U.S. Department of Transportation

Federal Railroad Administration

Office of Research, Development and Technology
Washington, DC 20590

Acoustical Warning Devices as Emergency Warning Systems, Phase 1

DOT/FRA/ORD-19/40

Final Report | October 2019

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	October 2019	Technical Report

4. TITLE AND SUBTITLE
Acoustical Warning Devices as Emergency Warning Systems, Phase 1

5. FUNDING NUMBERS
DTFR53-12-D-00003
Task Order 005

6. AUTHOR(S)
Tom Campbell*, Basant Parida, Ph. D.*, Jason Ross**, and Bud Zaouk, D. Sc.*

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
*Foster-Miller, Inc. d.b.a.
QinetiQ North America
360 Second Avenue77
Waltham, MA 02451-1196
**Harris Miller Miller & Hanson Inc.
South Bedford Street
Burlington, MA 01803

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Department of Transportation
Federal Railroad Administration
Office of Research, Development and Technology
Washington, DC 20590

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
DOT/FRA/ORD-19/40

11. SUPPLEMENTARY NOTES
COTR: Tarek Omar

12a. DISTRIBUTION/AVAILABILITY STATEMENT
This document is available to the public through the FRA eLibrary.

12b. DISTRIBUTION CODE

13. ABSTRACT
This program demonstrated the effectiveness of Acoustical Warning Devices (AWD) as secondary Emergency Warning Signals (EWS). The focus is to warn trespassers of an approaching train, through the development of an emergency warning signals that produce a sense of urgency, are noticeable to trespassers wearing headphones, and uniquely identifiable as train warning signals. Several EWS sounds were developed and evaluated in surveys to assess the participant's view of the sense of urgency and detectability. Sounds characteristics were identified that enhance detectability.

14. SUBJECT TERMS
Emergency warning, train horn, trespassers, music masking sounds, reaction time, Acoustic Warning Device

15. NUMBER OF PAGES
55

16. PRICE CODE

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

NSN 7540-01-280-5500

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

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 (he)	=	4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz)	=	28 grams (gm)
1 pound (lb)	=	0.45 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)

[(x-32)(5/9)] °F = y °C

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

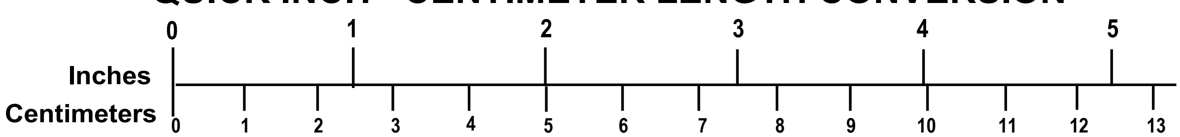
VOLUME (APPROXIMATE)

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)

[(9/5) y + 32] °C = x °F

QUICK INCH - CENTIMETER LENGTH CONVERSION



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. C13 10286

Updated 6/17/98

Contents

Figures

Tables

Executive Summary

QinetiQ North America (QNA) and Harris Miller Miller & Hanson Inc. (HMMH) have completed Phase 1of the Acoustical Warning Device as a Secondary Emergency Warning Signal (EWS) program. This program designed and tested a new on-board locomotive emergency warning signal which would be more effective at alerting trespassers and roadway workers of approaching trains. This study has been conducted under QNA contract DTFRA-12-D-00003 with the Federal Railroad Administration (FRA).

Train horns have not always been able to warn trespassers on the railroad right-of-way, especially when they are wearing earbuds or headphones. A parallel study is underway for developing directive electric speakers as an Acoustical Warning Device (AWD) that would replace train horns. These AWD systems could be used as Emergency Warning Signals (EWS) that employ specially designed sounds to maximize detectability and provide sufficient warning for trespassers to vacate the tracks.

Phase 1 of the program developed candidate EWS sounds and the initial factors determining detectability while wearing the latest listening devices. Finally, the local Institutional Review Board determined that the project's human subject tests met Department of Health and Human Services regulations.

1. Introduction

This program demonstrated the effectiveness of Acoustical Warning Devices (AWD) as secondary Emergency Warning Signals (EWS). The focus is in warning trespassers of an approaching train, through development of emergency warning signals that produce a sense of urgency, are noticeable to trespassers wearing headphones, and that are identifiable as a train signals.

