3 to 10 dB over the propagation path [8]. 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 8,000 Hz (providing the vegetation extends over a distance greater than 100 ft (30 m)) [8].

2.2.2 Analysis of Measured Sound Levels

Tables B- 1 through B- 12 in 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_{ASmax}, duration and distance from the microphone for each signal component, and the overall L_{AE} 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_{ASmax} (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-l through B- 12) and A-weighted time histories (Figures C-13 through C-22 in Appendix C) can be attributed to the specific signaling techniques of the individual locomotive personnel. Specifically, the long components range in duration 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 2.2.3).

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. 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_{ASmax} 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 584 and 345 ft (178 and 105 m), respectively. Assuming fairly standard over ground propagation characteristics, i.e., approximately 7.5 dB(A) per doubling of distance, the 240 ft (73 m) difference accounts for only 5.7 dB(A) of the total measured sound level difference. The remaining 9.0 dB(A) can be attributed to building attenuation. Shielding attenuation levels of this magnitude due to highway noise barriers are fairly common [8].

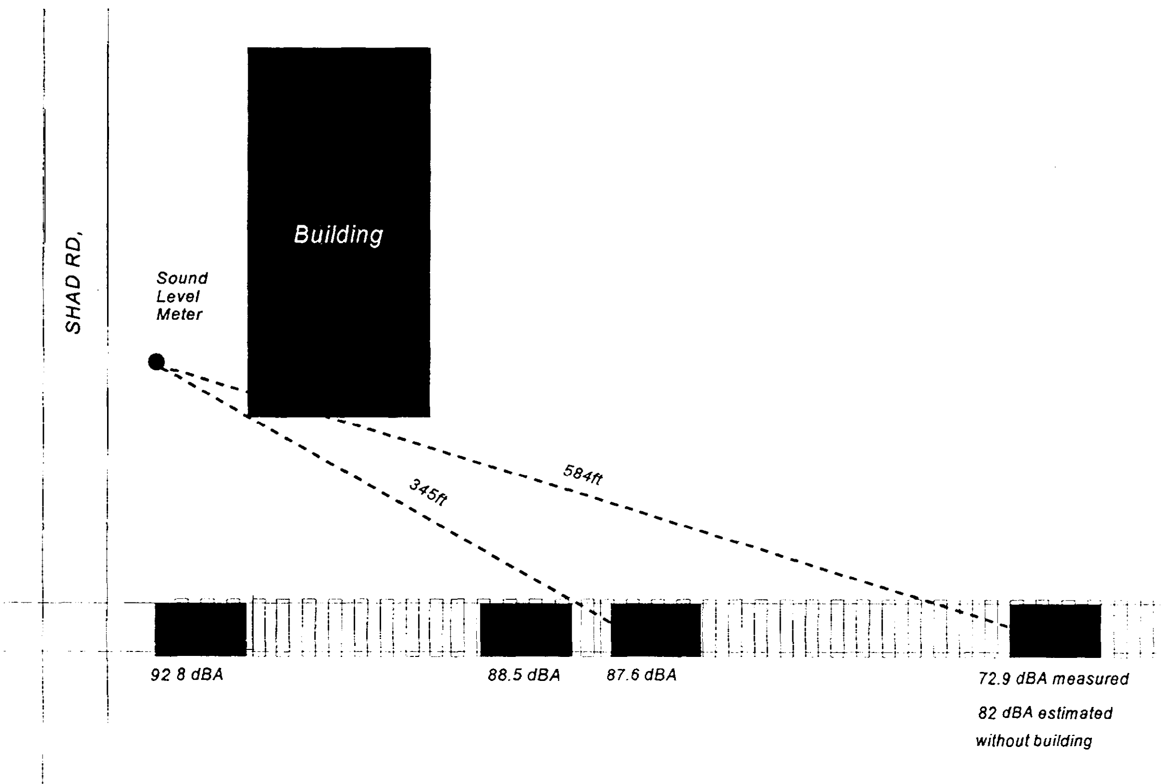

Figure 1. Effect of a Building on the Measured Sound Level During a Locomotive Pass-by

2.2.3 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 [9]. The upper limit for a "normally acceptable" environment is L_{dn} = 65 dB(A); an L_{dn} from 65 to 75 dB(A) is defined as "normally unacceptable"; and an L_{dn} above 75 dB(A) is "unacceptable." L_{dn} can be calculated by summing the L_{AE} from each noise event (in this case, each train pass-by) over a 24-hour period, as follows:

$$L_{dn} = \sum_{i=1}^{n} L_{AE_i} - 49.365 \qquad (1)$$

Or, if the L_{AE} is only known for a representative event, L_{dn} can be calculated by adding 10log of the number of events to the L_{AE}, as follows:

$$L_{dn} = L_{AE} + 10\log_{10}(\#TrainsDay + 10\#TrainsNight) - 49.365 \qquad (2)$$

The estimated L_{dn} at each measurement microphone location was computed using the average L_{AE} from Tables B-l 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 (7 AM to 10 PM) and one train per hour during nighttime hours (10 PM to 7 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 200 ft (61.0 m) from the crossing would not meet the HUD's "normally acceptable" criterion of L_{dn} = 65 dB(A).

Table 1. Estimated Day-Night Sound Level

	L_{dn} (Estimated) (dB(A))			
Distance from Crossing, ft (m)	**50 (15.2)**	**75 (22.9)**	**150 (45.7)**	**200 (61)**
Sunbeam Rd.	78.22			69.75
Shad Rd.		68.93	68.95	
Mussells Acres Rd.	78.43			69.25
Old St. Augustine Rd.	80.29			72.95
Cedar St.	79.61			69.85
Greenland Rd.	74.83			65.80

The L_{dn} at any other distance from the crossing can be computed from Equation 1 or 2 using the following to extrapolate the L_{AE} to other distances:

L&distance x) = L_{AE}(reference distance) +25$\log_{10}$(reference distance/x)
- 1 0log(reference distance/x) **(3)**

The relationship between L_{dn}, number of trains, and distance can be expressed most simply in terms of the number of **equivalent daily operations** (EDO) corresponding with the 65 dB(A) L_{dn} limit used by HUD. Equivalent Daily Operations = #TrainsDay + 10#TrainsNight (i.e., if the train frequency is 1 train/hour, the number of equivalent daily operations is 105). By combining the above equations, EDO can also be expressed as a function of L_{AE} and distance corresponding with the 65 dB(A) L_{dn} limit. For example, Table 2 shows that for a resident positioned at a distance of 500 ft, the 65 dB(A) L_{dn} criterion would be exceeded if there were more than 139 equivalent daily operations.

Table 2. Equivalent Daily Operations at Sunbeam Road

Ldn = 65 dB(A), SEL = 98.9 dB(A) at 200 ft					
Distance From Crossing (ft)	100	250	500	750	1000
Equivalent Daily Operations	12.5	49.2	139.3	255.9	394.0

3. 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 on the subject of motor vehicle acoustic characteristics were conducted in the 1970s and 1980s [9] [10] [11]. 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 and automotive magazines which suggests that interior noise levels alone have decreased by at least 10 dB since 1970 [9]. 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.

3.1 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 dependent upon the operating conditions of the vehicle. These 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 2. These interior noise levels may be as loud as or louder than the warning signal which penetrates the vehicle, and can reduce its detectability.

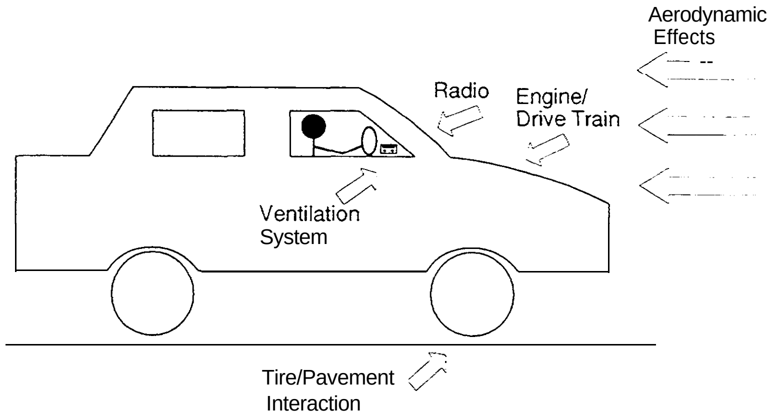

Figure 2. Sources of Interior Noise Due to Normal Vehicle Operation

3.2 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 3. 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.

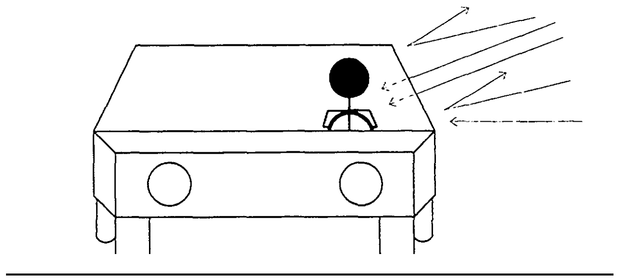

Figure 3. The Effect of Insertion Loss on the Warning Signal

3.3 EXPERIMENTAL PROCEDURE

The following sections describe the equipment and procedures used during measurements of interior noise levels and insertion loss. Measurements were conducted during the period June 23 to 25, 1992. Detailed descriptions of the data acquisition systems, artificial source, and calibration procedures are included in Appendix A.

3.3.1 Test Vehicles

A brief description of each of the motor vehicles tested follows. 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

3.3.2 Test Sites

Interior noise level data (dynamic measurements) were collected at speeds of up to 30 mph (48.3 km/h) on Memorial Drive in Cambridge, Massachusetts, a four-lane east-west roadway. The level roadway was made up of dense-graded asphaltic concrete pavement, 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 492 ft (150 m) to the west. The microphone was placed 25 ft (7.6 m) from the noise source in the center of the test area. The noise source was directed to the east at a row of hedges.

3.3.3 Interior Noise Measurements

Dynamic interior noise measurements were conducted so that a baseline interior noise level could be quantified. Baseline conditions were considered to be windows closed, ventilation systems off, and radio off. With this baseline level, only a minimal number of additional measurements would be required to accurately represent any adjustments for various ventilation options and radio loudness levels. Due to measurement site constraints, the vehicle was operated at a constant speed of 30 mph. 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.

The following measurement practices followed the guidelines of the Society of Automotive Engineers Recommended Practice [12]. Sound level data were 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 2.3 ft (0.7 m) above the seat). The tripod and microphone/preamplifier assembly were mounted in a manner that minimized the effects of vehicle vibrations.

3.3.4 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. Artificial electrical noise was used so that an accurate measure of insertion loss in each one-third octave-band could be obtained. The level broadcast was monitored 4 ft (1.2 m) 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 4 ft (1.2 m) above the ground, 15 ft (7.62 m) 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 3.3.3. 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 pink 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 4 ft (1.2 m) above ground level at the reference position 15 ft (7.62 m) from the source. Octave bands of pink 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 [13]. 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.

3.3.5 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 70°F (21°C), with a relative humidity of 60 percent. Wind speeds ranged from 0 to 10 knots.

3.3.6 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 30 mph (48 km/h) 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.

3.4 ACOUSTIC DATA ANALYSIS

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

3.4.1 Interior Noise

Figure C-l 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 30 mph (48 km/h). Although the interior noise frequency spectra for each of the seven vehicles are similar,' some general trends are discernible. The interior noise levels of the minivan in the range from 500 Hz to 4000 Hz are 5 to 10 dB lower than those of other vehicles tested. This may be due, in part, 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 predominate 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-to-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 3 presents baseline interior A-weighted noise levels as published in recent automotive magazines for several 1992-1993 model year vehicles [14][15].

Table 3. Interior Noise Levels of 1992-1993 Model Year Automobiles

Auto	Interior Noise Level at Idle (dB(A))	Interior Noise Level at 70 mph (dB(A))
Audi 100S	47	71
Acura Legend L	44	72
BMW 325i	51	73
BMW 740i	43	61
Eagle Vision TSi	44	70
Ford Taurus 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 was conducted. The following effects were found to be applicable to late-model motor vehicles [1 0] [I 1] [16].

- Open windows will increase interior noise levels by 2 to 3 dB at low frequencies (< 1000Hz) and by 5 to 10 dB at high frequencies.

- Air conditioning systems operating at medium or high will increase interior noise levels by 2 to 5 dB at low frequencies (<1000 Hz) and 5 to 10 dB at high frequencies.

- Radio operation at a “normal volume” will increase interior noise levels by 10 to 30 dB [IO].

3.4.2 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 in each one-third octave band was calculated to be representative of the seven vehicles tested in this study. This insertion loss can be used to calculate the warning signal strength that reached the driver inside the vehicle by subtracting the insertion loss from the warning signal level on a one-third octave band by one-third octave band basis (Figure C-11).

A review of the insertion loss data found in previous studies was conducted [11]. It was found that open windows cause a decrease in insertion loss of approximately 5 to 15 dB. This decrease can be applied to current motor vehicles, because any gap in the vehicle structure will have the same effect [17].

4. ANALYSIS OF DETECTABILITY

Sections 4.1 through 4.4 discuss the ability of the horn systems selected for this study (i.e., Nathan K-5-LA, Leslie RSL-3L-RF, Leslie RS-3L, and Automated Horn System (AHS)) to be detected by the motorist in several scenarios. Section 4.5 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 purposes of this study, the detectability of a railroad horn system is defined as the probability that a person with normal hearing will hear the warning signal. Thus, the detectability can have values ranging from zero to one (0 percent to 100 percent). The probability of detection can be arrived at if the following two factors are known: 1) the difference between the signal level and the background noise level, defined as the signal-to-noise ratio (S/N), and 2) the perceived frequency of trains (i.e., the motorist's perception of the likelihood of an encounter with a train). It is assumed that the higher the perceived frequency of trains, the more attentive the motorist will be in listening for the train horn. The perceived frequency of trains can be likened to a probability and can vary between zero and one. Using signal detection theory (this theory is further discussed in Appendix D), the detectability can be calculated for a range of perceived train probabilities and S/N, as shown in Figure 4. The S/N ratio does not need to be present in each one-third octave band; it was suggested in a previous study [10] that the required S/N ratio must be present in at least two octave bands. For this study, it was decided the required S/N must be present in a minimum of five one-third octave bands.

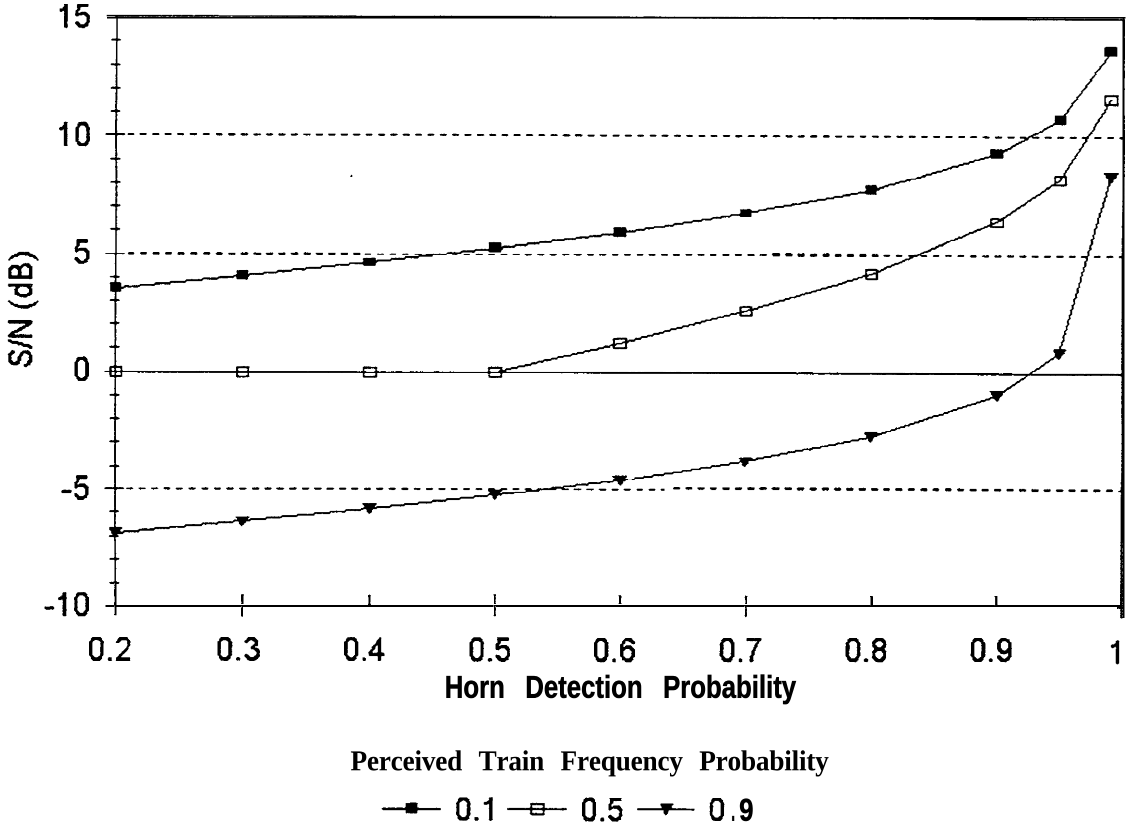

Figure 4. **Horn Detection Probability vs. S/N**

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 perception of the likelihood of encountering a train (perceived frequency). Based upon the perceived frequency, the detectability of each horn system was determined for a range of locomotive speeds (and therefore minimum warning distances) between 20 and 110 mph. 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.

- **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, and because the gates are lowered, the motorist may have a high expectation of encountering a train. Therefore, the perceived train frequency probability is set at 0.9.

- **Active Crossings Equipped with a Wayside Horn System-** The train/motorist encounter occurs at an active crossing equipped with a wayside horn system as described in Volume I [5]. 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 cannot 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 probability is set at 0.5.

4.1 PASSIVE CROSSINGS

Given the passive crossing scenario stated above, during the train/motorist encounter at the passive crossing, the motorist perceives that there is only a small chance of encountering a train. At a typical passive crossing, most motorists have rarely encountered a train.

4.1.1 <u>Minimum Warning Distance</u>

The minimum warning distance (MWD) is defined as the distance between the motor vehicle and the front of the locomotive (Figure 5) at the critical time (T_{cr}), as shown in Equation 3.

$$MWD = \sqrt{(T_{cr} * LocomotiveSpeed)^2 + (T_{cr} * VehicleSpeed)^2} \quad (3)$$

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), critical track zone (CTZ), and motor vehicle length, as shown in Equation 4 [1].

$$T_{cr} = \frac{MSD\ (m) + CTZ + Vehicle\ Length}{Vehicle\ Speed\ (m/s)} + Driver\ Reaction\ Time \qquad \textbf{(4)}$$

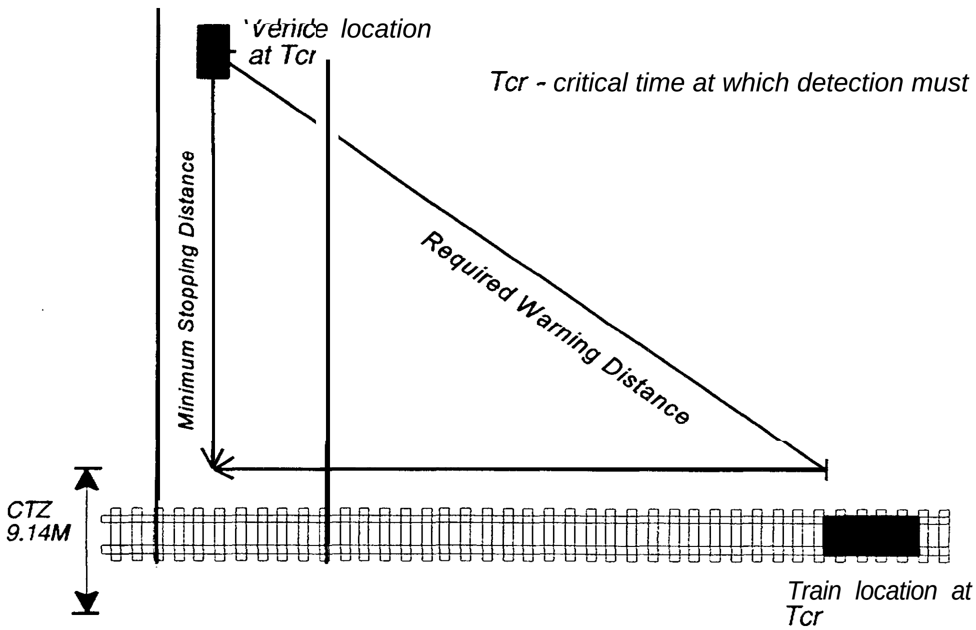

Figure 5. Required Warning Distance

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

$$MSD = V_m^2 / 255(f \pm g), \qquad \textbf{(5)}$$

where V_m is the motor vehicle speed (km/h), g is the pavement grade, and f is the skidding friction coefficient, in accordance with the American Association of State Highway and Transportation 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 4 for various vehicle speeds and train speeds, using the methodology outlined by Aurelius and

Korobow [1]. These calculations assumed a roadway perpendicular to the railroad track, a vehicle length of 19 ft (5.8 m), and a driver reaction time (i.e., the time elapsed between the instant when the warning signal is perceived and when the brake is engaged) of two and one-half seconds [19].

Table 4. Minimum Required Warning Distance

Motor Vehicle Speed, mph (km/h)	Train Speed, mph (km/h)	Minimum Warning Distance, ft (m)	Motor Vehicle Speed, mph (km/h)	Train Speed, mph (km/h)	Minimum Warning Distance, ft (m)
	20 (32.2)	220 (67)		20 (32.2)	291 (88.8)
	30 (48.3)	281 (86)		30 (48.3)	343 (104)
	40 (64.4)	348 (106)		40 (64.4)	404 (123)
	50 (80.5)	419 (128)		50 (80.5)	471 (144)
20	60 (96.6)	492 (150)	30) (96.6)	60 (96.6	542 542 (165)
(32.2)	70 (112.7)	567 (173)	48) (112.7)	.	615 (188)
	80 (128.8)	642 (196)	) (128.8)		690 (210)
	90 (144.8)	718 (219)	90 (144.8)		766 (234)
	100 (160.9)	794 (242)	100 (160.9)		843 (257)
	110 (177.0)	870 (265)	110 (177.0)		919 (280)
	20 (32.2)	399 (122)		20 (32.2)	540 (165)
	30 (48.3)	447 (136)		30 (48.3)	584 (178)
	40 (64.4)	505 (154)		40 (64.4)	642 (196)
	50 (80.5)	572 (174)		50 (80.5)	709 (216)
40	60 (96.6)	644 (196)	50	60 (96.6)	783 (239)
(64.4)	70 (112.7)	720 (220)	(80.5)	70 (112.7)	862 (263)
	80 (128.8)	799 (244)		80 (128.8)	946 (288)
	90 (144.8)	880 (268)		90 (144.8)	1032 (315)
	100 (160.9)	962 (293)		100 (160.9)	1120 (342)
	110 (177.0)	1045 (319)		110 (177.0)	1211 (369)

4.1.2 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 minimum warning distance. As stated at the beginning of Section 4, the warning signal probability of detection is calculated for a range of locomotive speeds based on the five highest one-third octave band S/Ns at the minimum warning distance.

To determine the probability of detection, the warning signal level inside the vehicle at the minimum warning distance was compared with the average measured background noise level for a vehicle traveling 30 mph (48.3 km/h). 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 4.1, 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 in each one-third octave band (Figure C-l 1) from the signal levels obtained through measurements, extrapolated to various distances using a drop-off rate of 7.5 dB per distance doubling.

Tables 5-7 summarize the probability of detection for each horn system for locomotive speeds of 20 to 110 mph and a motor vehicle speed of 30 mph. Appendix E shows an example detection probability calculation.

Table 5. Probability of Detection for the Nathan K-5-LA at a Passive Crossing

Locomotive Speed (mph)	Motor Vehicle Speed (mph)	Minimum Warning Distance (ft (m))	SIN (dB)	Probability of Detection
20	30	291 (88.8)	26.33	>99%
30	30	343 (104)	24.54	>99%
40	30	404 (123)	22.77	>99%
50	30	471 (144)	21.1	>99%
60	30	542 (165)	19.58	>99%
70	30	615 (188)	18.21	>99%
80	30	690 (210)	16.96	>99%
90	30	766 (234)	15.82	>99%
100	30	843 (257)	14.78	>99%
110	30	919 (280)	13.84	99%

Table 6. Probability of Detection for the Leslie RSL-3L-RF at a Passive Crossing

Locomotive Speed (mph)	Motor Vehicle Speed (mph)	Minimum Warning Distance (ft (m))	S/N (dB)	Probability of Detection
20	30	291 (88.8)	7.34	75%
30	30	343 (104)	5.55	55%
40	30	404 (123)	3.78	25%
50	30	471 (144)	2.11	≈0%
60	30	542 (165)	0.59	≈0%
70	30	615 (188)	-0.79	≈0%
80	30	690 (210)	-2.04	≈0%
90	30	766 (234)	-3.17	≈0%
100	30	843 (257)	-4.21	≈0%
110	30	919 (280)	-5.15	≈0%

Table 7. Probability of Detection for the Leslie RS-3L at a Passive Crossing

Locomotive Speed (mph)	Motor Vehicle Speed (mph)	Minimum Warning Distance (ft (m))	S/N (dB)	Detection Probability
20	30	291 (88.8)	3.02	10%
30	30	343 (104)	1.23	≈0%
40	30	404 (123)	-0.54	≈0%
50	30	471 (144)	-2.21	≈0%
60	30	542 (165)	-3.73	≈0%
70	30	615 (188)	-5.11	≈0%
80	30	690 (210)	-6.36	≈0%
90	30	766 (234)	-7.49	≈0%
100	30	843 (257)	-8.53	≈0%
110	30	919 (280)	-9.47	≈0%

4.2 ACTIVE CROSSINGS

As stated at the beginning of Section 4, 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.