Fortunately, the number of accidents and fatalities of highway-rail grade crossings has decreased by almost 46 percent in the last decade. However, there were 459 fatalities and 413 injuries in the United Stated from trespassers away from the highway-rail crossing on the railroads in 2015 Federal Railroad Administration Office of Safety). To understand the role that headphone use by pedestrians has played in train-pedestrian accidents, a recent study analyzed injury data between 2004 and 2011 (Lichenstein et al., 2012), and there were 116 reports of death or injury to pedestrians wearing headphones. Approximately 74% of train-related case reports stated that the victim was wearing headphones at the time of the crash. The study also found that approximately one-third of the injury cases mentioned that a warning was sounded before the crash.

In order to reduce trespassing fatalities, a secondary EWS could supplement the standard train horn. This enhanced EWS must be capable of alerting trespassers with headphones, or ear buds, that a train is within a mile and approaching. The development of electric AWDs with high amplitude output and a directive sound pattern offer the potential for customized EWS sounds that cannot be produced with standard train horns.

2. Literature Review of Emergency Warning Signals

A literature review was conducted by the project to investigate the following topics:

- The need for developing a new effective on-board locomotive EWS, regulations and standards relating existing EWSs
- Descriptions and audible demonstrations of the most commonly used EWSs on emergency response vehicles
- Fundamentals of human hearing and psychoacoustics
- The noise reducing and masking effects of headphones
- The range of sound levels that people typically listen to music with headphones
- Methods that can be used to measure in-ear sound levels
- Existing research into the design and assessment of the effectiveness of EWSs, and
- Recommendations for the design of a new on-board locomotive EWS.

2.1 Need for a New Locomotive Emergency Warning Signal

The history of the train horn begins with the original "steam trumpet" that was built for steam locomotives in 1832 by the Leicester and Swannington Railway, and evolved into modern-day two, three, four and five chime air-pressure horns. Locomotive horns have historically been designed to produce three or five distinct musical notes which together form a chord. For example, the Nathan K-5-LA generates $D^{\#}_4$, $F^{\#}_4$, $G^{\#}_4$, B_4 and $D^{\#}_5$ notes which is a "G-sharp minor 7" chord. While the chord and the timbre that train horns produce has the distinct sound identified as a train, it may not be the most effective method for alerting railroad trespassers and railroad workers when danger is imminent. Train horns rely primarily on their high amplitude and low-frequency tonal content for humans to detect the presence of trains.

The public is very familiar with the sounds of sirens on ambulances, fire engines and police cars, and the sirens attract attention from pedestrians and motorists. Some trains, such as light rail and heavy rail trains, have several different audible warning devices, including bells, gongs, low horns, and high horns. However, standard air-pressure train horns on FRA-compliant trains can only generate a single sound and cannot reproduce dynamic sounds such as sirens. In contrast, electronic acoustic sources, such as loudspeakers, can reproduce any sound, and if they are used on locomotives, an effective EWS could better alert railroad trespassers and railroad workers of oncoming trains and save lives.

Though the number of incidents, accidents and fatalities of highway-rail grade crossings has decreased in recent years, there were 459 fatalities and 413 injuries in the United Stated from trespassers away from the highway-rail crossing on the railroads in 2015 (Federal Railroad Administration Office of Safety). A recent study which analyzed how headphone use by pedestrians has contributed to train-pedestrian accidents from 2004–2011 (Lichenstein et al., 2012) discovered that:

- 116 pedestrians wearing headphones were killed or suffered injuries during the period
- 74% of case reports involving trains stated that the victim was wearing headphones at the time of the crash

- Approximately one-third of the injury cases mentioned that a warning was sounded before the crash

The study concluded that further research is needed to determine if and how headphone use compromises pedestrian safety.

The Los Angeles Metro Blue Line has had to deal with many pedestrian accidents and suicides. Since opening in 1990, the line has been linked to 101 fatalities. The line travels mostly at street level through 103 crossings, and some of the Blue Line's accidents involve pedestrians wearing ear buds and headphones (Nguyen, 2010). It is critical that a locomotive's EWS alert all pedestrians, including those who are listening to music with headphones.

2.2 Existing Emergency Warning Signals

This section summarizes a few of the regulations and standards relating to EWSs. The current on-board locomotive EWS (standard air pressure horn) and the most common signals used on emergency response vehicles are presented along with the ability to present audio samples.