4.2.1 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 is 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.

Table 8 summarizes the minimum warning distances required at active crossings to allow the 10 seconds needed to circumvent the gate for four locomotive speeds:

Table 8. Minimum Warning Distances at Active Crossings

Locomotive Speed (mph)	20	30	40	50	60	80	110
Distance from Locomotive to Motorist (ft(m))	293 (89)	440 (134)	587 (179)	733 (233)	880 (268)	1173 (358)	1613 (492)

4.2.2 Signal Detectability

To determine the probability of detection, the warning signal level inside the vehicle (Section 4.1.2) at the minimum warning distance is compared with the average measured interior noise level for a vehicle traveling 30 mph (48.3 km/h) (Section 3.4.1 and Figure C-2). Although the minimum warning distance is based upon the assumption that the vehicle is stopped at the gates, interior noise levels at 30 mph (48.3 km/h) 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 to 25 dB(A) lower at idle than at 30 mph (48.3 km/h), therefore, this assumption is conservative and errs on the side of safety. Unfortunately, the necessary one-third octave band data needed to apply this estimation is unavailable.

Tables 9 to 11 summarize the probability of detection for each horn system for locomotive speeds of 20 to 110 mph and a motor vehicle speed of 0 mph.

Table 9. Probability of Detection for the Nathan K&LA at an Active Crossing

Locomotive Speed (mph)	Motor Vehicle Speed (mph)	Minimum Warning Distance (ft (m))	S/N (dB)	Probability of Detection
20	0	293 (89)	26.26	>99%
30	0	440 (134)	21.84	>99%
40	0	587 (179)	18.71	>99%
50	0	733 (233)	16.30	>99%
60	0	880 (268)	14.32	>99%
70	0	1026 (313)	12.65	>99%
80	0	1173 (358)	11.19	>99%
90	0	1329 (405)	9.84	>99%
100	0	1466 (447)	8.77	>99%
110	0	1613 (492)	7.74	98%

Table 10. Probability of Detection for the Leslie RSL-3L-RF at an Active Crossing

Locomotive Speed (mph)	Motor Vehicle Speed (mph)	Minimum Warning Distance (ft (m))	S/N (dB)	Probability of Detection
20	0	293 (89)	7.26	98%
30	0	440 (134)	2.85	96%
40	0	587 (179)	-0.28	93%
50	0	733 (233)	-2.69	81%
60	0	880 (268)	-4.68	60%
70	0	1026 (313)	-6.34	30%
80	0	1173 (358)	-7.80	5%
90	0	1329 (405)	-9.15	≈0%
100	0	1466 (447)	-10.22	≈0%
110	0	1613 (492)	-11.26	≈0%

Table 11. Probability of Detection for the Leslie RS-3L at an Active Crossing

Locomotive Speed (mph)	Motor Vehicle Speed (mph)	Minimum Warning Distance (ft (m))	S/N (dB)	Probability of Detection
20	0	293 (89)	2.94	96%
30	0	440 (134)	-1.47	87%
40	0	587 (179)	-4.60	60%
50	0	733 (233)	-7.01	20%
60	0	880 (268)	-9.00	≈0%
70	0	1026 (313)	-10.66	≈0%
80	0	1173 (358)	-12.12	≈0%
90	0	1329 (405)	-13.47	≈0%
100	0	1466 (447)	-14.54	≈0%
110	0	1613 (492)	-15.58	≈0%

4.3 ACTIVE CROSSINGS EQUIPPED WITH WAYSIDE HORN SYSTEMS

As stated in the beginning of Section 4, 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).

4.3.1 Required Warning Distance

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

Table 12 summarizes the minimum warning distances at wayside horn-equipped crossings for various motor vehicle speeds:

Table 12. Minimum Warning Distances at Wayside Horn-Equipped Crossings

Vehicle Speed (mph)	10	20	30	40	50	60	70
Minimum Stopping Distance (ft(m))	95 (29)	154 (47)	243 (74)	358 (109)	501 (153)	669 (204)	705 (215)

To determine the probability of signal detection, the warning signal level inside the vehicle (Section 4.1.2) at the minimum warning distance is compared with the average noise level inside a vehicle traveling 30 mph (48.3 km/h) (Section 3.4.1 and Figure C-2). Although a determination of detectability is made for a range of motor vehicle speeds, interior noise levels at 30 mph (48.3 km/h) 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.

Table 13 summarizes the probability of detection for the wayside horn for motor vehicle speeds of 10 to 70 mph.

Table 13. Probability of Detection for the Wayside Horn

Locomotive Speed (mph)	Motor Vehicle Speed (mph)	Minimum Warning Distance (ft (m))	S/N (dB)	Probability of Detection
N/A	10	95 (29)	8.15	95%
N/A	20	154 (47)	2.90	71%
N/A	30	243 (74)	-2.05	≈0%
N/A	40	358 (109)	-6.26	≈0%
N/A	50	501 (153)	-9.91	≈0%
N/A	60	669 (204)	-13.05	≈0%
N/A	70	705 (215)	-13.62	≈0%

4.4 DETECTABILITY 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. Tables 14 to 16 summarize the probability of detection for the warning signals in each scenario for various locomotive speeds and/or motor vehicle speeds.

Table 14. Passive Crossings

	Locomotive Speed (mph)									
	20	30	40	50	60	70	80	90	100	110
Nathan K-5-LA	>99%	>99%	>99%	>99%	>99%	>99%	>99%	>99%	>99%	99%
Leslie RSL-3L-RF	75%	55%	25%	≈0%	≈0%	≈0%	≈0%	≈0%	≈0%	≈0%
Leslie RS-3L	10%	≈0%	≈0%	≈0%	≈0%	≈0%	≈0%	≈0%	≈0%	≈0%

Note: motor vehicle speed = 30 mph

Table 15. Active Crossings

	Locomotive Speed (mph)									
	20	30	40	50	60	70	80	90	100	110
Nathan K-5-LA	>99%	>99%	>99%	>99%	>99%	>99%	>99%	>99%	>99%	98%
Leslie RSL-3L-RF	98%	96%	93%	81%	60%	30%	5%	≈0%	≈0%	≈0%
Leslie RS-3L	96%	87%	60%	20%	≈0%	≈0%	≈0%	≈0%	≈0%	≈0%

Note: motor vehicle speed = 0 mph

Table 16. Active Crossings Equipped with Wayside Horn Systems

	Motor Vehicle Speed (mph)						
	10	20	30	40	50	60	70
AHS	95%	71%	≈0%	≈0%	≈0%	≈0%	≈0%

Note: locomotive speed is not applicable

4.5 TRAIN HORN EFFECTIVENESS

It was stated at the beginning of Section 4 that, for the purpose of this study, the detectability of a railroad horn system is defined as the probability that a person with normal hearing will detect the warning signal. The effectiveness of the train horn is its ability to reduce accidents at highway-railroad grade crossings. Data collected by the FRA's Office of Safety on train horn bans indicates that when train horn use is banned, accidents increase at grade crossings, and when tram horn use is allowed, accidents decrease. This information suggests that train horns are, indeed, effective.

Common sense indicates that for a train horn to be effective, it must be detectable, but experience with grade crossings indicates that even highly detectable devices are not 100 percent effective. Thus, the relationship between detectability and effectiveness is not simple. Partly this is because of the relationship between the train as a signal and the train horn as a part of that signal. Train horn effectiveness, if defined in terms of accident reduction, must consider the horn as a part of a multi-sensory signal which is the entire train, as well as other active warning devices at the crossing. The horn, as a separate component of that signal must be "added" into the total signal. This "addition" is psychological, so it is not ordinary addition. If we assume that we know how to perform this "addition," the relationship between train horn detectability and accidents can be derived. 1994 data on grade crossing accidents and the signal detection analysis outlined in Appendix D are used in this derivation [20].

In 1994 there were 900 accidents at grade crossings with Gates (active crossings) and 1578 at grade crossings with Crossbucks (passive crossings) as indicated in Table 17. As noted above, we know from the horn ban studies that if the train horn is not used at the crossing, accidents increase. This means that without a horn the S/N ratio for the train will be reduced. Table 17 shows that, if there is a hypothetical 30 percent increase in accidents without a train horn [for gates, ((1170-900)/900), for crossbucks, ((205 l-l 578)/1 578)], the S/N ratio decreases. Note that in this example, the effectiveness of the train horn is, by definition, 23 percent because the reduction in accidents that the horn causes is [(1170-900)/ 1170] for gates and [(205 1 - 1578)/205 1] for crossbucks.

Since the S/N of the tram with and without a horn are known, it should be possible to determine the change in train S/N due to the horn. The "addition" of components into multisensory signals usually assumes that components that come from different sensory domains (e.g., visual brightness and auditory loudness) are orthogonal (i.e., their magnitudes are perpendicular to each other). Under these circumstances, a common "addition" strategy is to use Euclidean addition [21]:

$$A^2 = B^2 + C^2 \text{, or}$$

$$C = \pm(A^2+B^2)^{1/2}$$

In our case, A is the S/N of the train with horn, B is the S/N of the train without horn, and C is the change in tram S/N due to the horn. Since we know the value of A and B, it is easy to determine C. C is not the horn S/N, but *the change* in the horn S/N from the baseline where the horn has zero effectiveness and zero detectability. The baseline is different for active and passive grade crossing devices. The change in horn S/N can be used to relate horn detectability to changes in accidents.

For the example presented in Table 17, the S/N of the horn is 3.88 at crossings with gates and 3.51 at crossings with crossbucks. For these values of S/N, the probability of detecting the horn is .51 with gates and 0.54 for crossbucks.

Table 17. Changes in S/N Given a 30% Increase in Accidents

	A. WITH HORNS	
	GATES	CROSSBUCKS
Total Accidents	900	1578
S/N (A)	17.35	17.77
	B. WITHOUT HORNS	
	GATES	CROSSBUCKS
Total Accidents	1170	2051
S/N (B)	16.91	17.42
	C. HORN ALONE	
	GATES	CROSSBUCKS
S/N (C)	3.88	3.51

It is possible, of course, to perform these calculations for a known range of horn effectivenesses (percent decrease in accidents) and relate that to horn detection. Figure 6 shows the probability of horn detection as a function of percent decrease in accidents for both crossings with gates and crossings with crossbucks. The base (0 percent effectiveness) for gates and crossbucks was equated to a 200 percent increase in the 900 accidents for gates and 1578 accidents for crossbucks. A 200 percent increase in accidents is approximately the largest increase that has been observed when a horn ban is instituted [4]. A 0 percent decrease in accidents occurs for gates when the S/N of the horn is -9.27 and for cross bucks when the S/N of the horn is 0.21. Figure 6 shows that as the Figure probability of horn detection increases, accidents decrease. This result is consistent with the horn ban studies and establishes the relationship between horn use and grade crossing accidents.

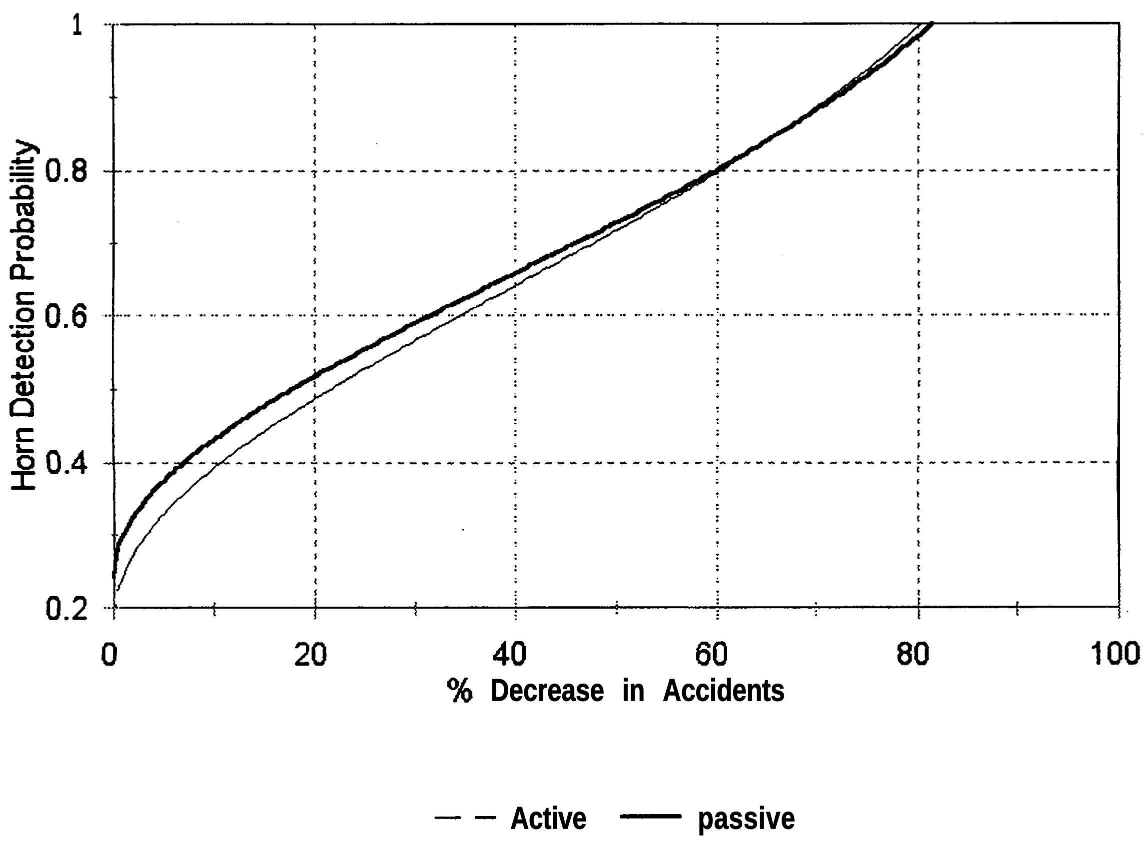

Figure 6. Percent Decrease in Accidents vs. Horn Detectability

4.6 EFFECTIVENESS OF WARNING SIGNAL DURATION

As stated in Section 2.2.2, for grade crossings having locomotives traversing at a rate of one per hour, the community noise environment at distances less than 200 ft (61.0 m) 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 to 15 seconds of advance warning before the critical time (T_{cr}, see Section 4.1.1). 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 signaling 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 to 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 [22].

Table 18 lists the locomotive's position 15 seconds before it reaches the crossing at a range of speeds. It shows that for a locomotive traveling 60 mph (96 km/h), a signaling cycle duration of 15 seconds would require actuation at a distance of 1,312 ft (400 m) from the crossing. It should be noted that the average distance from the whistle post to the grade crossing is 1,312 ft (400 m) in most states [23]. Therefore, for locomotives traveling faster than 60 mph (96 km/h), the signaling cycle should be actuated before passing the whistle post, and for locomotives traveling slower than 60 mph

(96 km/h), 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. Future research is needed to determine the effect of a change in the signal cycle on driver behavior.

Table 18. Locomotive Position at Signaling Cycle Actuation

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

5. RAILROAD HORN BANS, HORN EFFECTIVENESS, AND HORN DETECTABILITY

The FRA's Office of Safety systematically reviewed accident changes following horn bans in 1990 [3] and again in 1995 [4]. In each instance, despite widely varying geographic locations, types of grade crossings, and types of horn bans, it was found that accidents increased following horn bans and decreased when the horn ban was rescinded. There has been wide variability in the amount of change in accidents in each instance, but the consistency of the effect of a horn ban is impressive given the number of factors which the present study alone indicates influence the effectiveness of a train horn. These factors include train speed, highway speed, distance of train from the crossing, distance of the highway vehicle from the crossing, type of grade crossing warning device, the type train horn, the sound level of the train horn at the source, the insertion loss of the highway vehicle, the presence of sound barriers, type of terrain, noise level in the highway vehicle from fans, radio, etc., and other factors. Since every grade crossing situation has its own unique combination of these factors, it should not be surprising that there is considerable variability in and among studies of the effectiveness of train horns. Nevertheless, the variability which has been seen between horn ban studies may cause some individuals to question the basic effectiveness of train horns. The information presented in this study can be used to demonstrate that the results of the Florida Horn Ban Study and the National Horn Ban Study are compatible despite the observed differences between them.

In the Florida horn ban study, it was determined that horns reduced accidents by 69 percent. In contrast, the National horn ban study found that the average reduction in accidents was 38 percent (with individual reductions as high as 53 percent and 59 percent). As was noted above, each grade crossing situation will have a unique combination of characteristics that will affect horn effectiveness. Take for example two factors examined in this report: type of train horn and type of grade crossing device. These two factors are examined in this report in Tables 5-7 and 9-11. For the average grade crossing, the time table speed is 30 mph [24]. Table 19 is constructed from Tables 5-7 and 9-1 1 to show the range of horn detectabilities that can occur at this locomotive speed. It can be seen that horn detectability at this speed ranges from 0 percent for the Leslie RS-3L to greater than 99 percent for the Nathan K-5-LA at a passive crossing and from 87 percent for the Leslie RS-

3L to >99 percent for the Nathan K-5-LA at active crossings. Table 19 also shows the percent reduction in accidents (effectiveness) that corresponds to these horn detectabilities (see Figure 5).

Table 19. Horn Detectability and Effectiveness

	Passive		Active	
	Detectability	Effectiveness	Dectectability	Effectiveness
Nathan K-5-LA	>99%	82%	>99%	80%
Leslie RS-3L-RF	55%	30%	96%	75%
Leslie RS-3L	≈0%	≈0%	87%	69%

*locomotive speed = 30 mph

Effectiveness varies from 0 percent to 82 percent for the passive crossings and from 69 percent to 80 percent for the active crossings. In the Florida ban all affected crossings had gates and all trains affected used the Leslie RS-3L horn. Table 19 shows that the predicted effectiveness of the horn for this situation is 69 percent, which is the same as the observed value of 69 percent. The National study, by contrast, included all types of devices and horns. An estimate of the predicted national effectiveness of train horns can be obtained by averaging the effectiveness of all horn types across passive and active devices. However, the ratio of passive crossings to active crossing is 60/40 so the average is weighted accordingly. The relative usage of the three horn types in the railroad industry is not known, so it will be assumed that the three horns occur with equal frequency. For the average national train speed of 30 mph, the predicted national train horn effectiveness, then, is 51 percent with a standard deviation (SD) of 33.8 percent. In individual case studies, decline rates as high as 53 percent and 59 percent were observed, which are again very close to the predicted effectiveness of 51 percent. However, the average decline of 38 percent observed in the National study is lower than this prediction, but is well within one standard deviation of the predicted value.

From the example above, it is clear that apparent inconsistencies between the Florida and National horn ban studies are easily resolved by reference to factors which are demonstrated in this report to influence horn detectability and effectiveness. Given very specific information about the crossings and horns in the Florida study, the model developed in this report predicted the observed effectiveness of train horns exactly. The prediction for the National study was not as close, but was well within the expected range of variability for the conditions that were assumed to apply. Better information concerning average train speeds at active and passive crossings, average car speeds, etc., would be expected to improve the model's prediction. In any case, it is clear that this report and the two horn ban studies provide solid support for the effectiveness of train horns in reducing grade crossing accidents.

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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 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 audio channel 1.

Digital Recording Systems (DAT Type)

The DAT type digital recording system consisted of the following components: 1.) A General Radio Model 1962-96 10 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 tape recorder. 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 S 1.4- 197 1 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 ½ 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: ACOUSTIC CHARACTERISTICS OF RAILROAD HORN SYSTEMS MOUNTED ON IN-SERVICE LOCOMOTIVES

This appendix contains a plan view of each measurement site (Figures B-l 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,, 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).

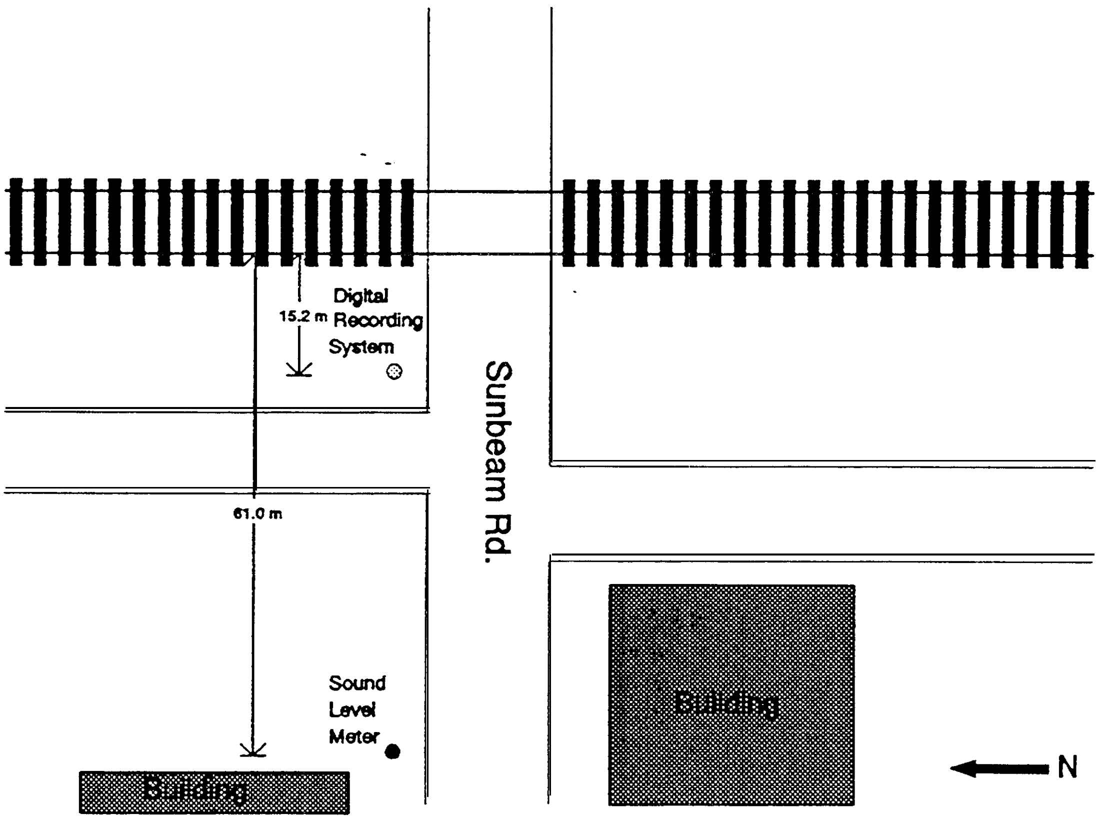


Figure B-l. **Plan View (Not to Scale)**
Sunbeam Road, Jacksonville, FL

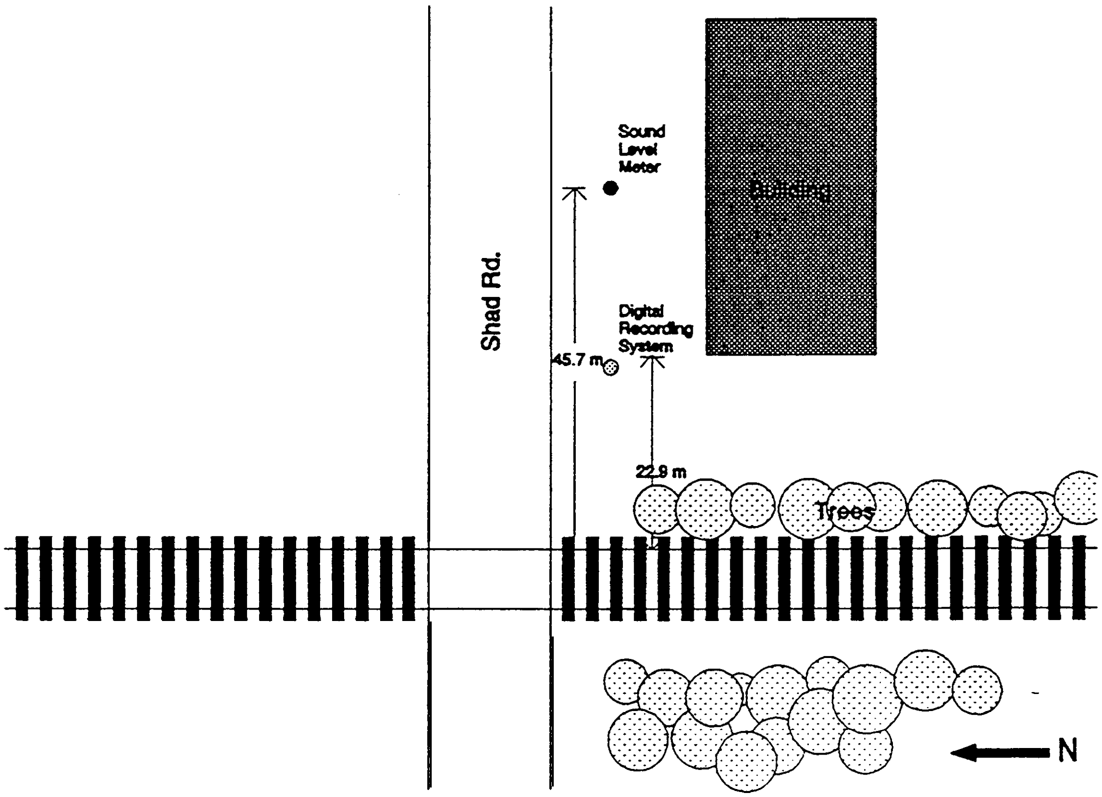


Figure B-2. **Plan View (Not to Scale)**
Shad Road, Jacksonville, FL

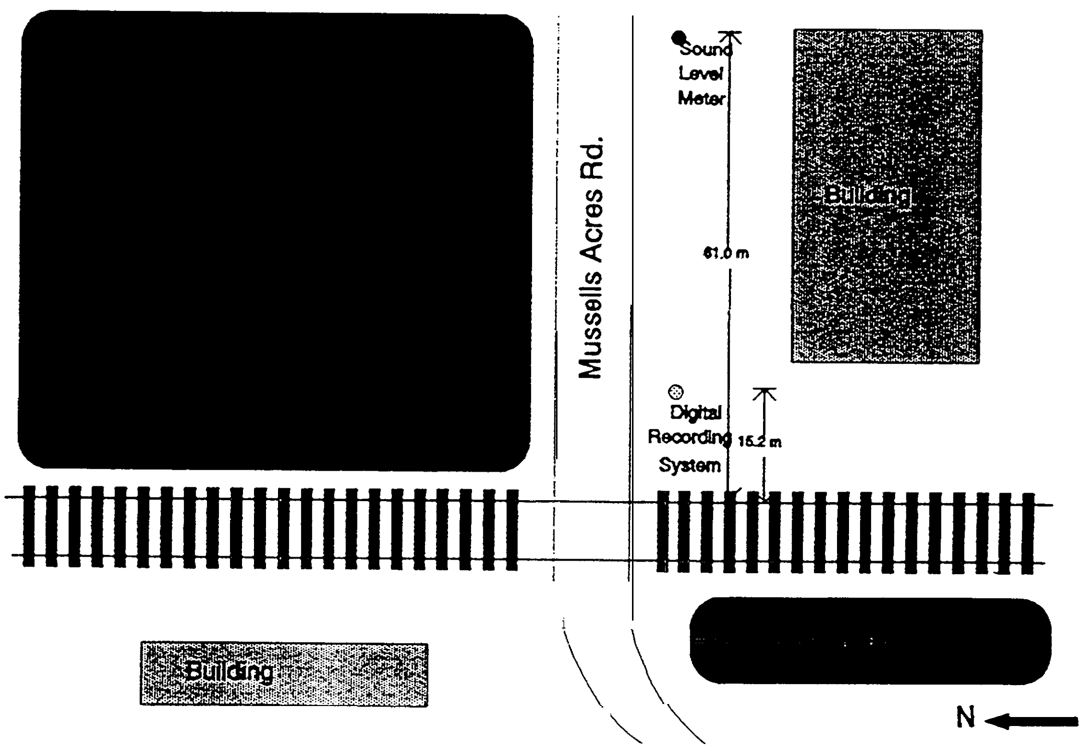


Figure B-3. **Plan View (Not to Scale)**
Mussells **Acres Road, Jacksonville, FL**

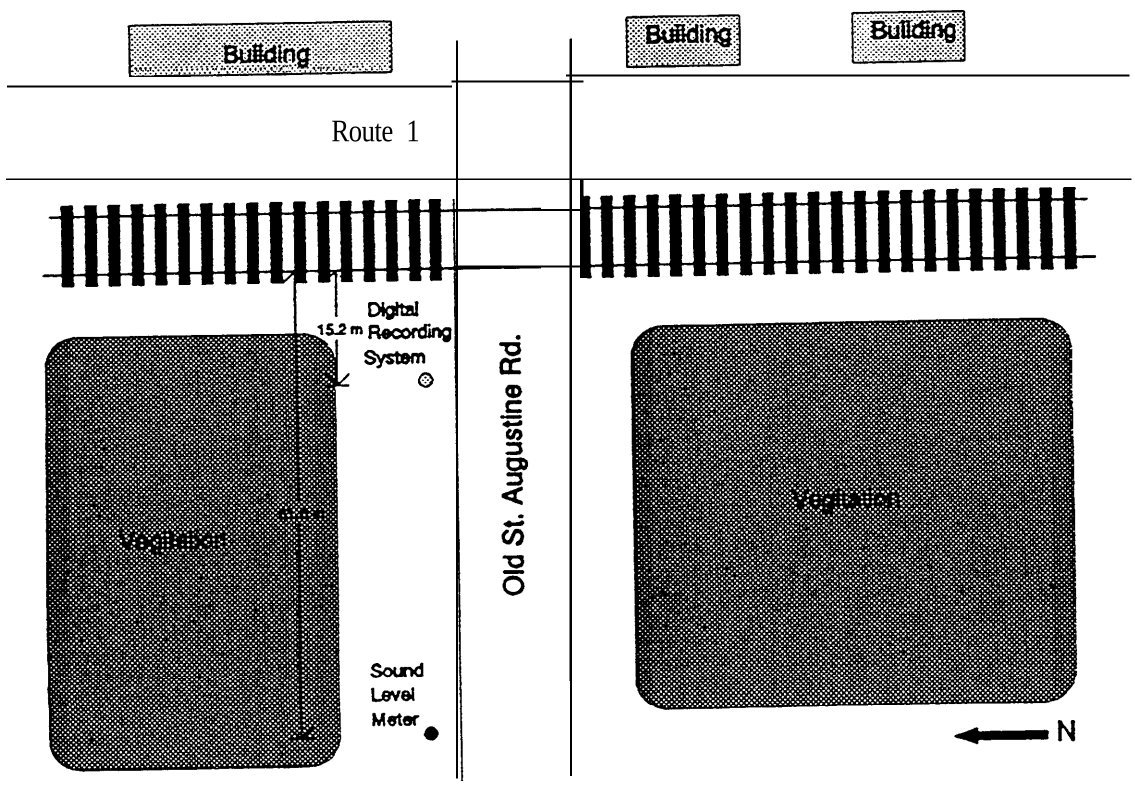


Figure B-4. **Plan View** (Not **to Scale)**
Old St. Augustine Rd., Jacksonville, FL

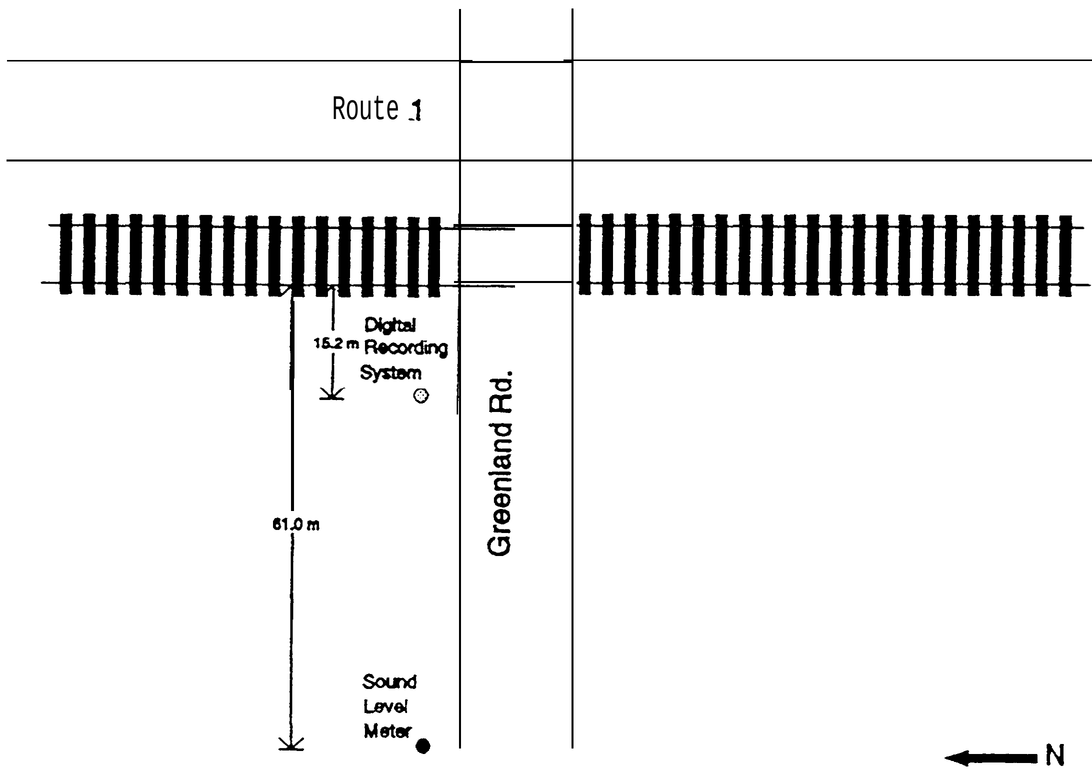


Figure B-5. **Plan View (Not to Scale)**
Greenland Road, Jacksonville, FL

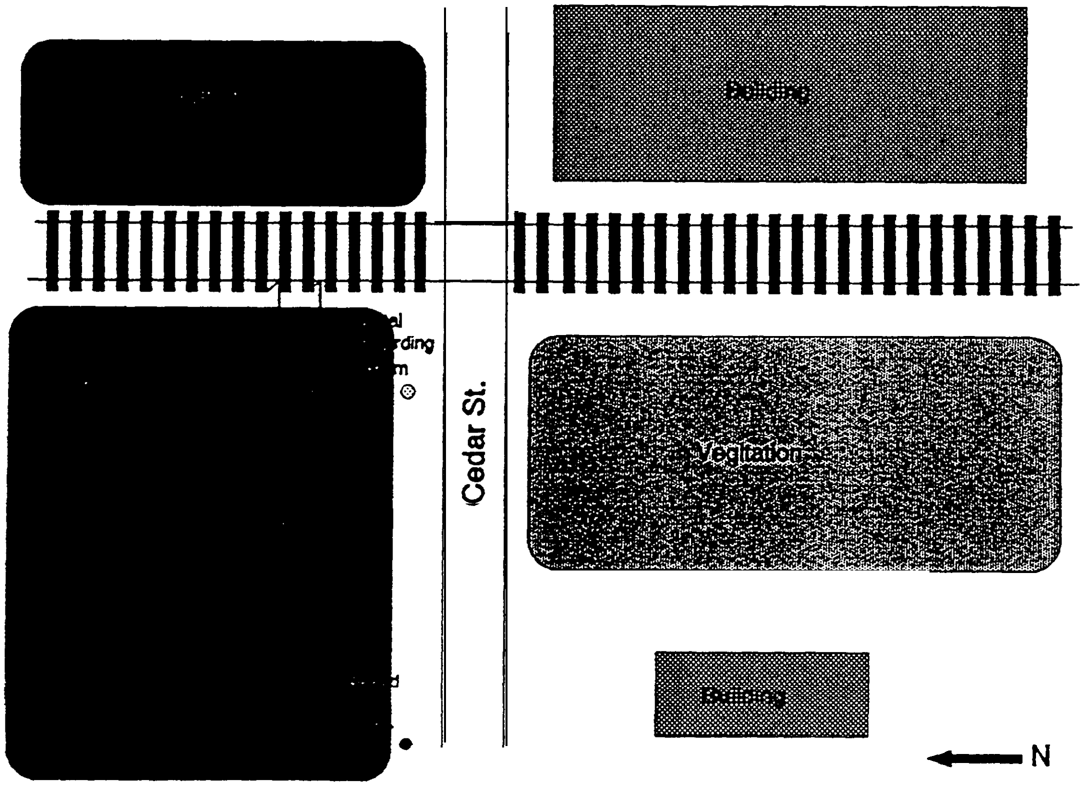


Figure B-6. **Plan View (Not to Scale)**
Cedar Street, Jacksonville, FL

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

Date:	07/08/92
Time:	06:59
Train Speed:	26 mph
Direction of Travel:	North
Speed Limit on Road:	45 mph
Type of Road:	Paved - Three lane
Temperature:	80°F
Relative Humidity:	88%
Source:	No air pressure regulator. Rated at 114 dBA at 100 ft.

Microphone Location: 50 ft east of tracks				
Signal Component	L_{AE} (dB(A))	L_{ASmax} (dB(A))	Duration (sec)	Distance from mic to Locomotive (ft)
1.) Long		91.94	4.75	443
2.) Long		98.69	3.75	262
3.) Short		99.73	1.38	246
4.) Long		112.14	5.00	66
Combined	114.43	112.14	14.88	

Microphone Location: 200 ft east of tracks				
Signal Component	L_{AE} (dB(A))	L_{ASmax} (dB(A))	Duration (sec)	Distance from mic to locomotive (ft)
1.) Long		89.10	4.75	482
2.) Long		97.00	4.00	325
3.) Short		95.50	1.50	259
4.) Long		101.30	5.38	203
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:	35 mph
Direction of Travel:	North
Speed Limit on Road:	45 mph
Type of Road:	Paved - Three lane
Temperature:	82 °F
Relative Humidity:	84%
Source:	Rated at 104 dBA at 100 ft.

Microphone Location: 50 ft east of tracks				
Signal Component	L_{AE} (dB(A))	L_{ASmax} (dB(A))	Duration (sec)	Distance from mic to locomotive (ft)
1.) Long		78.68	5.13	679
2.) Long		84.77	4.50	400
3.) Short		82.28	2.50	236
4.) Long		103.76	5.38	62
Combined	107.37	103.76	17.51	

Microphone Location: 200 ft east of tracks				
Signal Component	L_{AE} (dB(A))	L_{ASmax} (dB(A))	Duration (sec)	Distance from mic to locomotive (ft)
1.) Long		74.50	4.13	709
2.) Long		80.10	4.25	443
3.) Short		78.30	2.88	305
4.) Long		95.60	5.00	203
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:	47 mph
Direction of Travel:	North
Speed Limit on Road:	45 mph
Type of Road:	Paved - Three lane
Temperature:	83 °F
Relative Humidity:	84%
Source:	Rated at 104 dBA at 100 ft.

Microphone Location: 75 ft west of tracks				
Signal Component	L_{AE} (dB(A))	L_{ASmax} (dB(A))	Duration (sec)	Distance from mic to locomotive (ft)
1.) Long		86.14	2.75	505
2.) Long		89.85	2.13	308
3.) Short		90.54	1.38	220
4.) Long		96.86	5.63	105
Combined	98.1	96.86	11.88	

Microphone Location: 150 ft west of tracks				
Signal Component	L_{AE} (dB(A))	L_{ASmax} (dB(A))	Duration (sec)	Distance from mic to locomotive (ft)
1.) Long		74.60	3.13	522
2.) Long		86.10	1.88	335
3.) Short		86.20	1.25	265
4.) Long		92.60	6.38	167
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:	58 mph
Direction of Travel:	North
Speed Limit on Road:	45 mph
Type of Road:	Paved - Three lane
Temperature:	91 °F
Relative Humidity:	70%
Source:	Rated at 104 dBA at 100 ft.

Microphone Location: 75 ft west of tracks				
Signal Component	L_{AE} (dB(A))	L_{ASmax} (dB(A))	Duration (sec)	Distance from mic to locomotive (ft)
1.) Long		82.70	2.75	572
2.) Long		93.93	2.63	318
3.) Short		91.75	0.75	236
4.) Long		96.43	6.13	92
Combined	98.07	96.43	12.26	

Micronhone Location: 150 ft west of tracks				
Signal Component	L_{AE} (dB(A))	L_{ASmax} (dB(A))	Duration (sec)	Distance from mic to locomotive (m)
1.) Long		72.90	3.13	584
2.) Long		87.60	3.25	345
3.) Short		88.50	1.00	269
4.) Long		92.80	9.00	161
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:	42 mph
Direction of Travel:	south
Speed Limit on Road:	25 mph
Type of Road:	Unpaved
Temperature:	93 °F
Relative Humidity:	64%
Source:	Rated at 104 dBA at 100 ft.

Microphone Location: 50 ft west of tracks				
Signal Component	L_{AE} (dB(A))	L_{ASmax} (dB(A))	Duration (sec)	Distance from mic to locomotive (ft)
1.) Long		89.25	2.63	489
2.) Long		96.60	2.38	282
3.) Short		97.67	1.38	230
4.) Long		103.90	5.00	76
Combined	104.98	103.90	11.39	

Microphone Location: 200 ft west of tracks				
Signal Component	L_{AE} (dB(A))	L_{ASmax} (dB(A))	Duration (sec)	Distance from mic to locomotive (ft)
1.) Long		83.80	2.63	525
2.) Long		89.60	2.63	341
3.) Short		89.40	1.38	315
4.) Long		90.90	6.00	207
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:	43 mph
Direction of Travel:	south
Road Speed Limit:	25 mph
Road Type:	Unpaved
Temperature:	93 °F
Relative Humidity:	64%
Source:	Rated at 104 dBA at 100 ft.

Microphone Location: 50 ft west of tracks				
Signal Component	L_{AE} (dB(A))	L_{ASmax} (dB(A))	Duration (sec)	Distance from mic to locomotive (ft)
1.) Long		84.53	3.38	351
2.) Long		91.54	3.00	216
3.) Short		91.60	2.13	138
4.) Long		105.26	5.38	53
Combined	110.18	105.26	13.89	

Microphone Location: 200 ft 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:	26 mph
Direction of Travel:	South
Speed Limit on Road:	40 mph
Type of Road:	Paved - Two lane
Temperature:	76 °F
Relative Humidity:	86%
Source:	No air pressure regulator. Rated at 114 dBA at 100ft.

Microphone Location: 50 ft west of tracks				
Signal Component	L_{AE} (dB(A))	L_{ASmax} (dB(A))	Duration (sec)	Distance from mic to locomotive (ft)
1.) Long		95.26	4.38	630
2.) Long		104.00	3.63	315
3.) Short		105.60	2.25	226
4.) Long		112.02	5.38	85
Combined	115.14	112.02	17.75	

Microphone Location: 200 ft west of tracks				
Signal Component	L_{AE} (dB(A))	L_{ASmax} (dB(A))	Duration (sec)	Distance from mic to locomotive (ft)
1.) Long		84.10	5.13	659
2.) Long		94.60	3.83	368
3.) Short		95.90	2.38	299
4.) Long		98.00	6.75	210
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: 18 mph
Direction of Travel: North
Speed Limit on Road: 40 mph
Type of Road: Paved - Two lane
Temperature: 76 °F
Relative Humidity: 86%
Source: Rated at 104 dBA at 100 ft.

Microphone Location: 50 ft west of tracks				
Signal Component	L_{AE} (dB(A))	L_{ASmax} (dB(A))	Duration (sec)	Distance from mic to locomotive (ft)
1.) Long		89.08	4.25	397
2.) Long		94.10	3.13	243
3.) Short		92.79	2.50	181
4.) Long		107.19	5.00	79
Combined	109.44	107.19	16.50	

Microphone Location: 200 ft west of tracks				
Signal Component	L_{AE} (dB(A))	L_{ASmax} (dB(A))	Duration (sec)	Distance from mic to locomotive (ft)
1.) Long		88.80	4.00	440
2.) Long		91.70	3.50	312
3.) Short		91.70	2.63	266
4.) Long		95.30	5.75	217
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:	6 mph
Direction of Travel:	North
Road Speed Limit:	45 mph
Road Type:	Paved - Two lane
Temperature:	79°F
Relative Humidity:	92%
Source:	Rated at 104 dBA at 100 ft.

Microphone Location: 50 ft west of tracks				
Signal Component	L_{AE} (dB(A))	L_{ASmax} (dB(A))	Duration (sec)	Distance from mic to locomotive (ft)
1.) Long		98.07	3.13	299
2.) Long		101.89	3.25	131
3.) Short		98.86	3.25	69
4.) Long		107.02	6.88	53
Combined	109.79	107.02	18.38	

Microphone Location: 200 ft west of tracks				
Signal Component	L_{AE} (dB(A))	L_{ASmax} (dB(A))	Duration (sec)	Distance from mic to locomotive (ft)
1.) Long		91.00	3.50	233
2.) Long		94.10	3.50	213
3.) Short		89.50	3.75	207
4.) Long		93.90	6.88	66
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:	59 mph
Direction of Travel:	North
Speed Limit on Road:	45 mph
Type of Road:	Paved - Two lane
Temperature:	94 °F
Relative Humidity:	66%
Source:	Rated at 104 dBA at 100 ft.

Microphone Location: 50 ft west of tracks				
Signal Component	L_{AE} (dB(A))	L_{ASmax} (dB(A))	Duration (sec)	Distance from mic to locomotive (ft)
1.) Long		70.85	6.75	689
2.) Long		75.74	5.75	368
3.) Short		86.29	1.13	220
4.) Long		102.73	4.88	125
Combined	107.74	102.73	19.50	

Microphone Location: 200 ft west of tracks				
Signal Component	L_{AE} (dB(A))	L_{ASmax} (dB(A))	Duration (sec)	Distance from mic to locomotive (ft)
1.) Long		71.90	7.25	719
2.) Long		71.50	4.63	417
3.) Short		82.40	2.25	292
4.) Long		90.80	6.38	230
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:	44 mph
Direction of Travel:	North
Speed Limit on Road:	25 mph
Type of Road:	Unpaved
Temperature:	94 °F
Relative Humidity:	62%
Source:	Rated at 104 dBA at 100 ft.

Microphone Location: 50 ft west of tracks				
Signal Component	L_{AE} (dB(A))	L_{ASmax} (dB(A))	Duration (sec)	Distance from mic to locomotive (ft)
1.) Long		67.54	6.25	781
2.) Long		83.84	5.50	325
3.) Short		86.29	1.38	203
4.) Long		99.66	5.13	92
Combined	102.83	99.66	18.25	

Microphone Location: 200 ft west of tracks				
Signal Component	L_{AE} (dB(A))	L_{ASmax} (dB(A))	Duration (sec)	Distance from mic to locomotive (ft)
1.) Long		64.80	9.00	803
2.) Long		77.10	3.38	381
3.) Short		78.80	1.75	282
4.) Long		88.00	6.88	213
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:	60 mph
Direction of Travel:	North
Speed Limit on Road:	25 mph
Type of Road:	Unpaved
Temperature:	93 °F
Relative Humidity:	66%
Source:	Rated at 104 dBA at 100 ft.

Microphone Location: 50 ft west of tracks				
Signal Component	L_{AE} (dB(A))	L_{ASmax} (dB(A))	Duration (sec)	Distance from mic to locomotive (ft)
1.) Long		71.93	3.50	889
2.) Long		83.92	4.38	482
3.) Short		88.30	1.25	331
4.) Long		101.93	6.50	128
Combined	105.13	101.93	15.63	

Microphone Location: 200 ft west of tracks				
Signal Component	L_{AE} (dB(A))	L_{ASmax} (dB(A))	Duration (sec)	Distance from mic to locomotive (ft)
1.) Long		69.90	3.50	909
2.) Long		76.10	4.25	522
3.) Short		79.90	1.38	384
4.) Long		89.70	8.63	233
Combined	96.4	89.70	17.75	

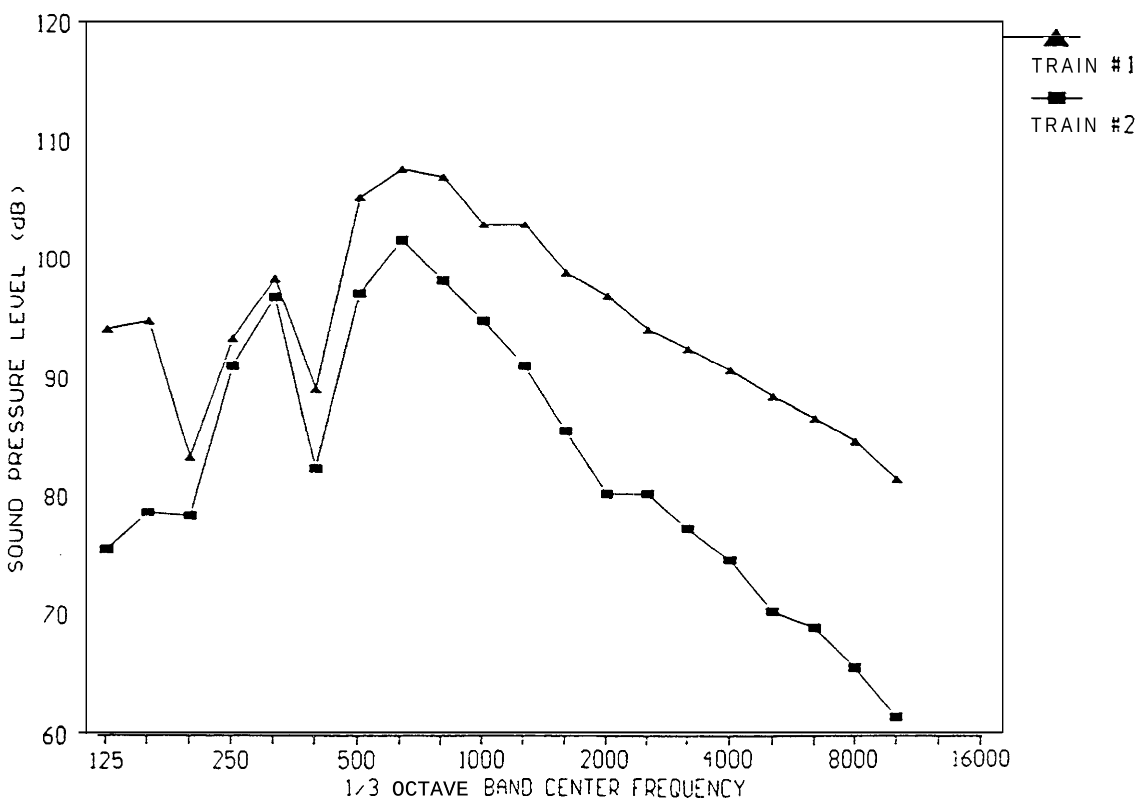


Figure B-7. **Frequency Spectra at A_{max}**
Sunbeam Road - Train I and Train 2

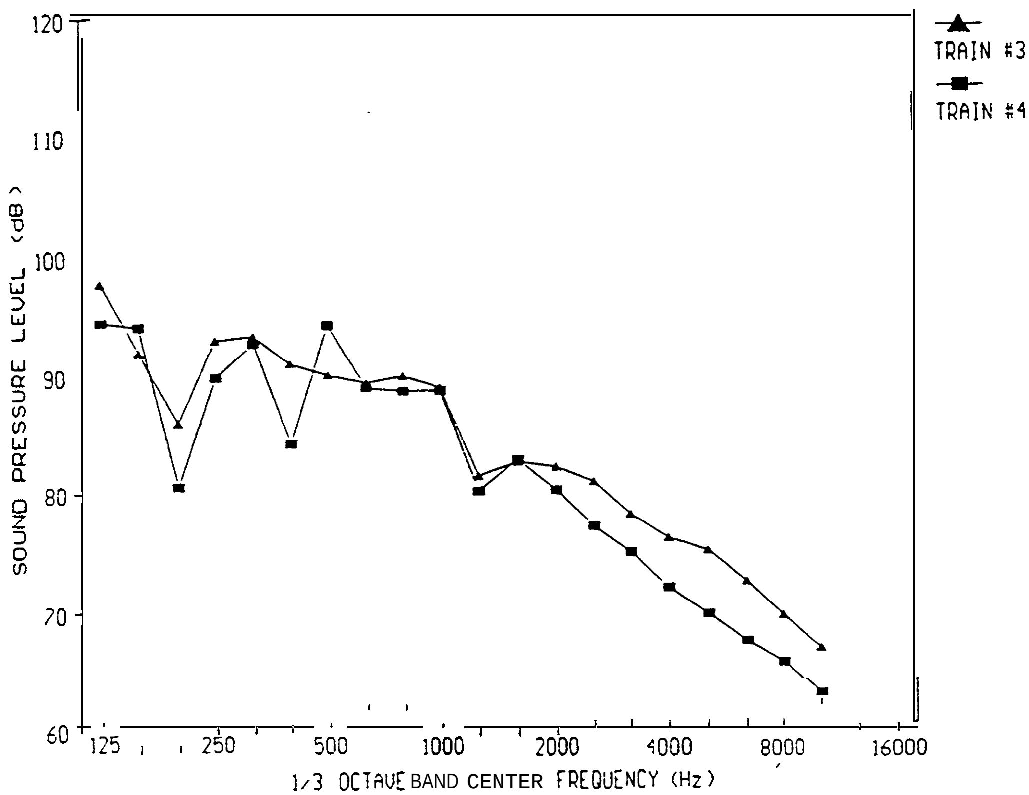


Figure B-8. Frequency Spectra at A_{max}
Shad Road - Train 3 and Train 4

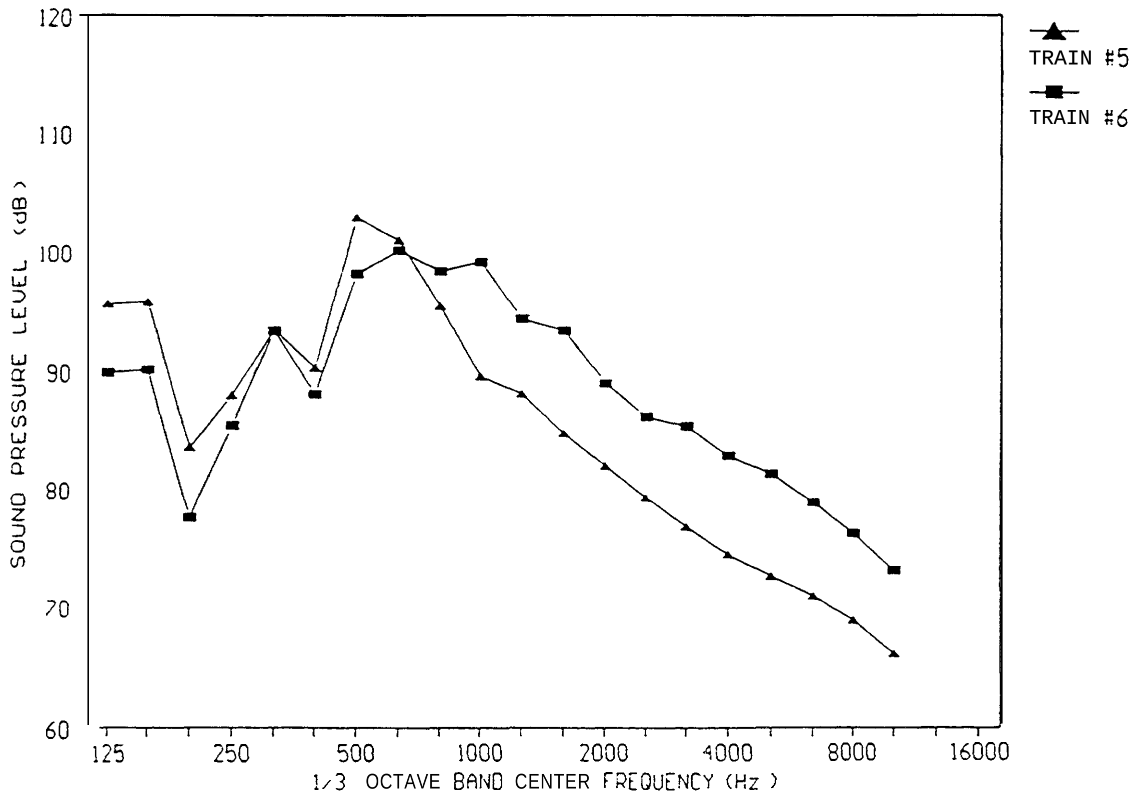


Figure B-9. Frequency Spectra at A_{max} Mussells Acres Road - Train 5 and Train 6

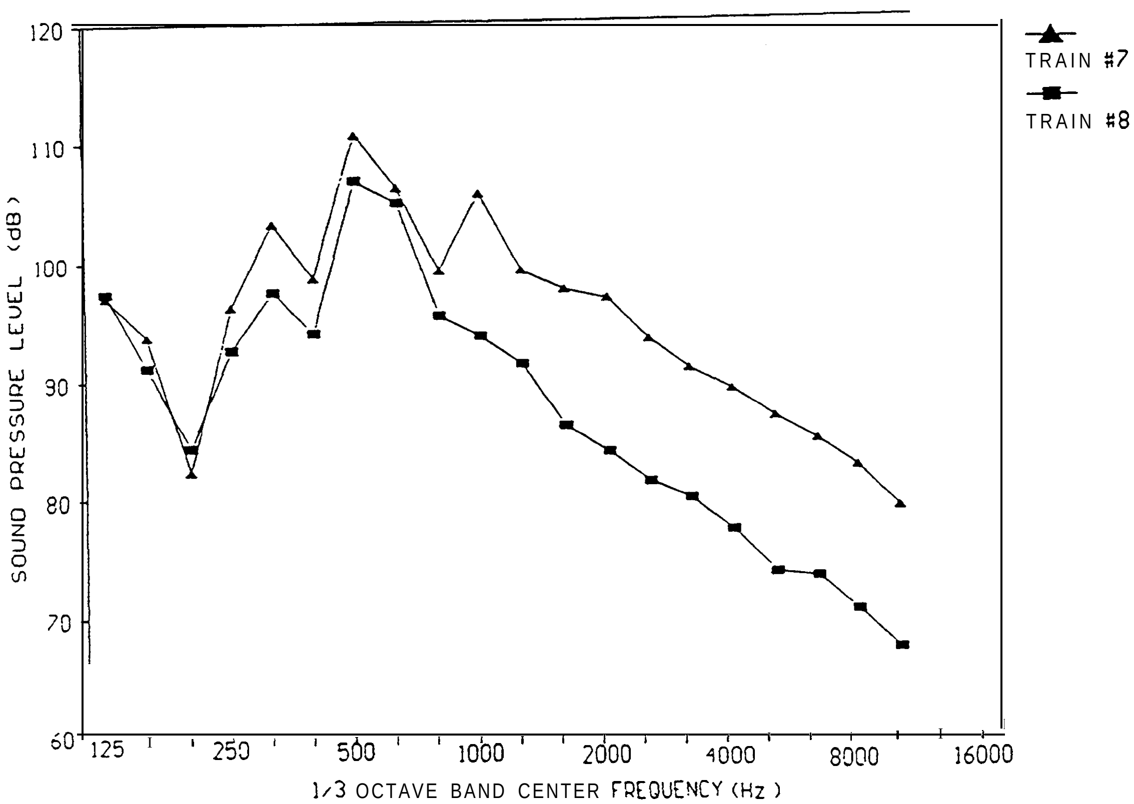


Figure B-10. Frequency Spectra at A_{max}
Old St. Augustine Road - Train 7 and Train 8

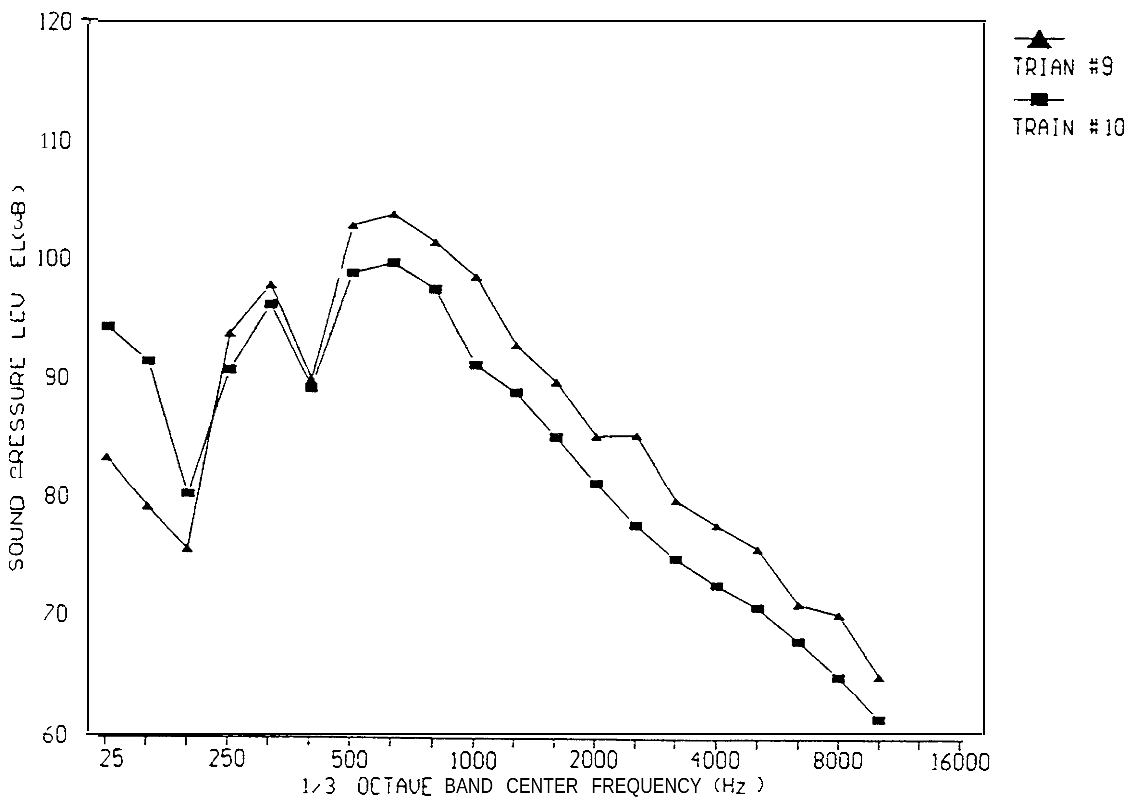


Figure B-11. **Frequency Spectra at A_{max} Greenland Road - Train 9 and Train 10**

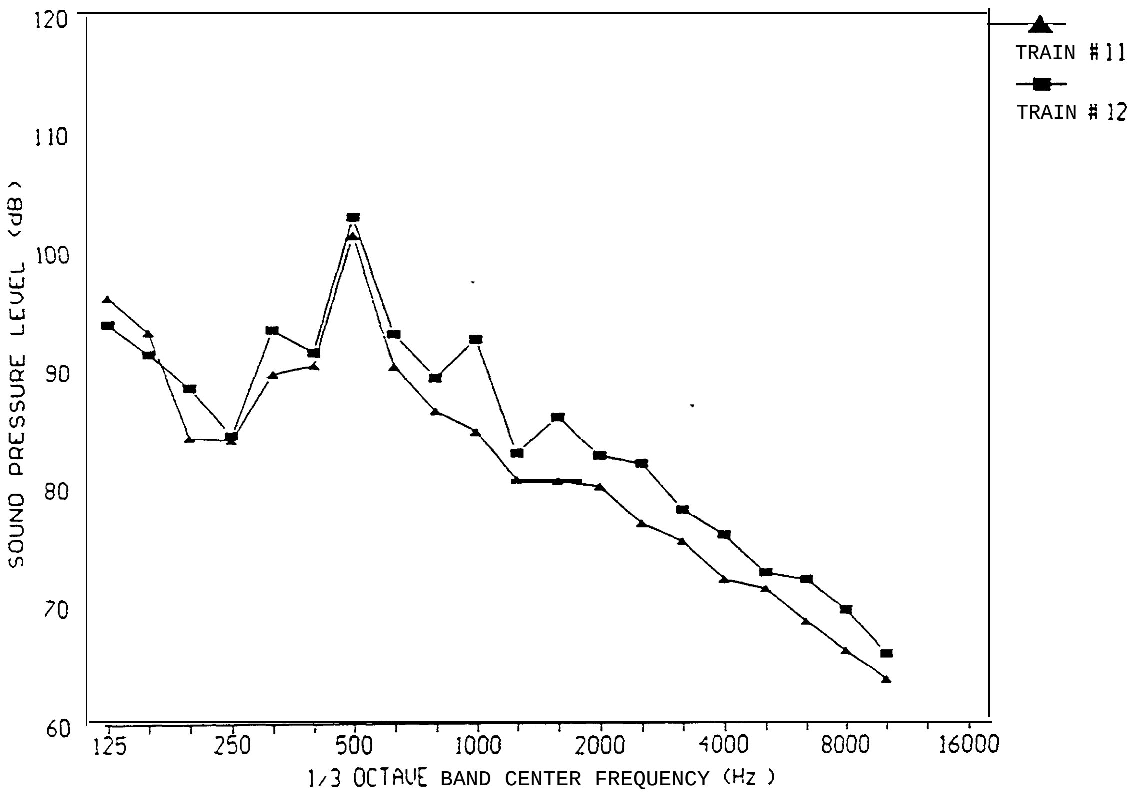
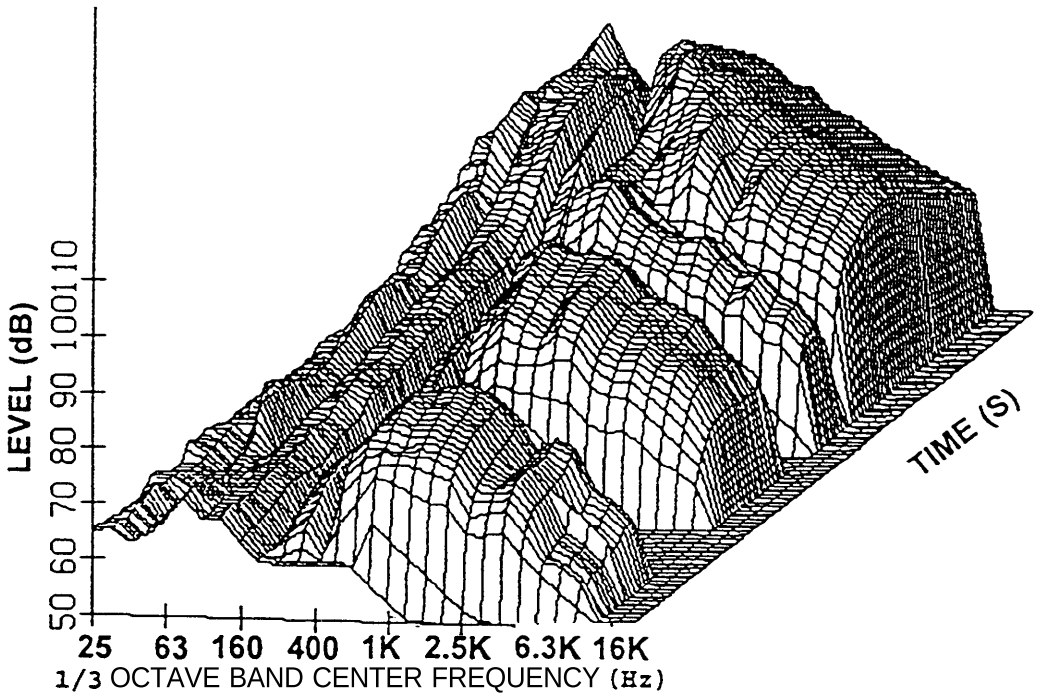


Figure B-12. Frequency Spectra at A_{max}
Cedar Street - Train 11 and Train 12



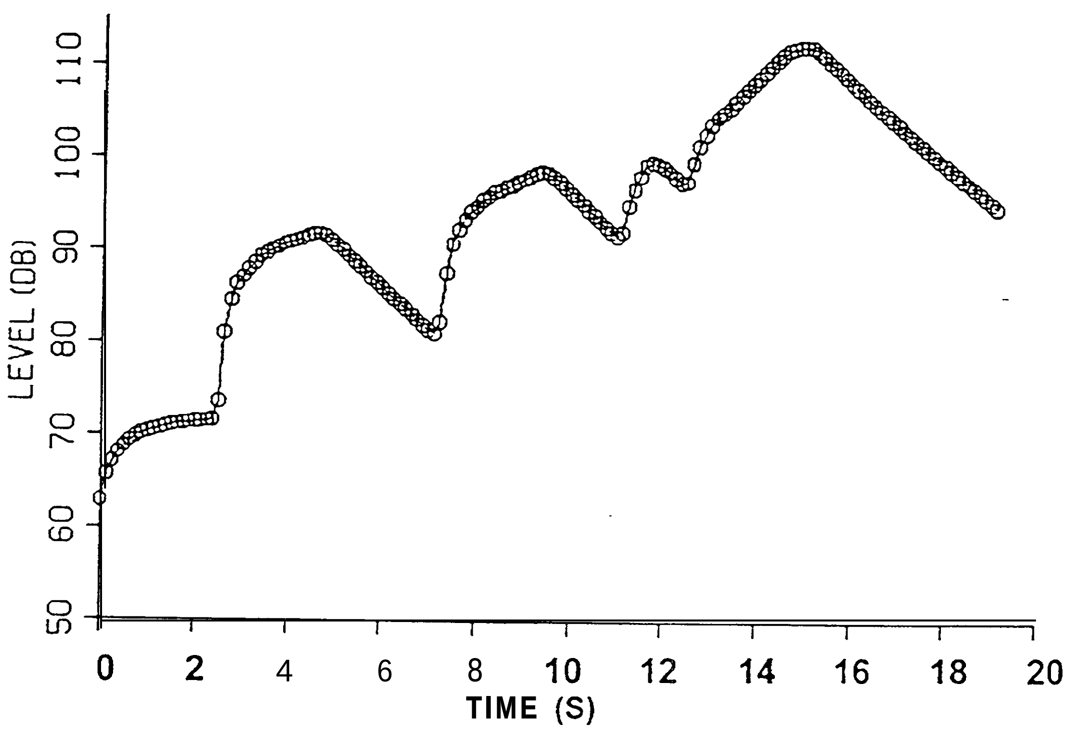
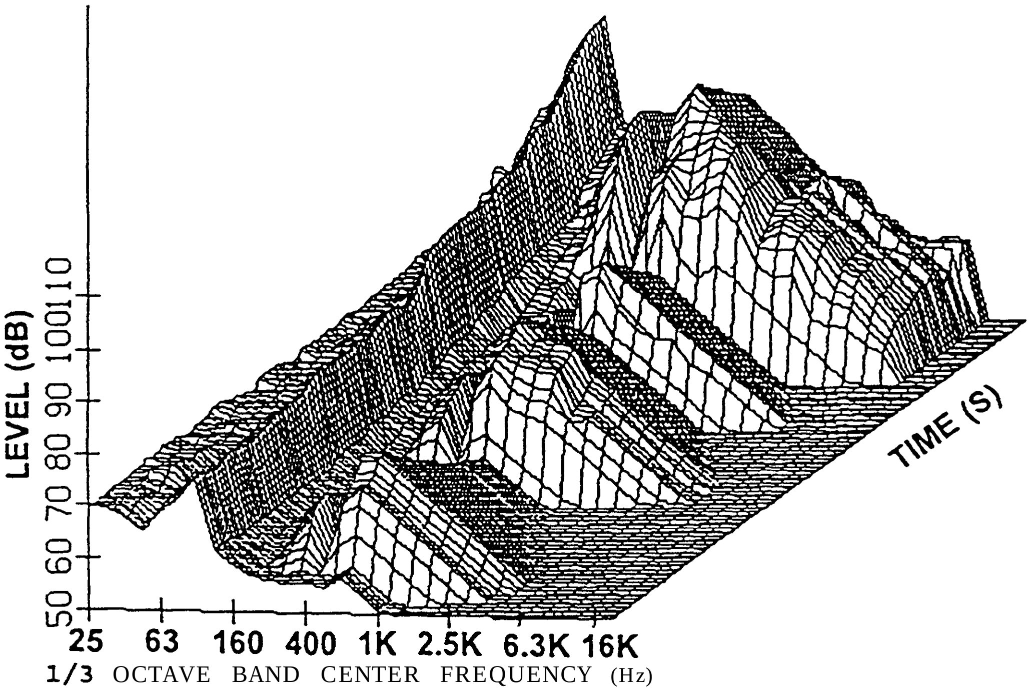


Figure B-13. **Sunbeam Road - Train 1**
A.) **Spectral Time History**
B.) **A-Weighted Time History**



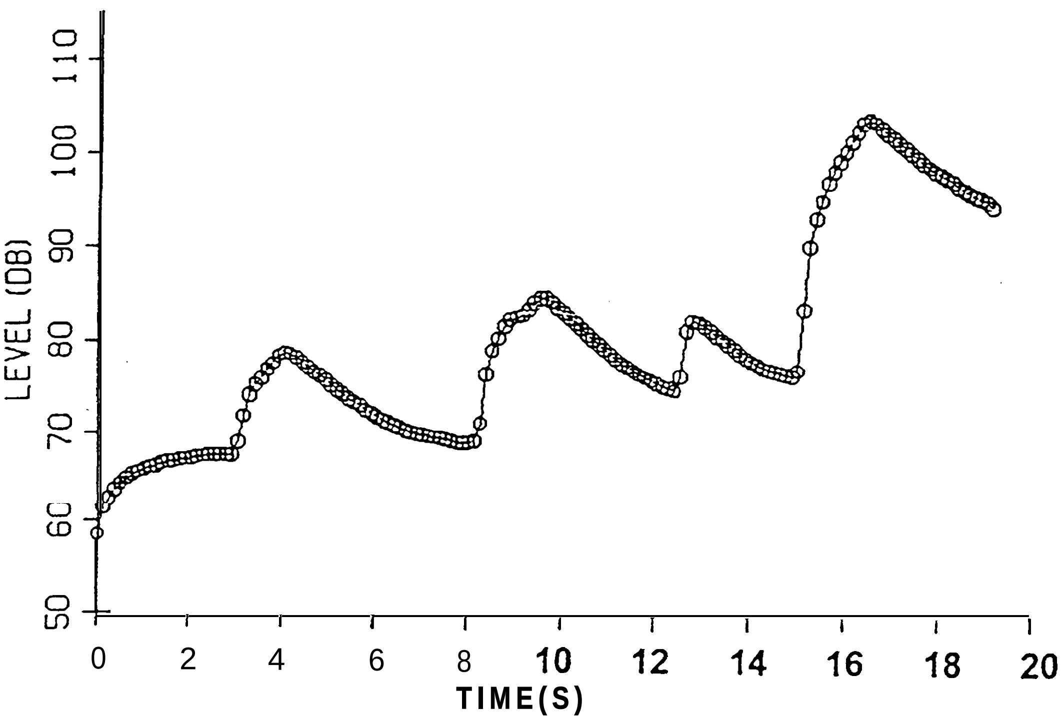
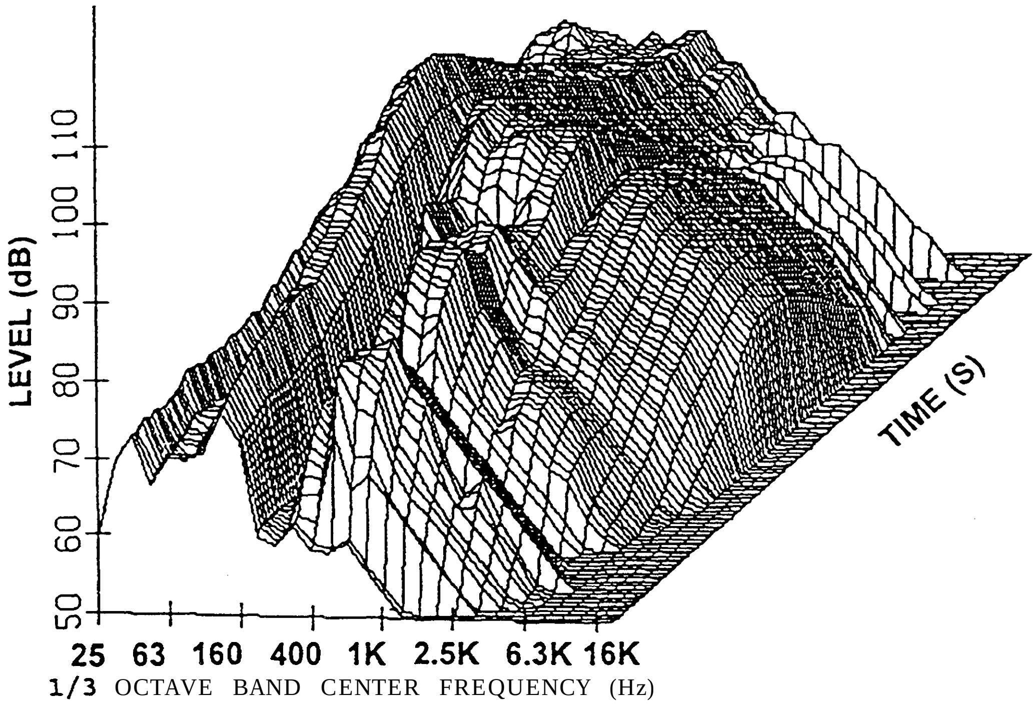


Figure B-14. **Sunbeam Road - Train 2**
A.) **Spectral Time History**
B.) **A-Weighted Time History**



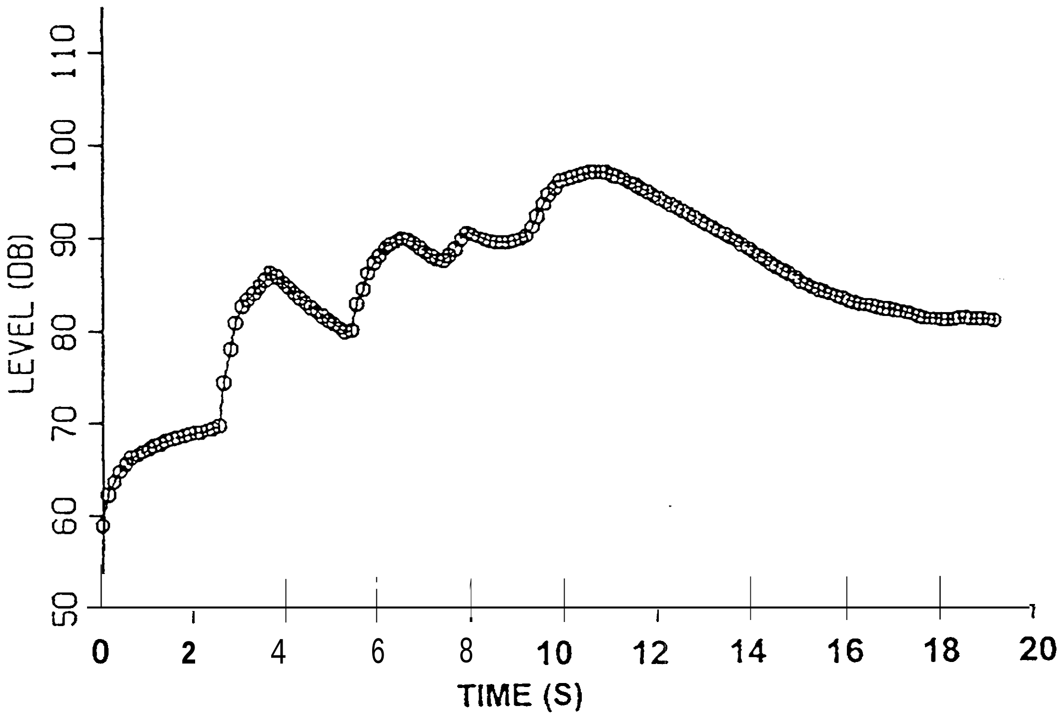
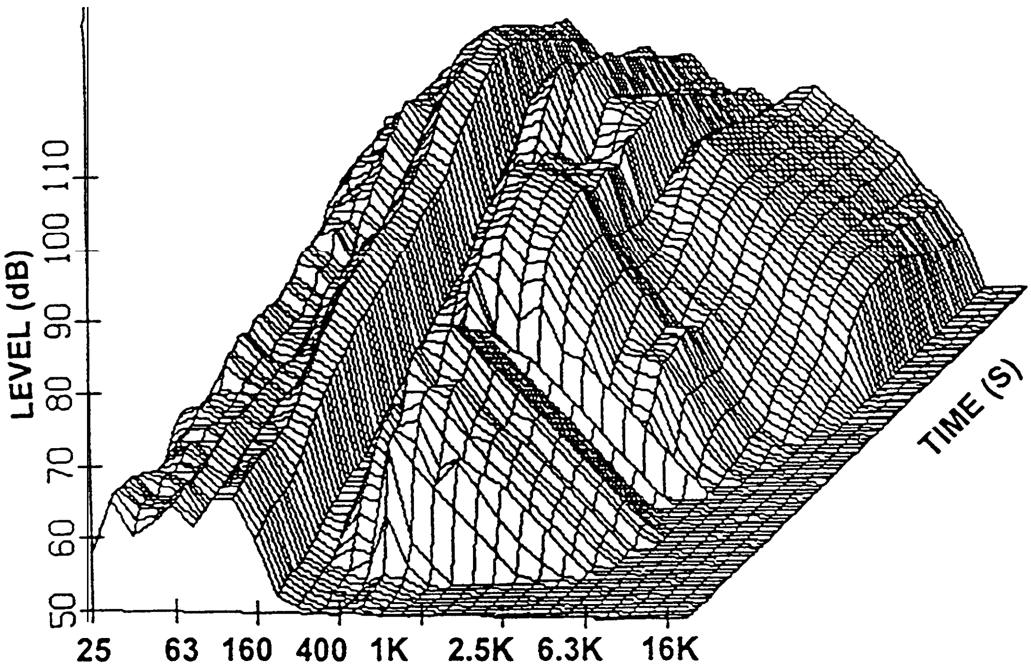


Figure B-15. **Shad Road - Train 3**
A.) **Spectral Time History**
B.) **A-Weighted Time** History



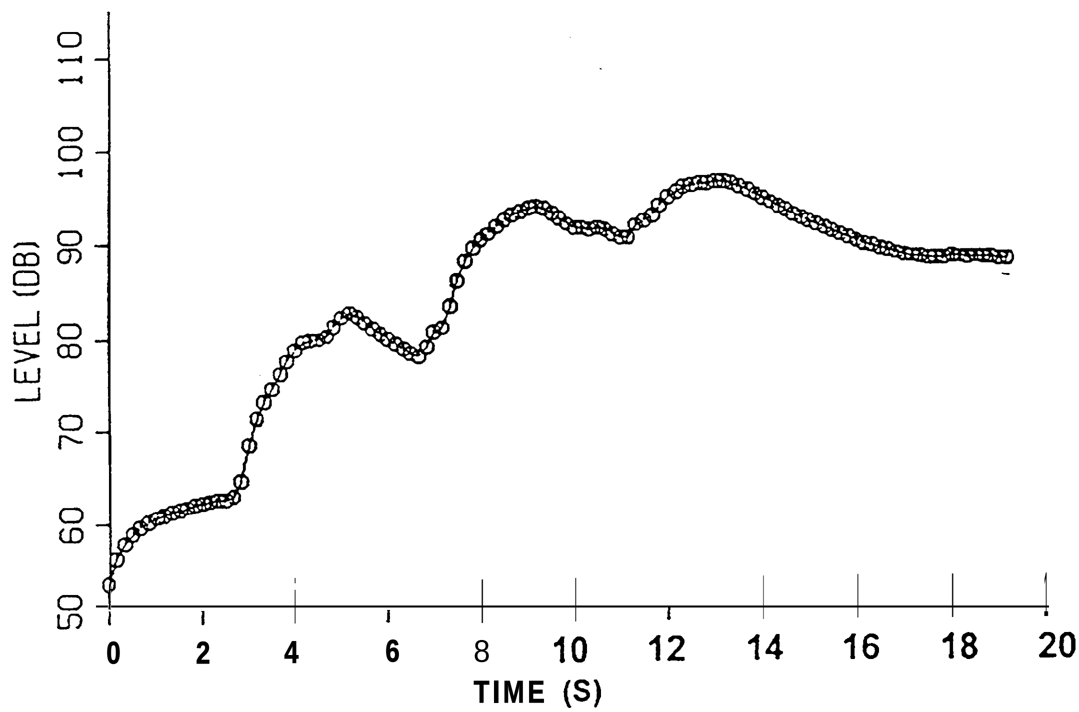
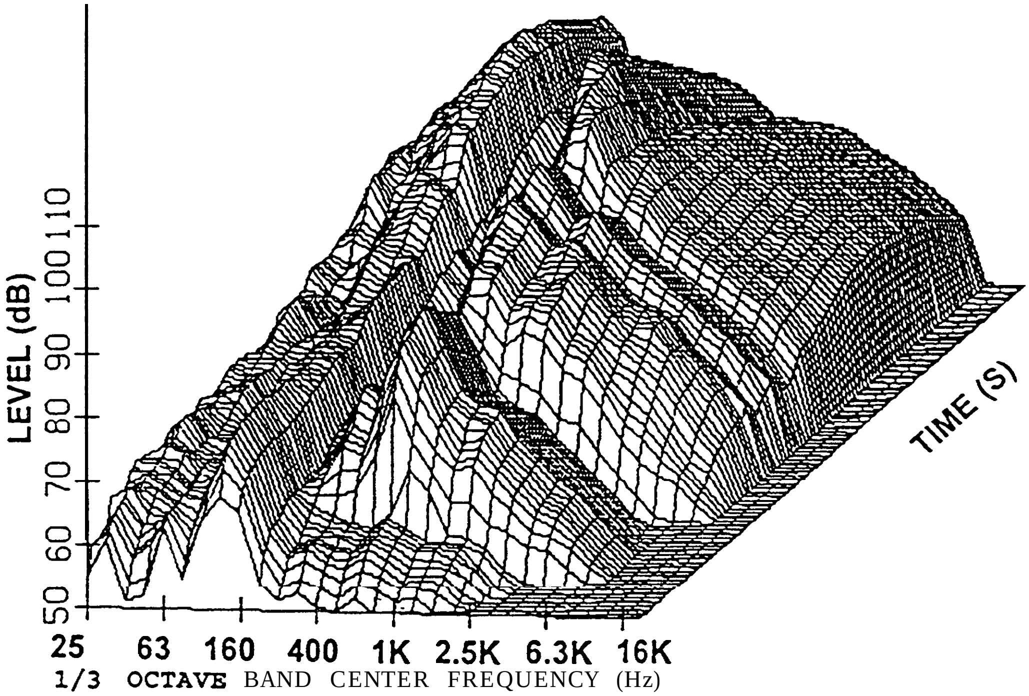


Figure B-16. **Shad Road - Train 4**
A.) **Spectral Time History**
B.) **A-Weighted Time History**



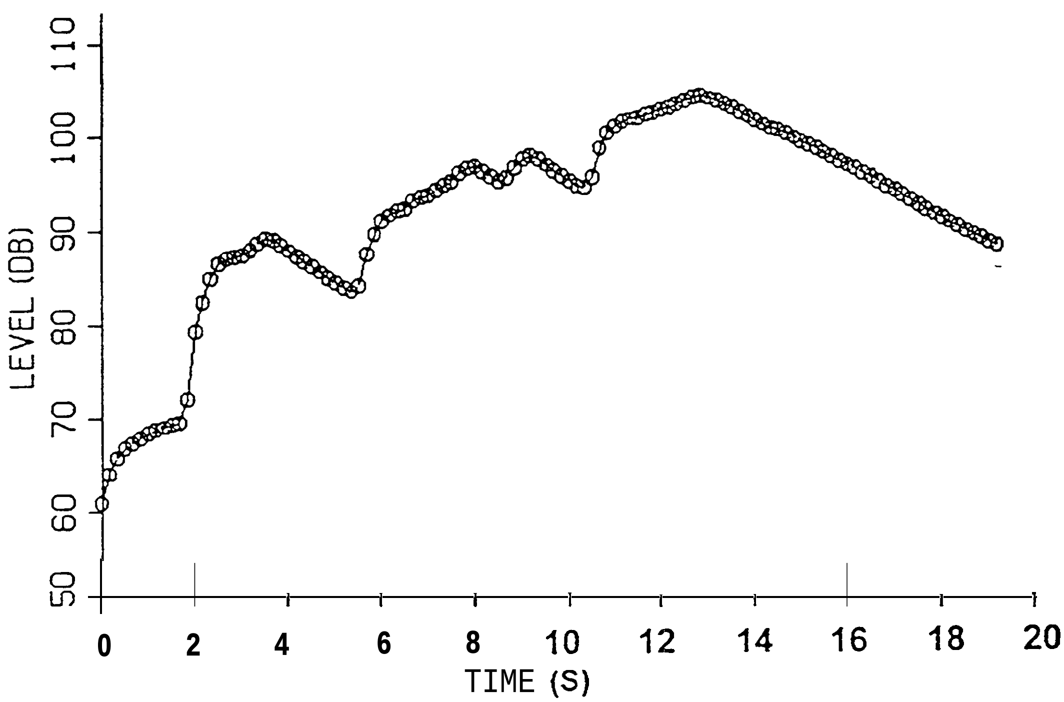
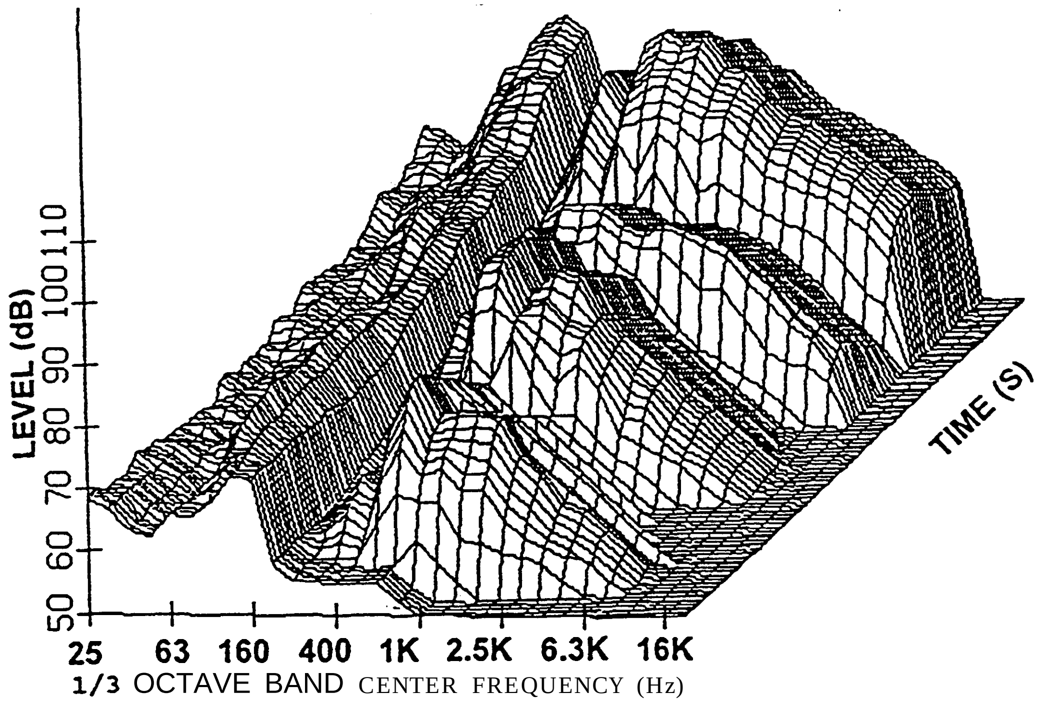


Figure B-17. Mussells **Acres Road - Train 5**
A.) **Spectral Time History**
B.) **A-Weighted Time History**



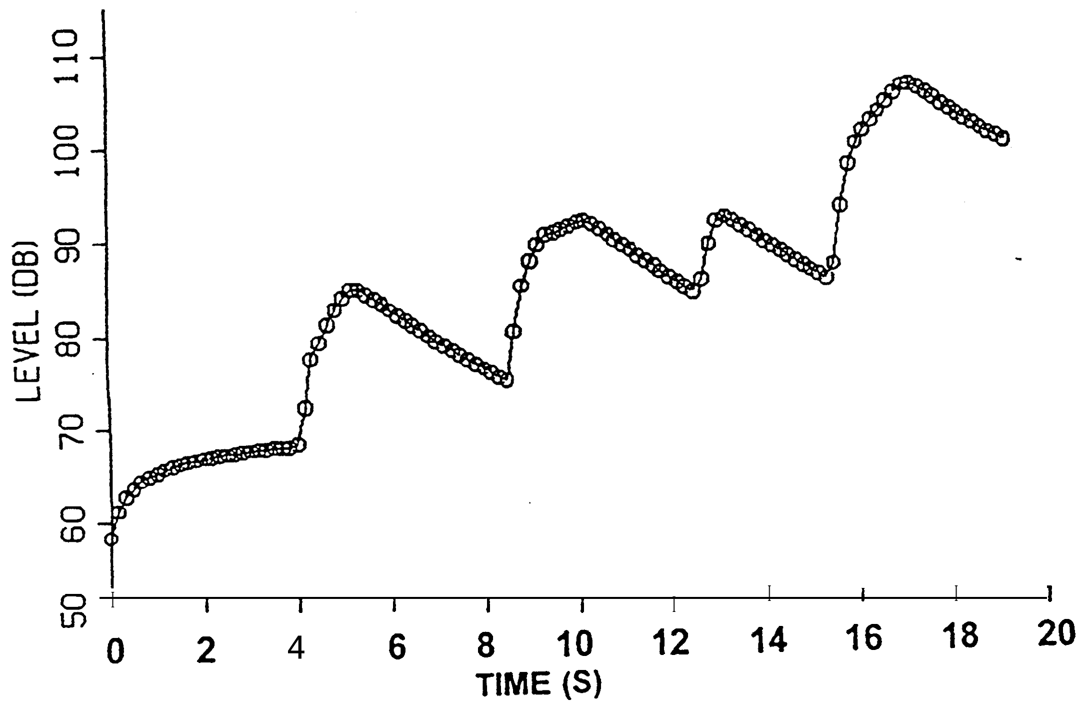
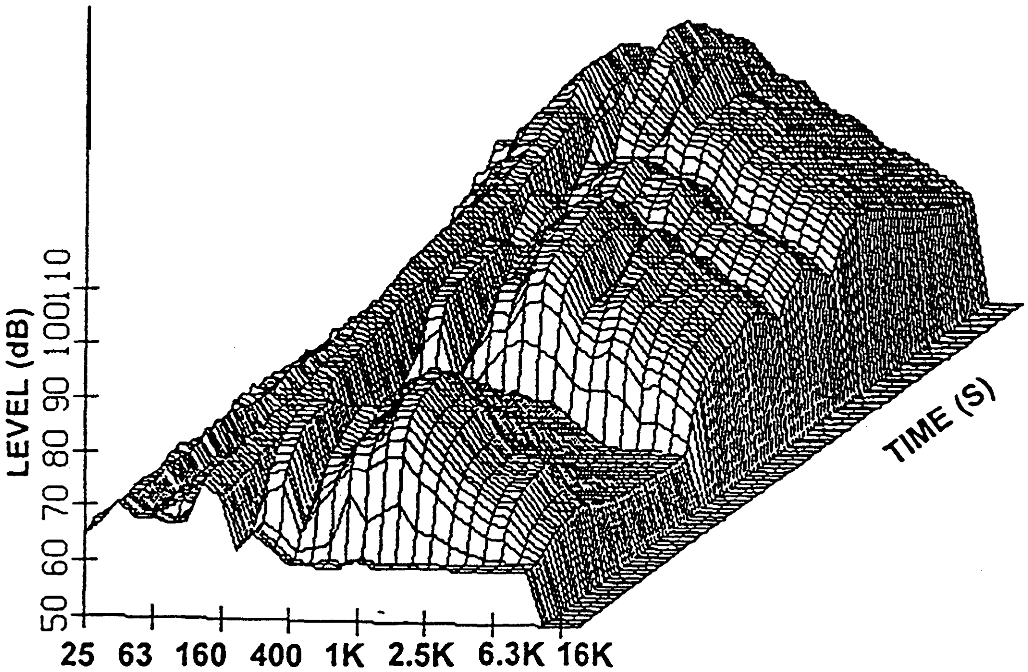


Figure B-18. Mussells **Acres Road - Train 6**
A.) **Spectral Time History**
B.) **A-Weighted Time History**



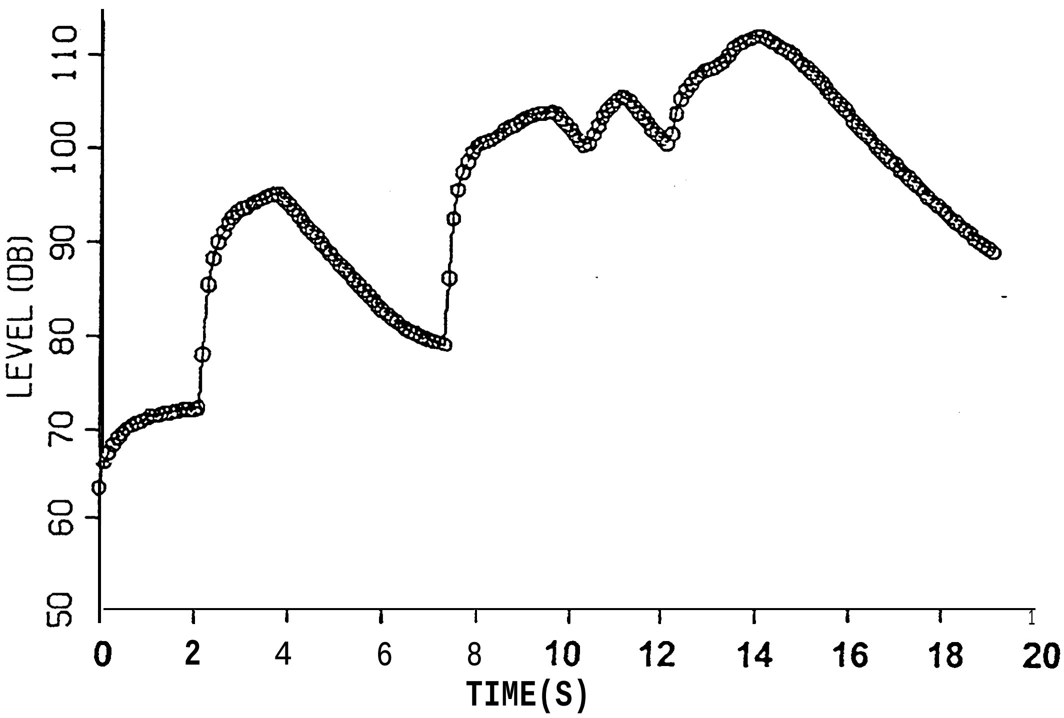
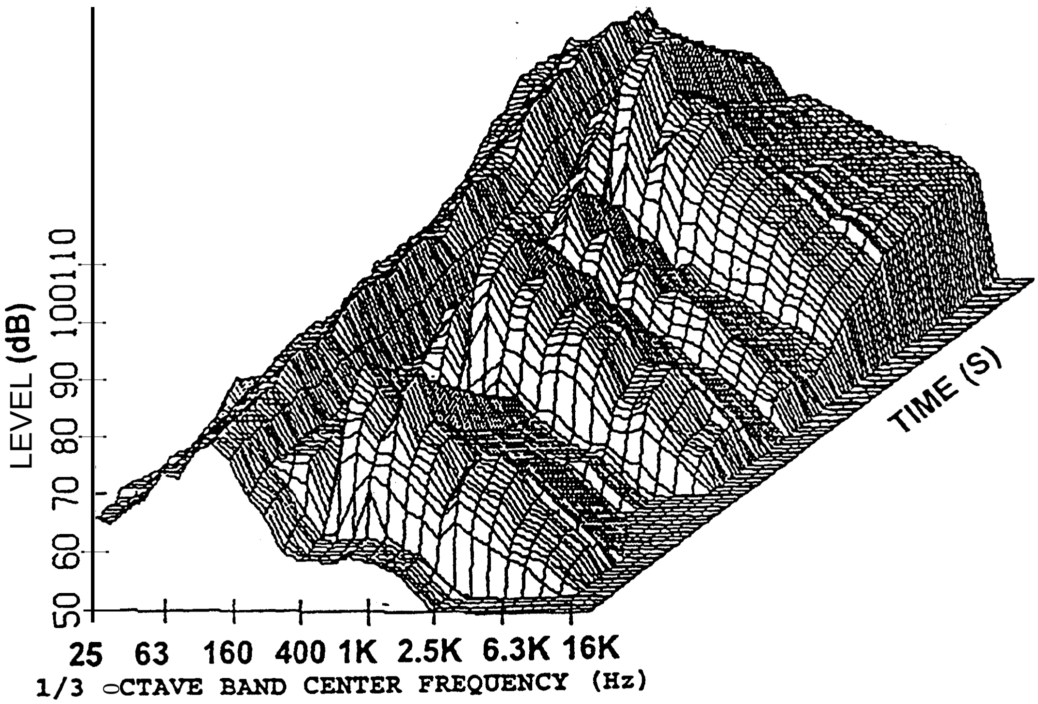


Figure B-19. Old St. Augustine Road - Train 7
A.) Spectral Time History
B.) A-Weighted Time History



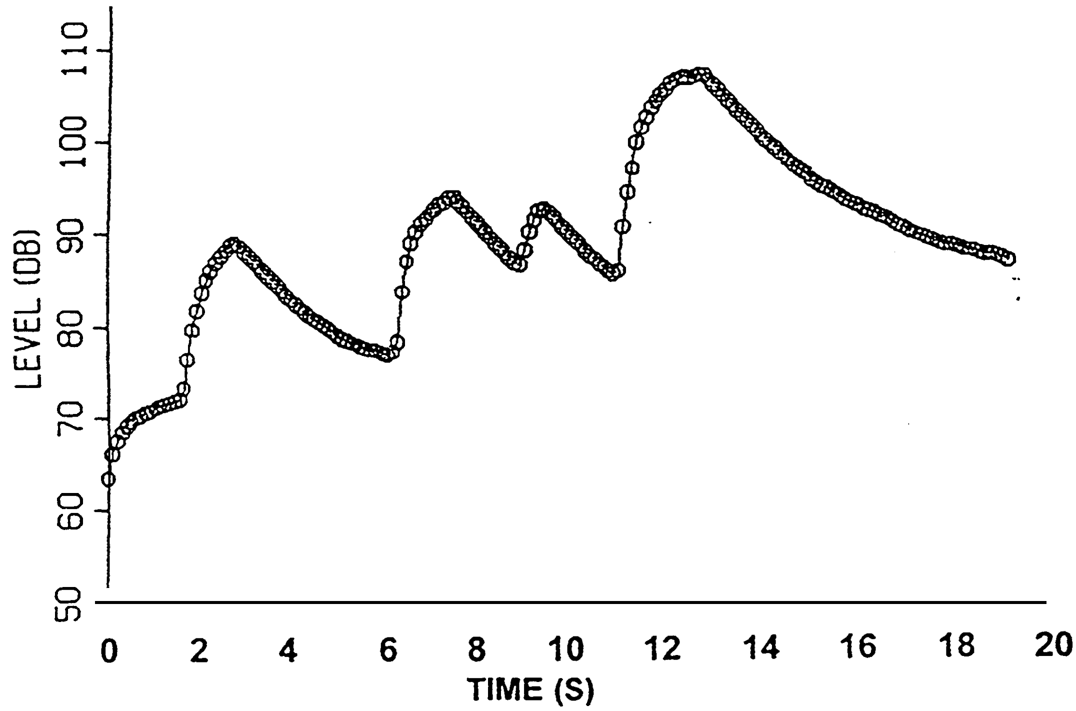
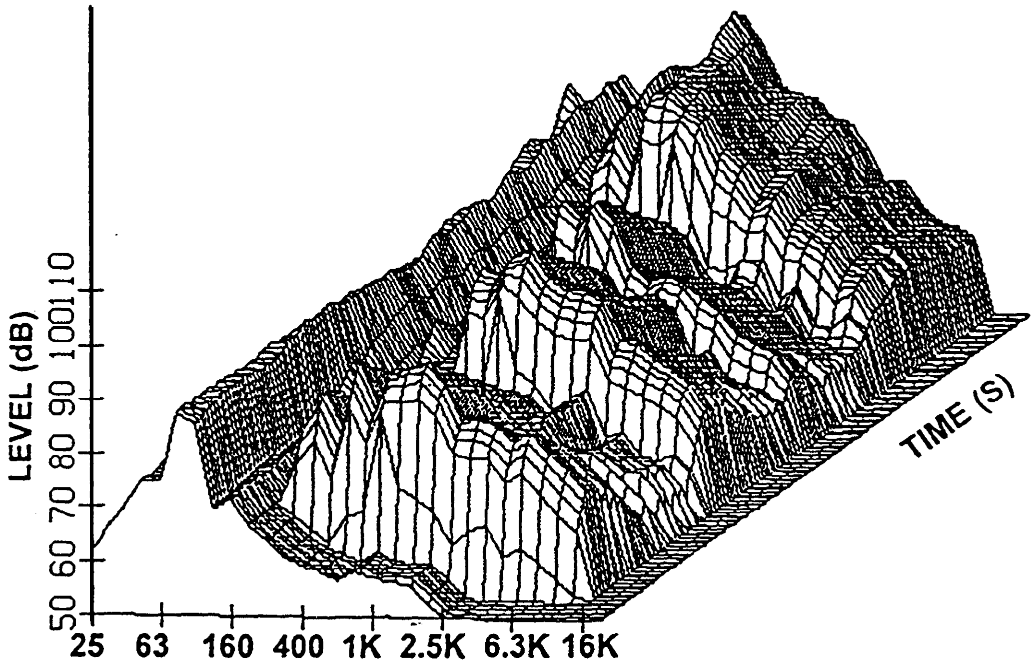


Figure B ⊘ Old St. Augustine Road - Train 8
A.) Spectral Time History
B.) A-Weighted Time History



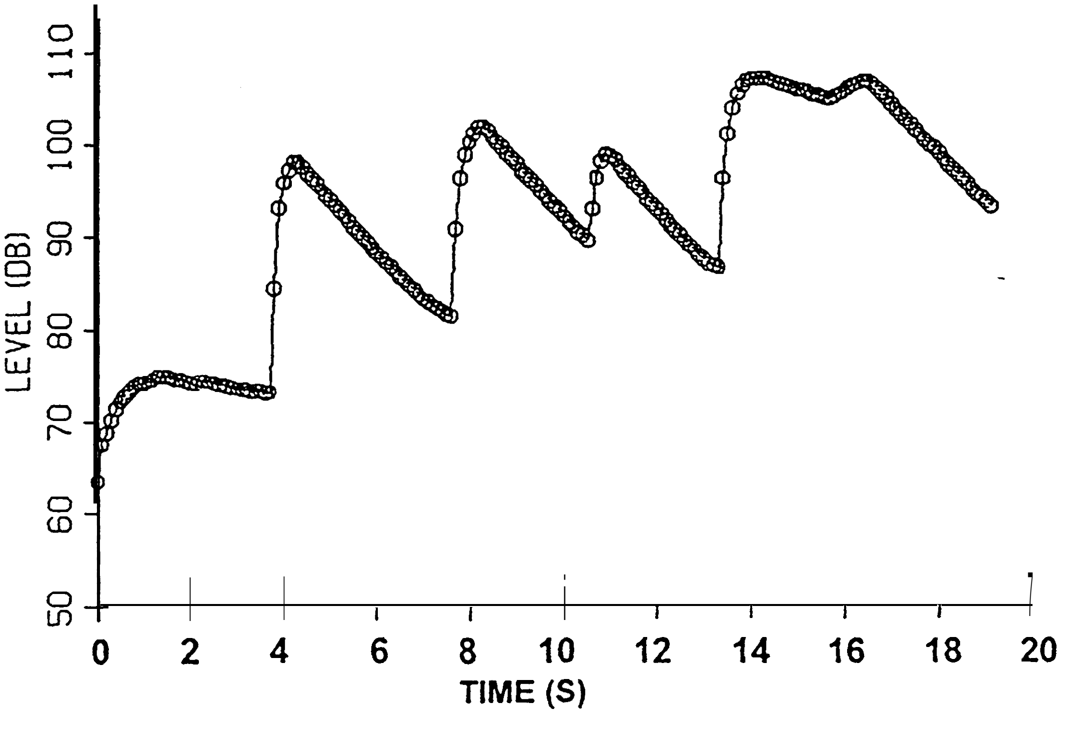
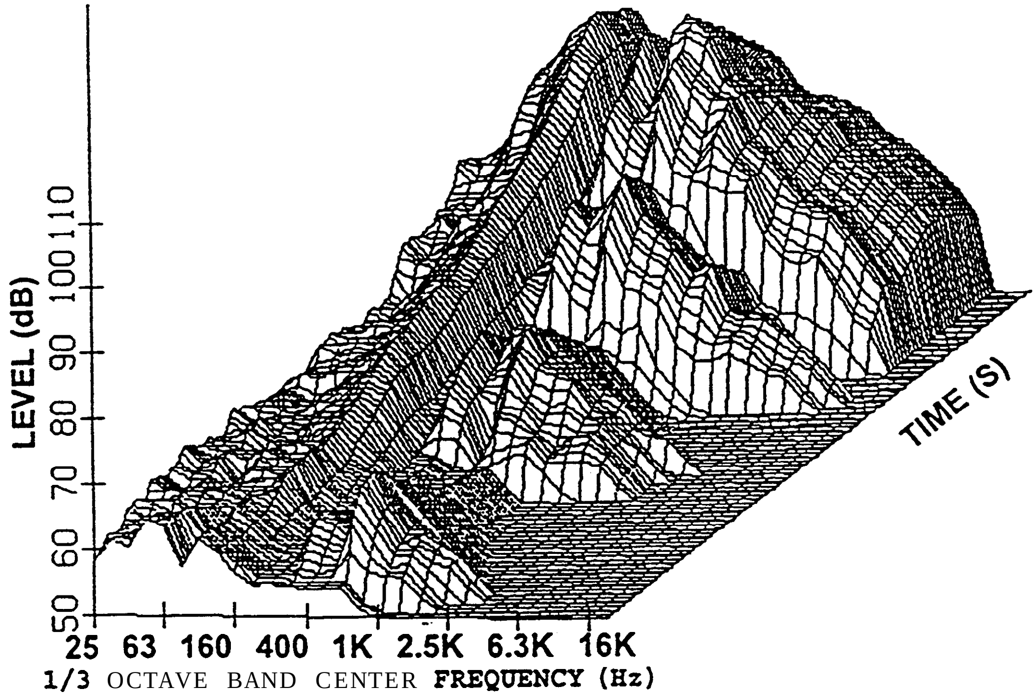


Figure B-21. **Greenland Road - Train 9**
A.) **Spectral Time** History
B.) **A-Weighted Time History**



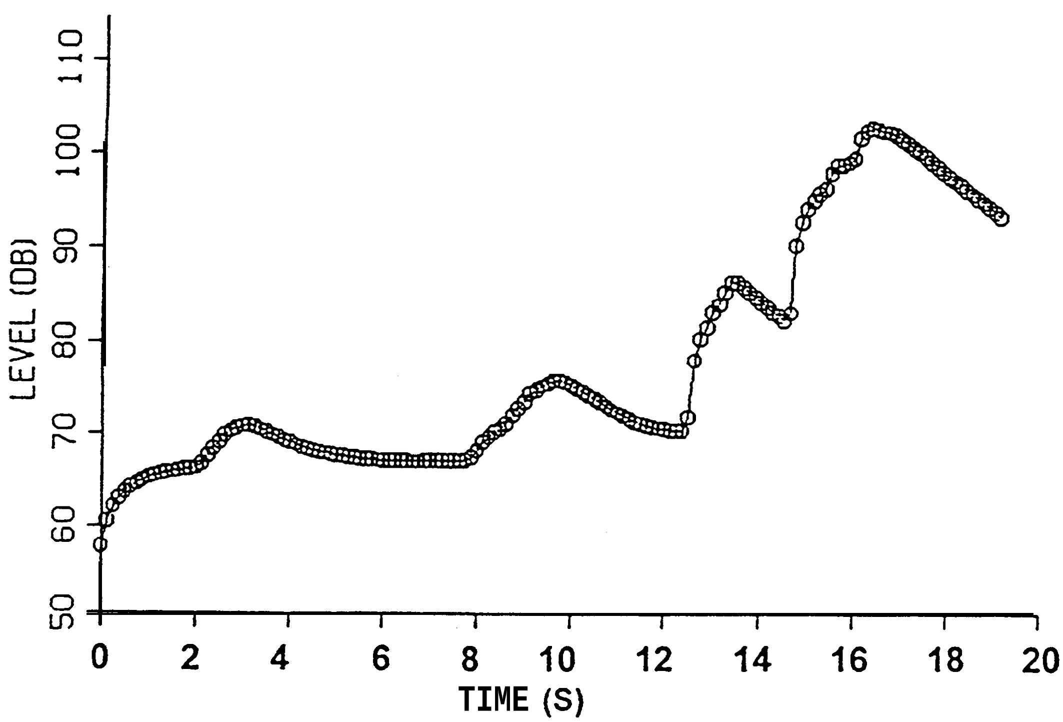
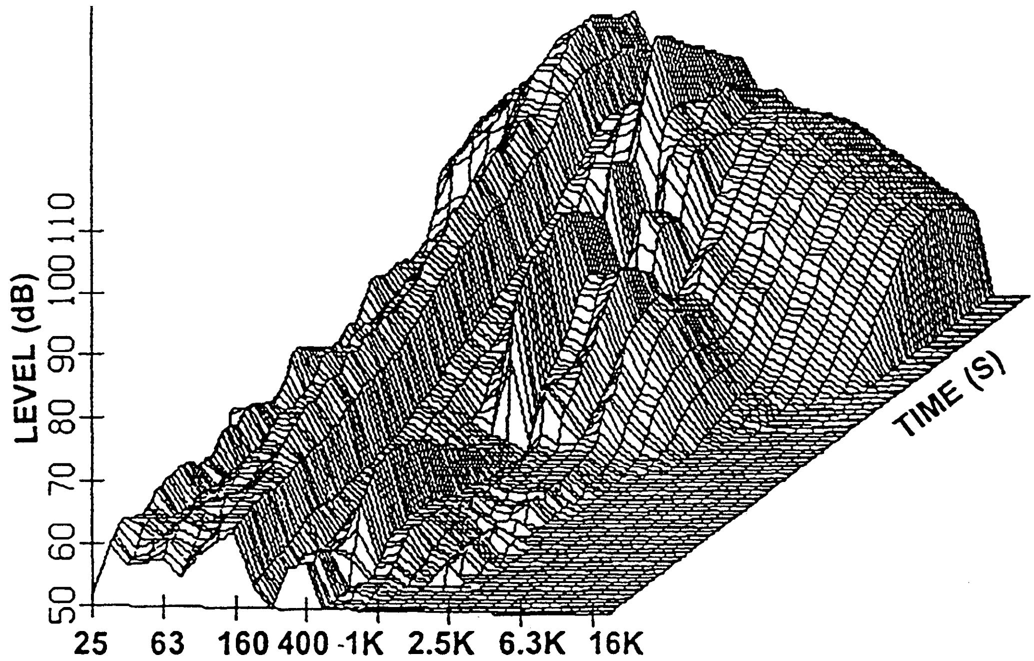


Figure B-22 **Greenland Road - Train** 10
A.) **Spectral Time History**
B.) **A-Weighted Time History**



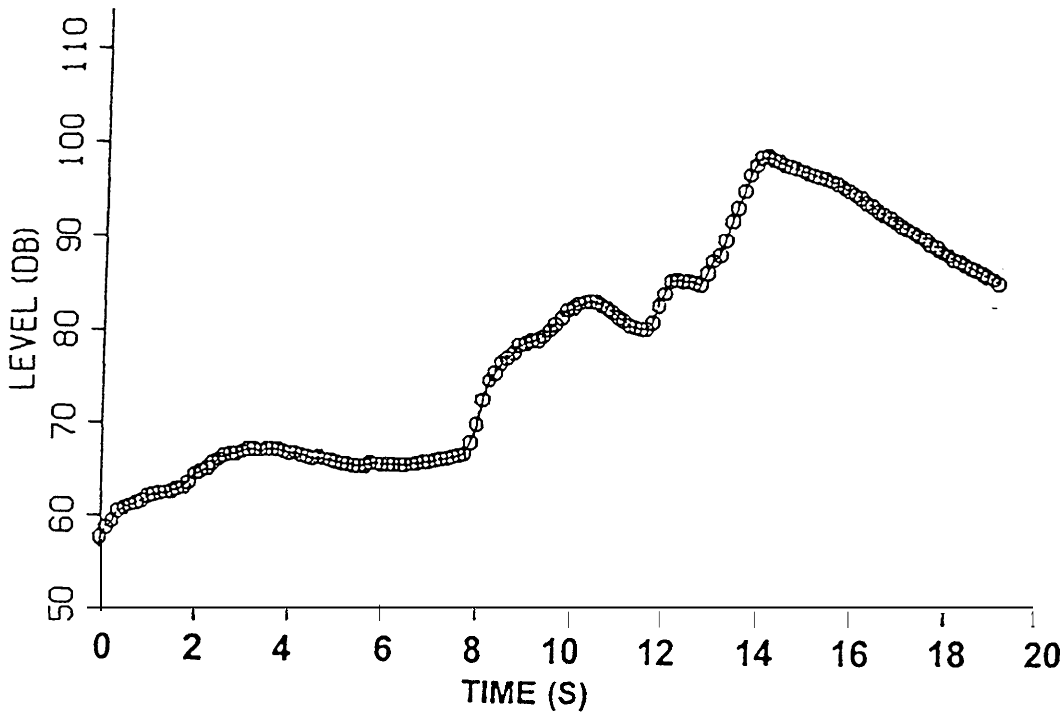
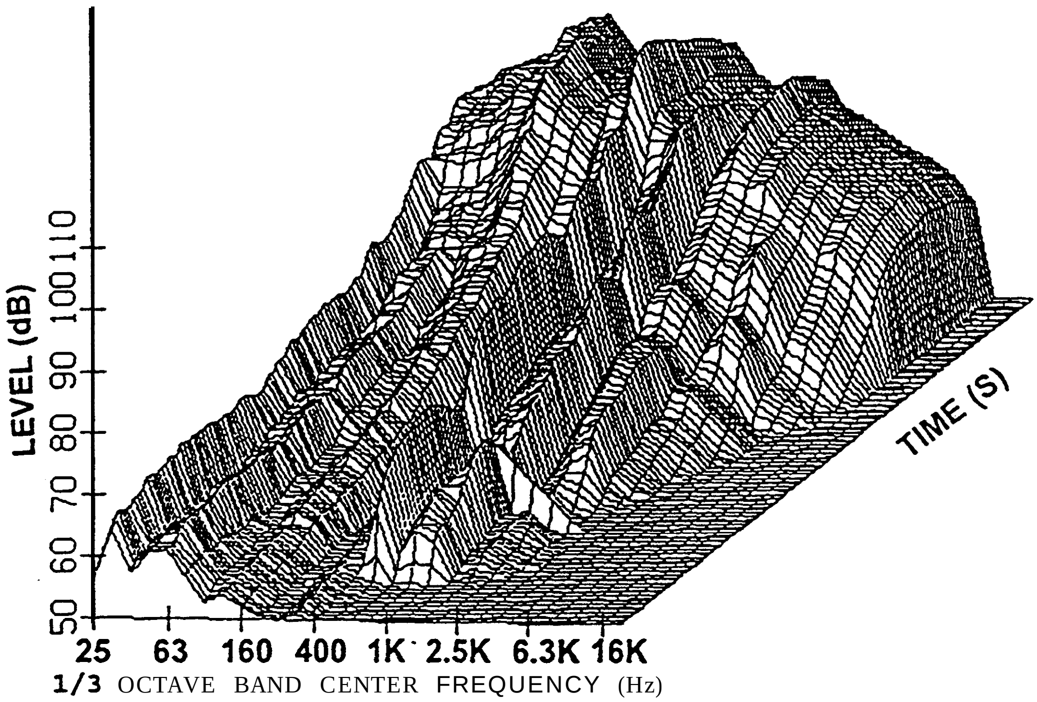


Figure B-23. **Cedar St. - Train** 11
A.) **Spectral Time History**
B.) **A-Weighted Time History**



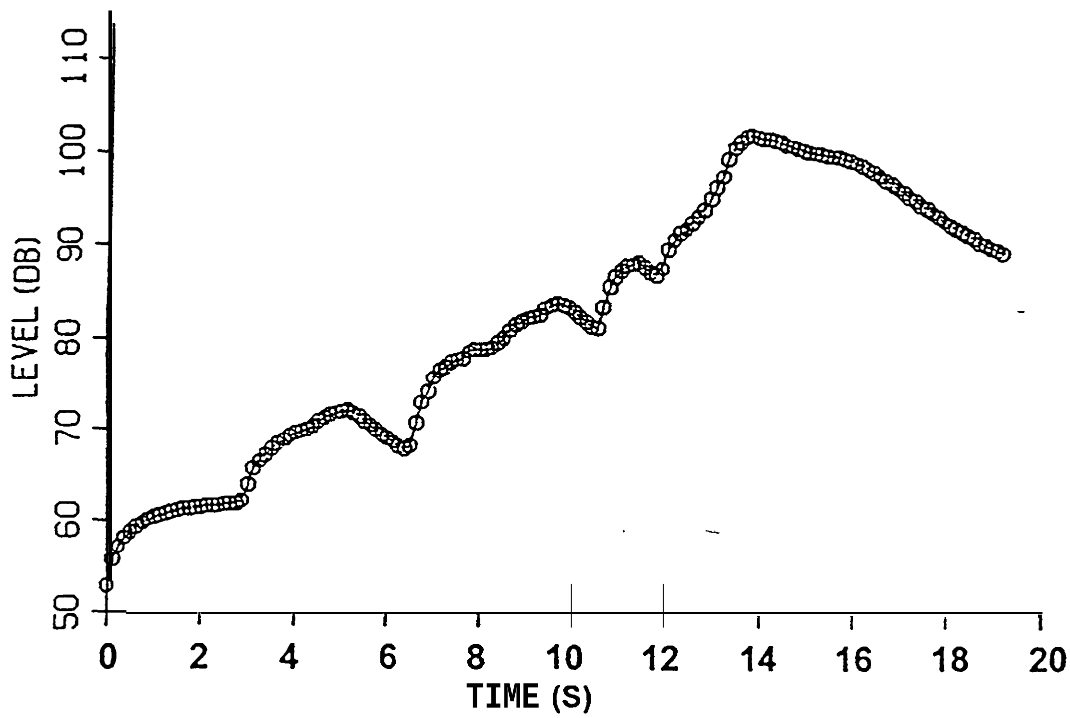


Figure B-24. Cedar St. - Train 12
A.) Spectral Time History
B.) A-Weighted Time History

APPENDIX C: ACOUSTIC CHARACTERISTICS OF AUTOMOBILES

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

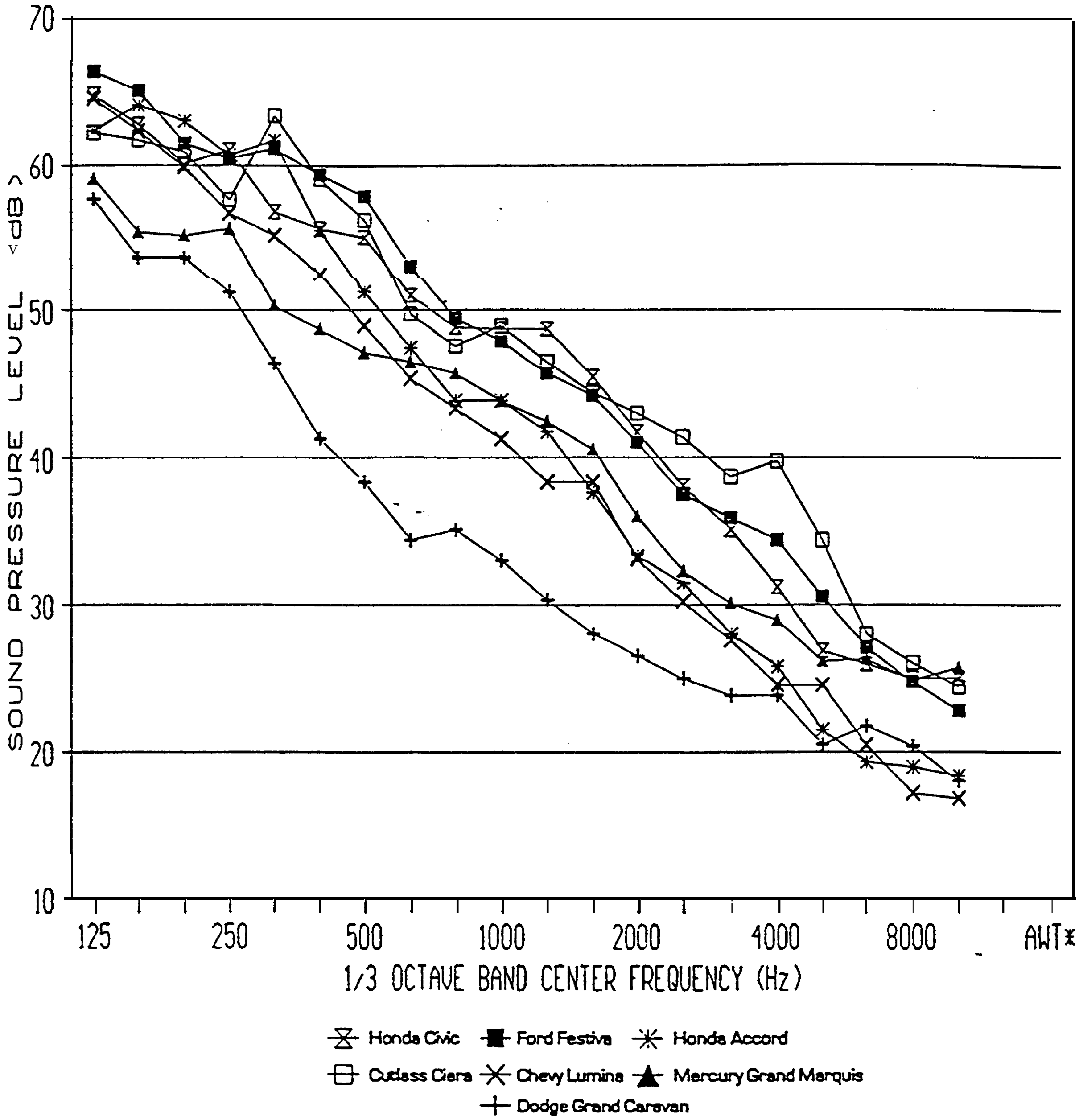


Figure C-l. Average Interior Noise Levels - 48.3 km/h

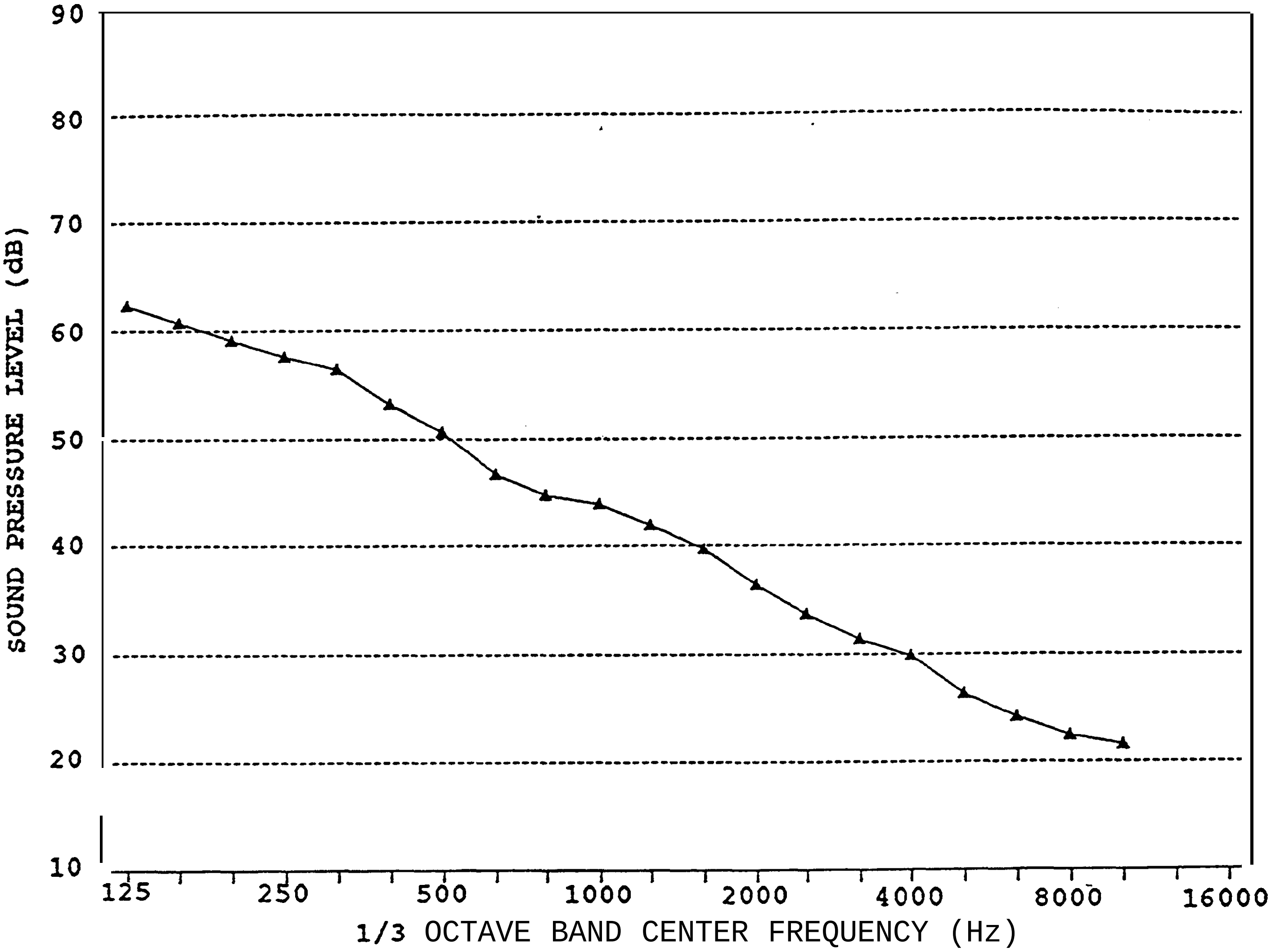


Figure C-2. Representative Interior Noise Level - 48.3 km/h
(Average of Seven Vehicles Tested)

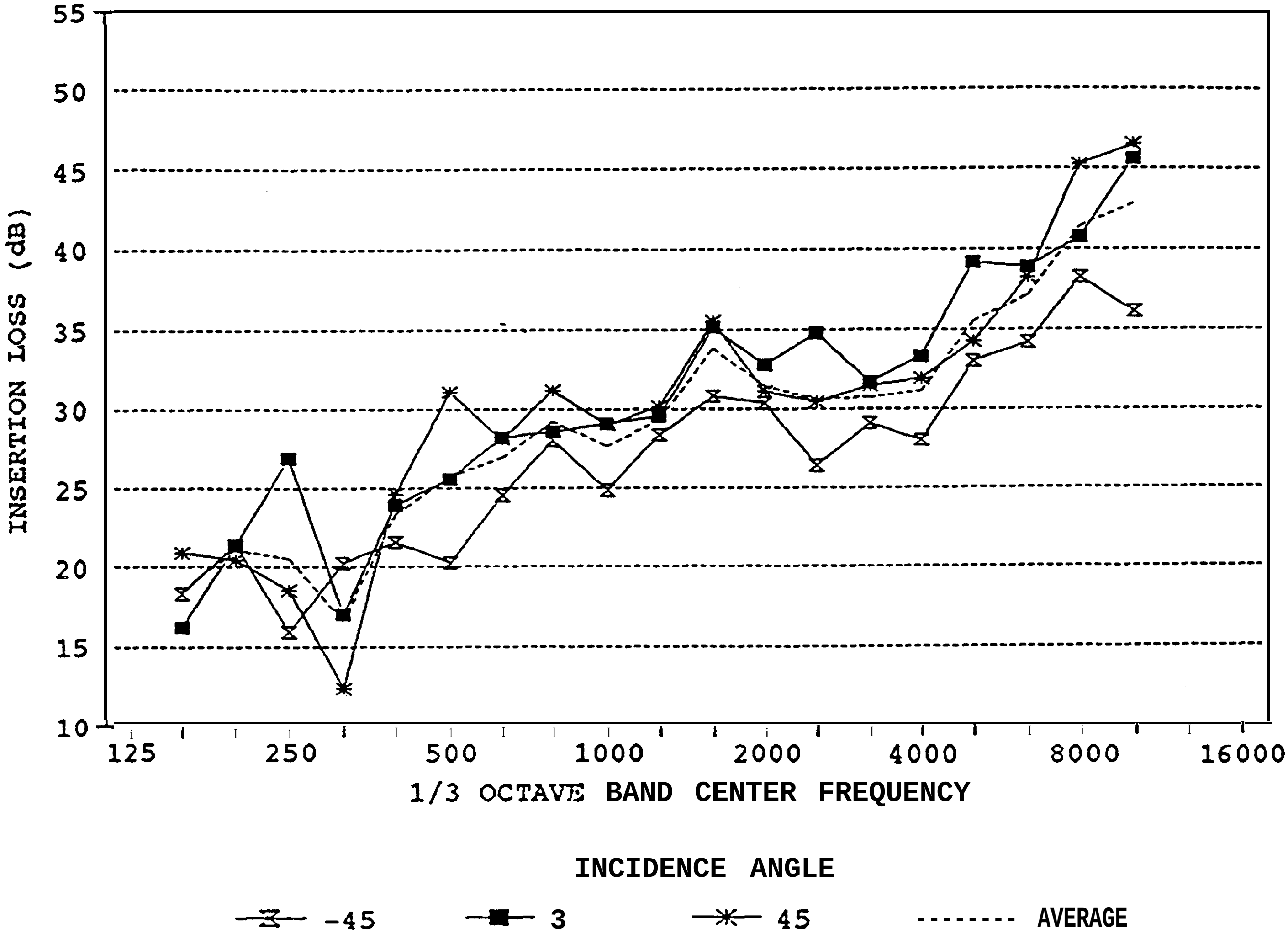


Figure C-3. Insertion Loss
1990 Honda Civic

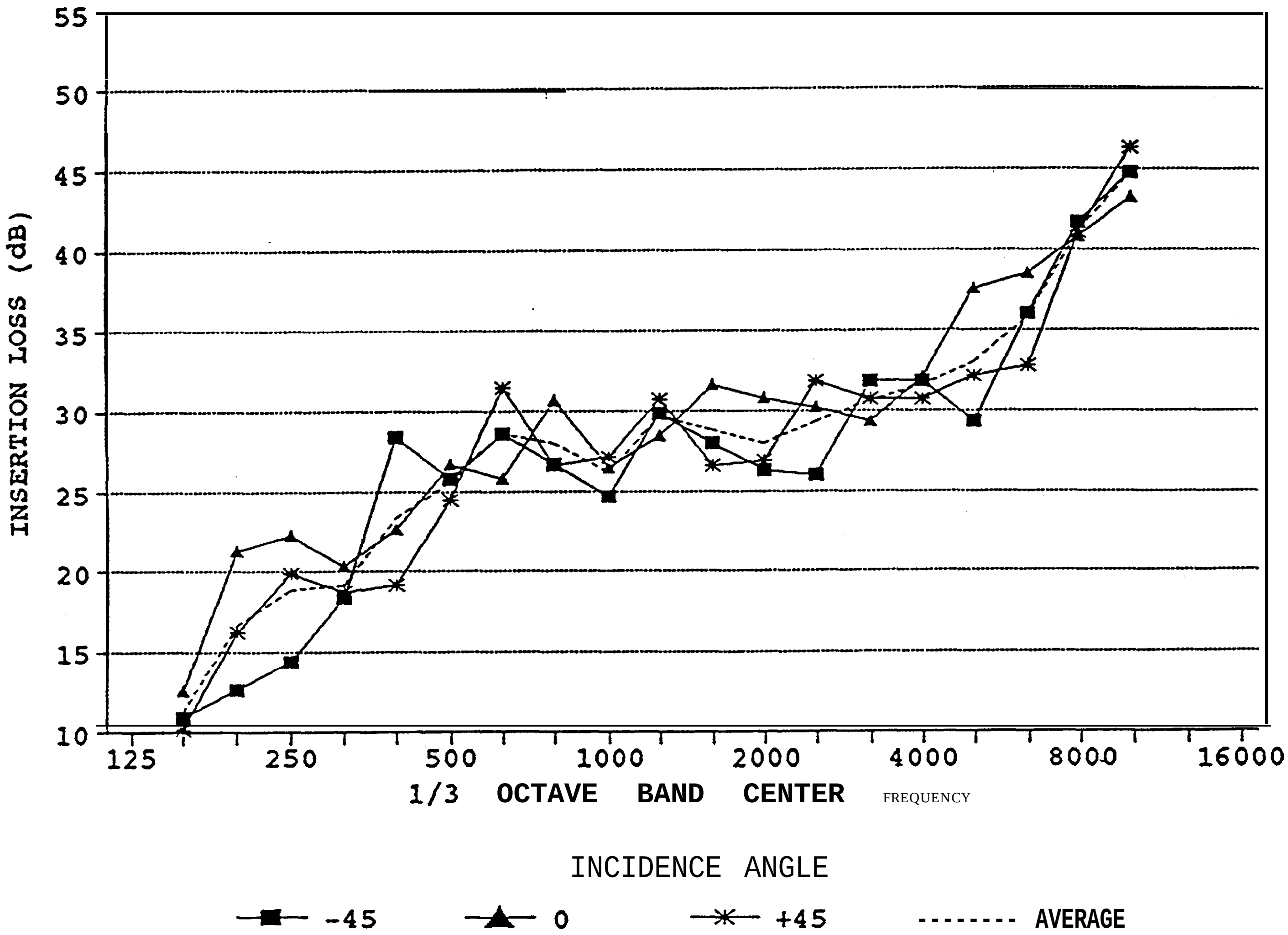


Figure C-4. Insertion Loss
1991 Ford Festiva

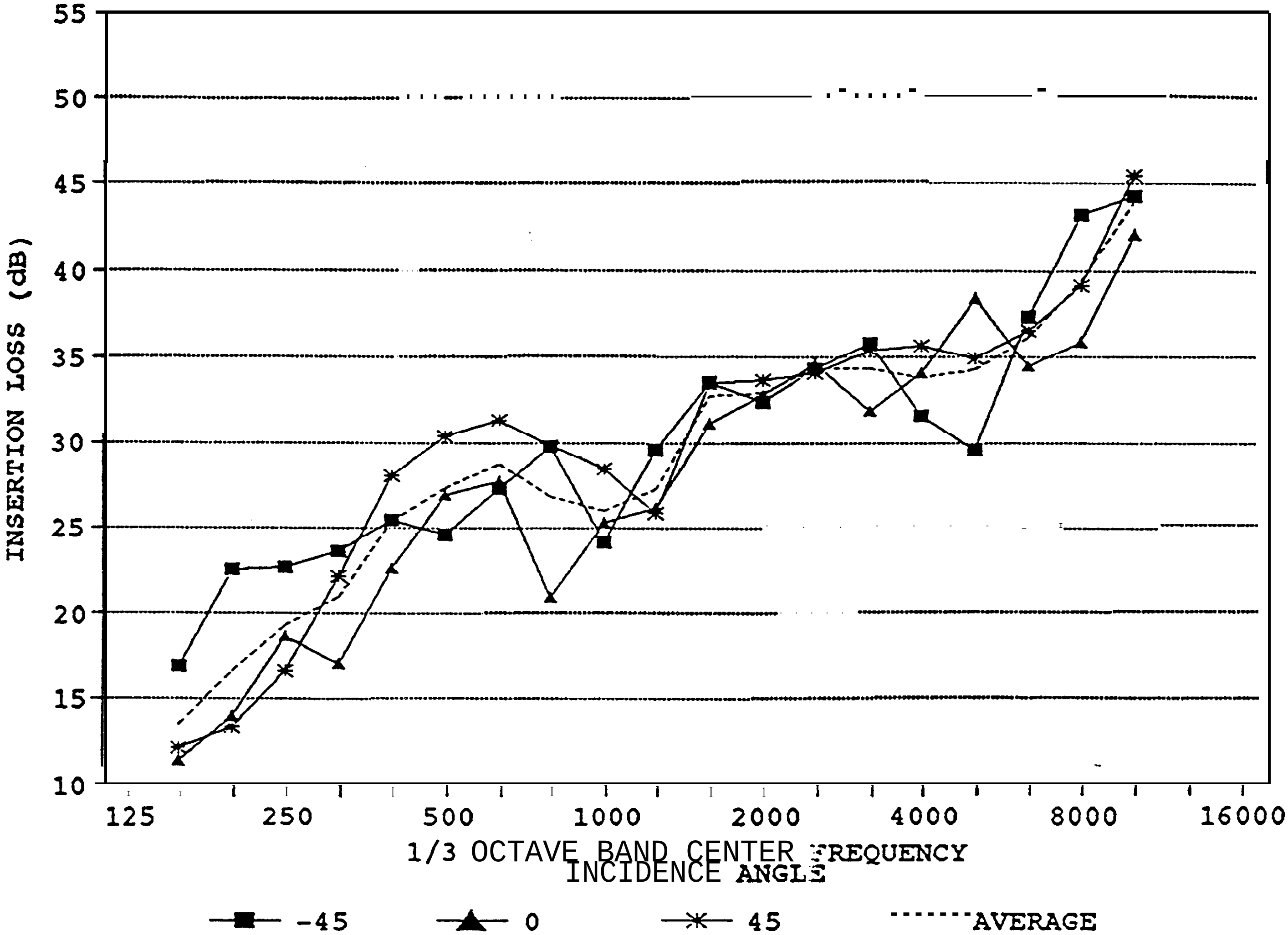


Figure C-5. Insertion Loss
1991 Honda Accord

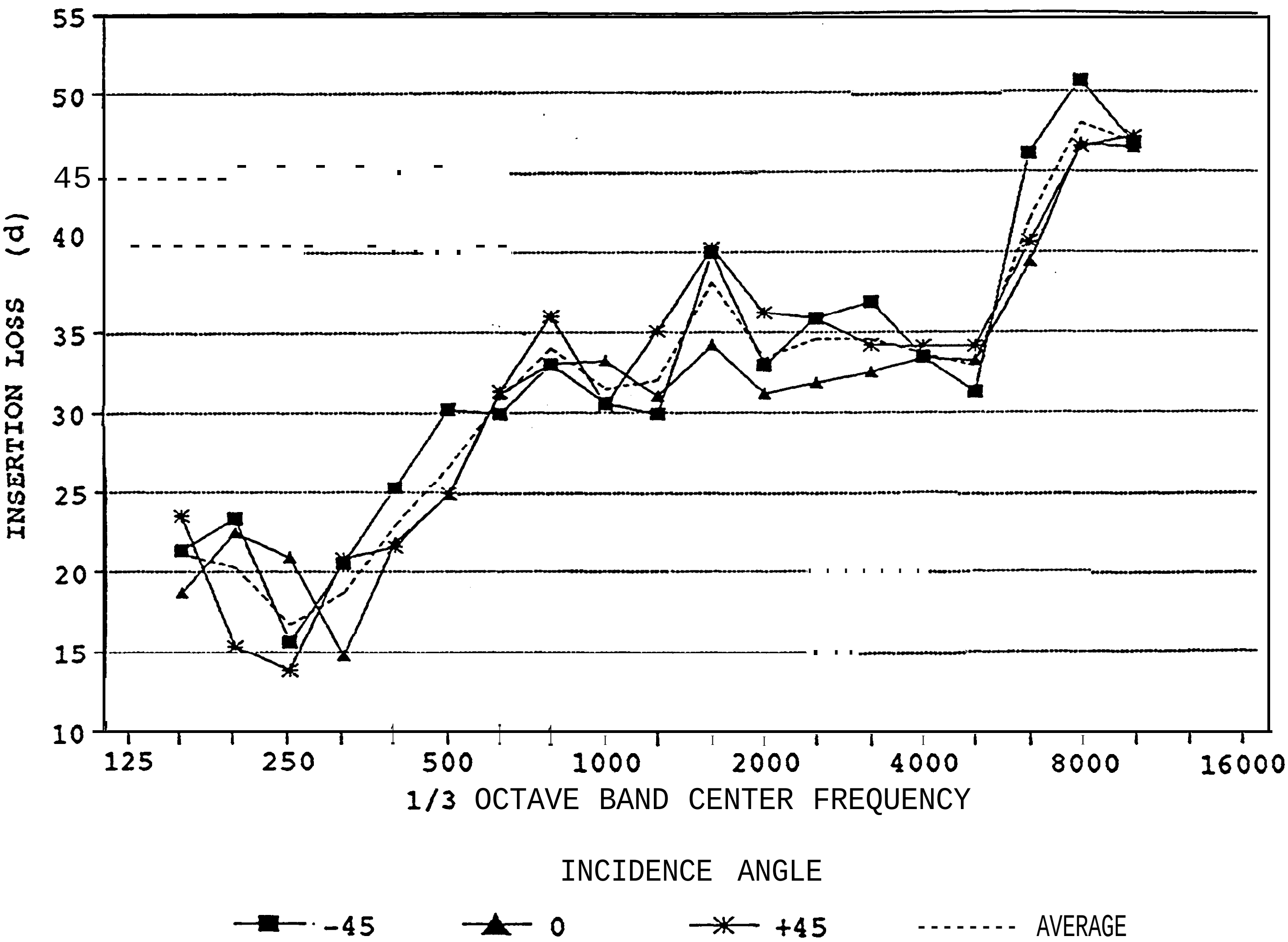


Figure C-6. Insertion Loss
1991 Cutlass Ciera

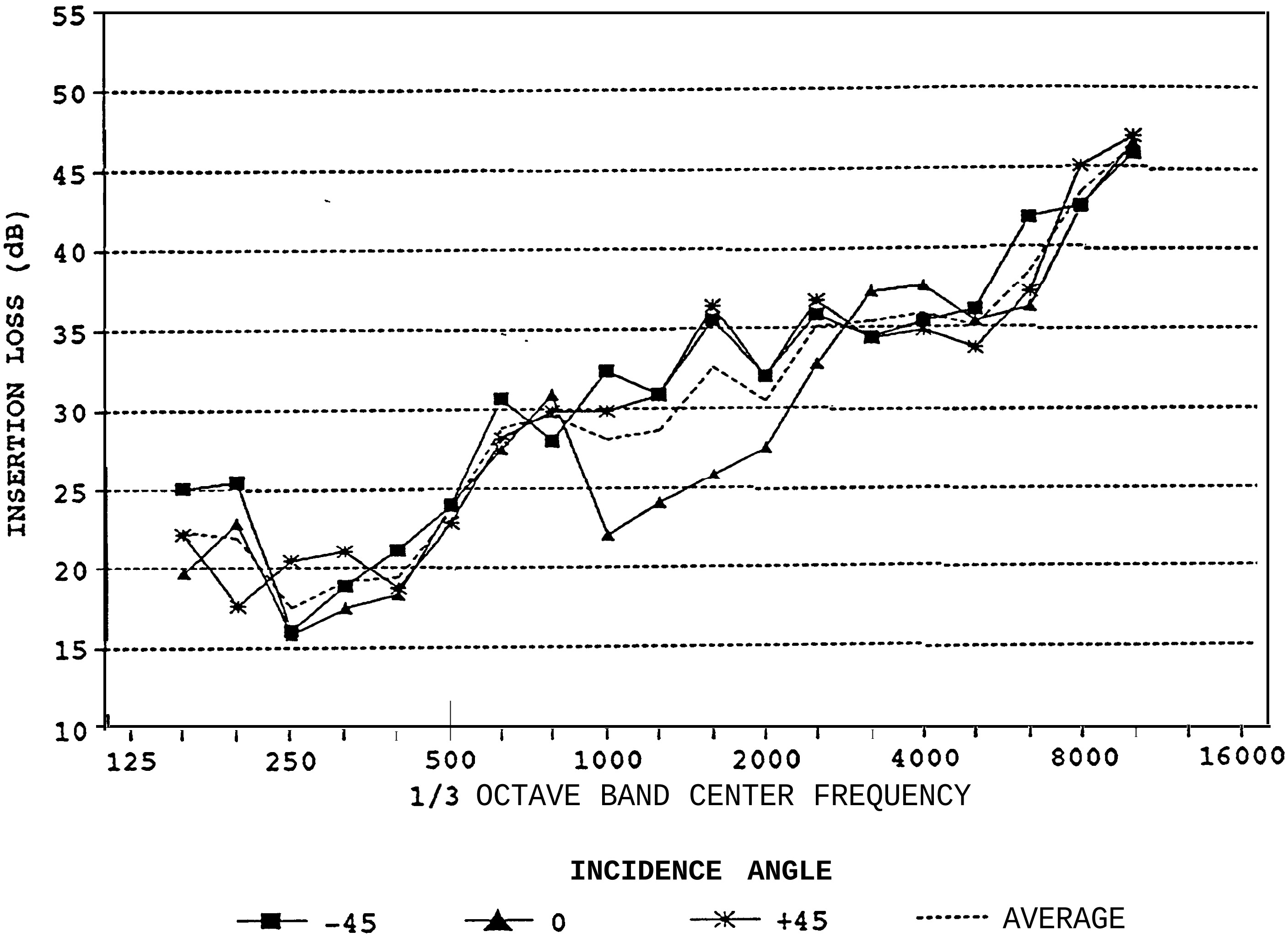


Figure C-7. **Insertion Loss**
1991 **Chevrolet** Lumina

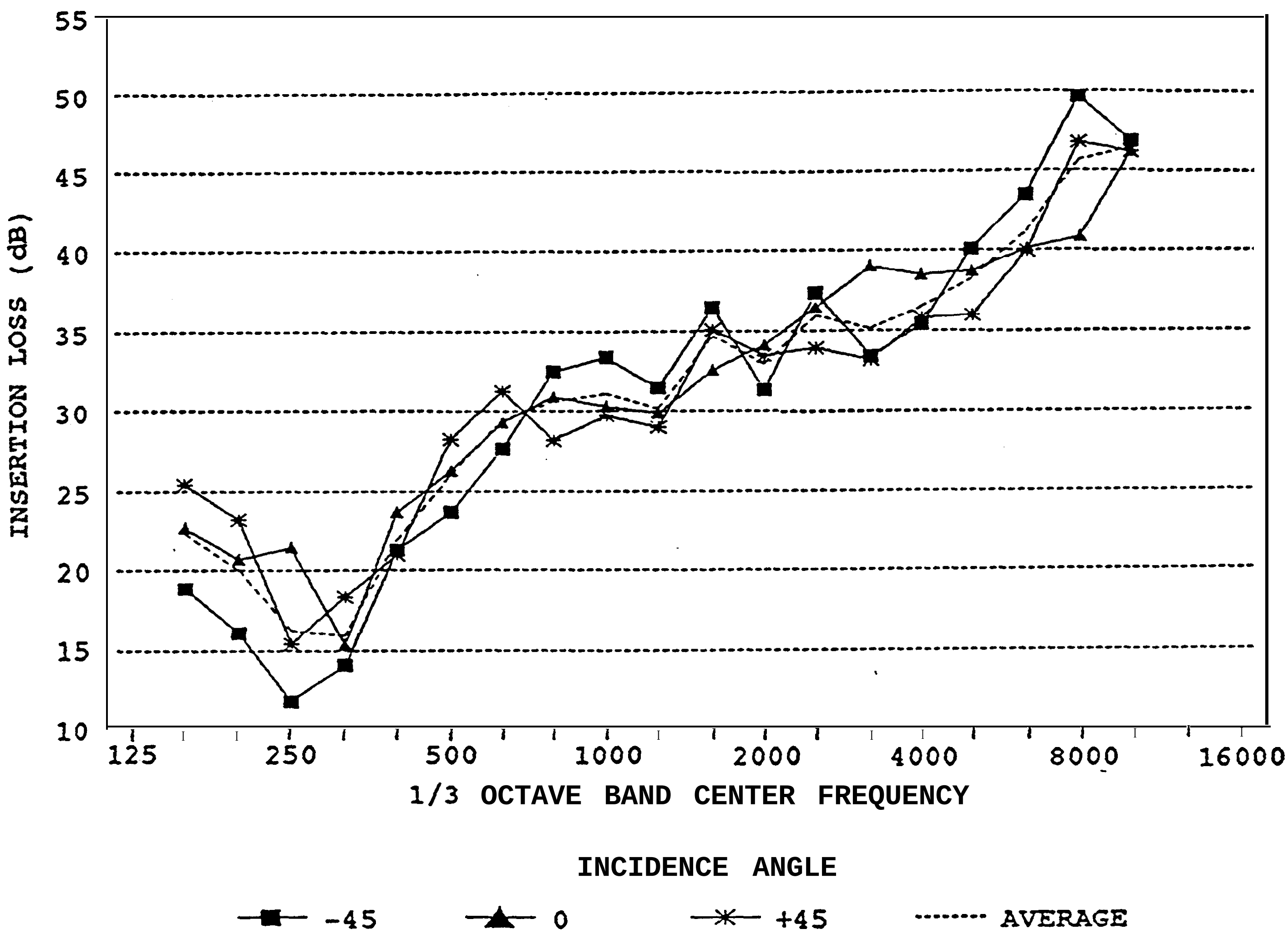


Figure C-8. Insertion Loss
1991 Mercury Grand Marquis

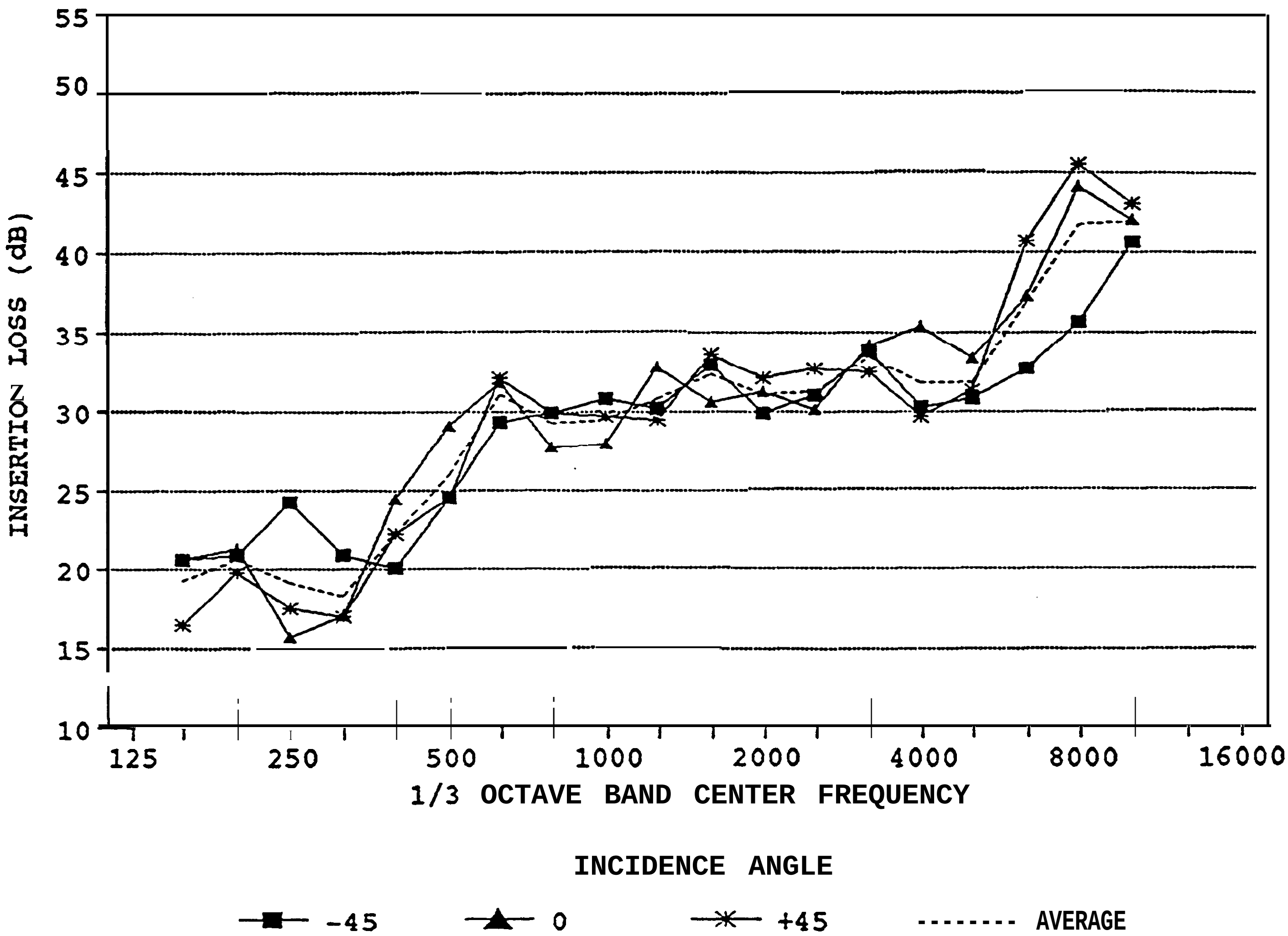


Figure C-9. Insertion Loss
1991 Dodge Grand Caravan

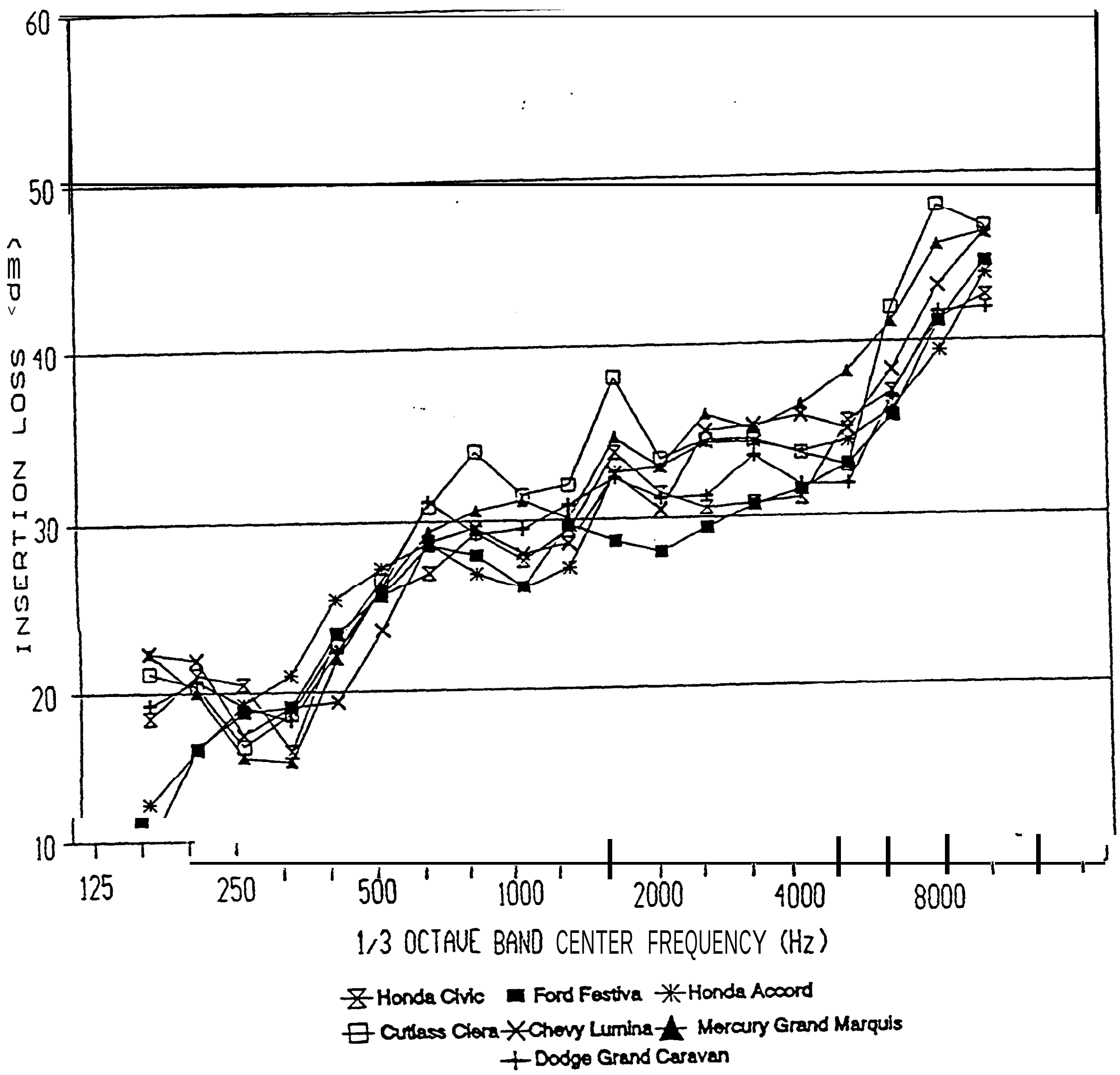


Figure C-10. Average Insertion Loss

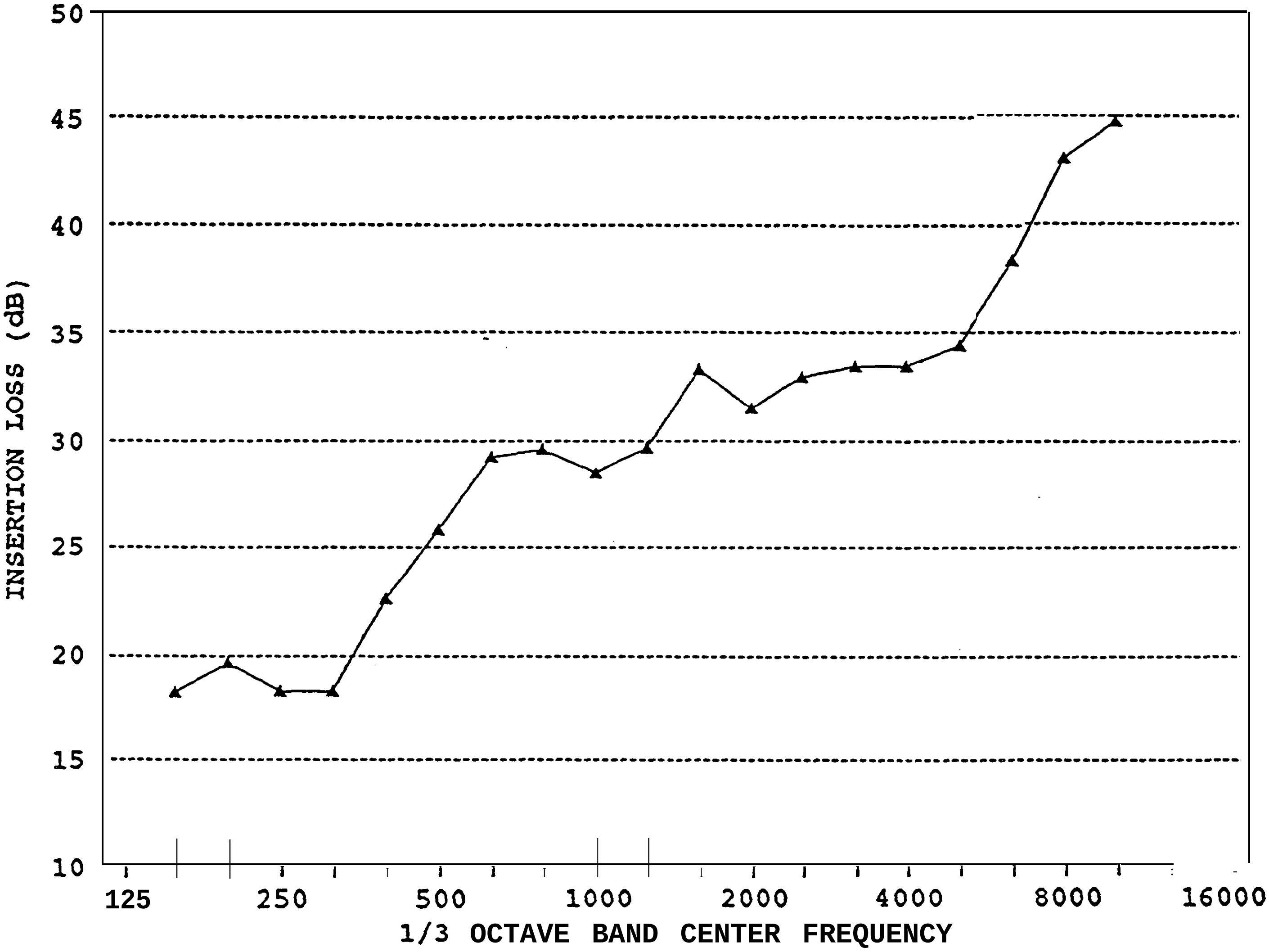


Figure C-11. Representative Insertion Loss
(Average of Seven Vehicles Tested)

APPENDIX D: SIGNAL DETECTION THEORY

This appendix contains a detailed description of the signal detection theory used to determine the probability of detection of a railroad horn system.

HORN DETECTABILITY

Train horn detectability is defined as the probability that a person with normal hearing will hear (detect) the horn. Detectability can have values from zero to one. Absolute auditory thresholds are often set at a detectability = 0.5. Difference thresholds (similar to what we have in the present case) are often set at an effectiveness = 0.75.

The perceived frequency of trains is like a probability and varies between 0 and 1. Most people overestimate low probability events and underestimate high probability events. Consequently, the real range of perceived probabilities is smaller than that which is physically possible. This fact can be used to set an upper-and lower limit on the expectation of trains at active and passive crossings.

The probability of hearing a horn is also the probability of a Hit [p(Hit)] in Signal Detection Theory (SDT). The measure of detectability in SDT is d' which is defined as

$$d' = z(Hit) - z(FA), \qquad (1)$$

where z(Hit) is the normalized value of p(Hit) and can be obtained from tables of the normal distribution. z(FA) is the normalized value of p(FA), the probability of a false alarm. An alternative definition of d' is

$$d' = \eta\ S/N, \qquad (2)$$

were η is approximately 0.4. η is a parameter which relates the performance of an ideal observer to a human observer. The ideal observer bases detection on the value of S/N, which the human observer does less efficiently. Equations 1 and 2 allow us to relate detectability to S/N, if the value of p(FA) is known.

The perceived frequency of trains allows a determination of bias, β, from which the value of p(FA) can be derived. In the absence of other costs and benefits, β is defined as

$$\beta = \frac{p(N)}{p(S)}, \qquad (3)$$

where p(S) is the probability of a train and p(N) = 1 - p(S). β is also calculated as the ratio of the ordinates of the standard normal curve corresponding to z(Hit) and z(FA):

$$\beta = \frac{y_{Hit}}{y_{FA}}, \qquad (4)$$

where y_{Hit} is

$$y_{Hit}=\frac{1}{\sqrt{2\pi}}e^{\frac{-z(Hit)^2}{2}}, \qquad (5)$$

and y_{FA} is similarly defined. Rearrangement of equations 4 and 5 yields:

$$z(FA)=\sqrt{2\ln\beta+z(Hit)^2}. \qquad (6)$$

β is determined by p(S), and z(Hit) is set at a predetermined level, so equation 6 can be solved for z(FA).

The following figure shows the range of values that S/N can have given selected values of p(S) and p(Hit). The parameter which varies between 0.1 and 0.9 is perceived train probability [p(S)]. At a 95% level of detectability S/N varies between 11 dB for low expectation of a train [p(S) = 0.1] to 1 dB for high expectation of a train [p(S) = 0.9].

HORN EFFECTIVENESS

Horn effectiveness is defined as the ability of the horn to reduce accidents. In applying signal detection theory here, the entire train is considered to be the "signal." An accident occurs when the train is present and the motorist fails to stop. In the jargon of signal detection theory this is a Miss. The complement of a Miss is a Hit (signal detected, as indicated by the motorist stopping, when the signal is present). The probability of a Hit, p(Hit), is 1- p(Miss) = 1- p(accident). The probability of an accident is determined by the number of accidents at the type. of crossing, the number of crossings of that type, the number of vehicles per unit time that use crossings of that type, and the number of trains per unit time that use crossings of that type. The probability of a False Alarm, p(FA), stopping when the train is not present, is estimated from the product of the probability that a car will be in the crossing [p(car)] and the probability that a train will be in the crossing [p(train)]. This is because the maximum probability of an accident is also p(car)*p(train), which is the risk of an accident. Stopping when no train is present is due to perceived risk.

Given p(Hit) and p(FA), z(Hit) and z(FA) can be determined, and d' and S/N are obtained from equations (1) and (2). β is calculated from equation (4). For a given change in accidents when horns are banned, p(Hit) is recalculated and equation (6) is used to determine z(FA). The new values of d' and S/N are obtained from equations (1) and (2).

Given the S/N of the train with and without a horn, the S/N of the horn can be determined if it is assumed that the horn's S/N is independent of the tram's S/N. Under these circumstances, if A is the S/N of the train with a horn, B is the S/N of the train without a horn and C is the change in S/N due to the horn, then

$$A^2 = B^2 + C^2. \qquad (7)$$

The addition of orthogonal (independent) elements of variance follows the same rule. The use of equation (7) to determine the change in S/N of the horn seems reasonable, and is supported by the literature on multidimensional scaling (e.g., Young, 1987).

Given the change of S/N of the horn, the decrease in accidents (effectiveness) can then be related to the detectability of the horn.

APPENDIX E: EXAMPLE CALCULATION

This appendix contains a detailed description of the calculation methodology used to determine the probability of detection of a railroad horn system.

Example calculation

A motorist is approaching a passive grade crossing (perceived train frequency probability = 0.1) at 30 mph. A locomotive is approaching the grade crossing at 50 mph. The locomotive is equipped with a Leslie RSL-3L-RF. From Table 4, the minimum required warning distance for this example is 471 ft.

1.) From Reference 4, the signal level at 200 ft for the Leslie RSL-3L-RF is as follows:

Freq (Hz)	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	6300	8000	10000
	61.04	60.83	80.39	85.09	81.75	84.72	87.62	88.80	84.65	81.78	79.62	79.89	76.22	71.61	67.41	63.18	59.12	55.24	51.47

2.) The signal level at 471 ft is calculated using a drop-off rate of 7.5 dB per distance doubling (25log(200/471)).

Freq (Hz)	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	6300	8000	10000
	51.74	51.53	71.09	75.79	72.45	75.42	78.32	79.5	75.35	72.48	70.32	70.59	66.92	62.31	58.11	53.88	49.82	45.94	42.17

3.) . The signal level inside the car at 47 1 ft is calculated by subtracting the average insertion loss (Figure C-11) from the above level.

Freq (Hz)	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	6300	8000	10000
	39.58	36.94	56.83	60.44	51.96	51.07	50.14	50.21	46.88	42.61	36.49	38.53	33.19	28.31	24.06	19.01	11.54	3.36	-1.62

4.) The average interior noise level is obtained from Figure C-2.

Freq (Hz)	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	6300	8000	10000
	60.69	59.15	57.60	56.41	53.17	50.67	46.81	44.81	43.92	41.97	39.82	36.42	33.76	31.34	29.82	26.40	24.13	22.49	21.60

5.) The S/N is obtained by subtracting 4.) from 3.).C-2.

Freq (Hz)	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	6300	8000	10000
	-21.10	-22.20	-0.76	4.03	-1.21	0.40	3.33	5.39	2.96	0.65	-3.34	2.11	-0.57	-3.03	-5.76	-7.39	-12.59	-19.12	-23.22

6.) The five highest S/N ratios are highlighted. The minimum of these is 2.11 dB. From the figure in appendix D, the detection probability for a S/N ratio of 2.11 dB and an expected train probability of 0.1 is <50%.