2.2.1 Emergency Response Vehicles

States typically regulate requirements for sirens on emergency vehicles, including their use, their mounting location and their sound emissions (CAC Title 13, Article 8). Audible warning devices on emergency response vehicles, including police, fire and ambulances, are usually required to meet acoustical requirements in the Society of Automotive Engineers standard J1849:201210 (SAE, Wagner, GSA, CCR, NFPA). This SAE standard includes laboratory test procedures, requirements and guidelines for electronic siren systems with a single loudspeaker, and electromechanical sirens for use on authorized emergency vehicles. The SAE standard specifies that warning devices must generate the following signals:

- The Wail EWS has sound bursts cycle at a rate between 10 and 30 times per minute (e.g. every 2 to 6 seconds). Each sound burst varies in frequency and in amplitude. Each sound burst spans a frequency range of at least 850 Hz with a minimum allowable fundamental frequency of 650 Hz and a maximum allowable fundamental frequency of 2000 Hz.
- The Yelp EWS has sound bursts cycle at a rate between 150 and 250 times per minute (e.g. every 0.24 to 0.4 seconds). Each sound burst varies in frequency and in amplitude. Each sound burst spans a frequency range of at least 850 Hz with a minimum allowable fundamental frequency of 650 Hz and a maximum allowable fundamental frequency of 2000 Hz.
- The sound bursts of the Wail and Yelp devices must generate amplitude no less than 111 dBA at its minimum and no less than 118 dBA at its maximum. The GSA specification for ambulances requires sirens to be capable of generating a continuous warning sound of at least 123 dBA (fast detection) at 10 feet (3 m) from the device for Wail and 122 dBA (fast) for Yelp (GSA).
- The air horn is a combination of tones based on a fundamental frequency of 65 Hz and overtones (e.g. 130, 195, 260, etc.) up to approximately 10,000 Hz. The air horn is typically reproduced in a series of manually controlled sound bursts each one to two seconds in duration.

- The Rumbler is a low-frequency pulsating signal. The sound includes a series of tones between 150 and 450 Hz, each separated by approximately 20 Hz. The sound bursts cycle at a rate of approximately 720 times per minute (e.g. every 0.08 seconds).

2.2.2 Federal Railroad Administration-Compliant Trains

Standard locomotive horns in the United States include three and five-chime air pressure horns. Individual horns may be directed all in one direction or they may be bi-directional where some of the horns point forward and some backward. The FRA regulates the amplitude of locomotive-mounted and wayside-mounted horns (49 CFR 229.129). The regulations specify the minimum (96 dBA) and maximum (110 dBA) overall A-weighted noise levels, which is measured 100 feet forward of the locomotive. Additionally, the warning device may not be sounded beyond ¼-mile from the grade crossing and should be sounded for a total of 15 to 20 seconds, with a maximum of 25 seconds, using a long-long-short-long pattern. This long-long-short-long pattern is the Morse code for the letter 'Q' which originated in England to signify that the Queen was arriving by train. The engineer should also sound the horn until the first locomotive has passed through the crossing.

Railroad operating procedures require the locomotive engineer to sound the train horn with a "succession of short blasts" as an alarm for employees, roadway workers, other persons, or animals on or near the track (Manion, 2012).

Table 1. Summary of EWS amplitudes at 10 and 100 feet

Emergency Warning Device Standard	Maximum Sound Level at 10 feet (dBA)	Maximum Sound Level at 100 feet (dBA)
SAE J1849 (police, fire)	118 a	98 a
GSA (ambulance)	123 b	103 b
FRA minimum (train)	116 c	96 c
FRA maximum (train)	130 c	110 c

a Measured with slow-response (LAS).

b Measured with fast-response (LAF).

c Measured in equivalent sound level (Leq).

In comparison, FRA limits the maximum sound level of train horns between 96 and 110 dBA at 100 feet forward of the locomotive, while warning signals on emergency response vehicles are limited to a maximum sound level up to 98 dBA (SAE standard) and 103 dBA (General Services Administration, 2007) at 100 feet. To some extent, the higher amplitude used by train horns addresses the need for motorists and pedestrians to be warned at farther distances for trains versus automobiles due to relative stopping distances. Other reasons for this include the critical nature of potential incidents and the effectiveness of different EWSs. A more effective EWS may allow the amplitude to be reduced and improve safety.

Spectrograms of these existing EWSs are presented in Figure 1 to Figure 4 below. Spectrograms show the frequency content and amplitude of sound as a function of time. The horizontal axis is time, the vertical axis is frequency and the coloration of the figure indicates amplitude. The spectrogram and the spectrum of a train horn are shown in Figure 5.

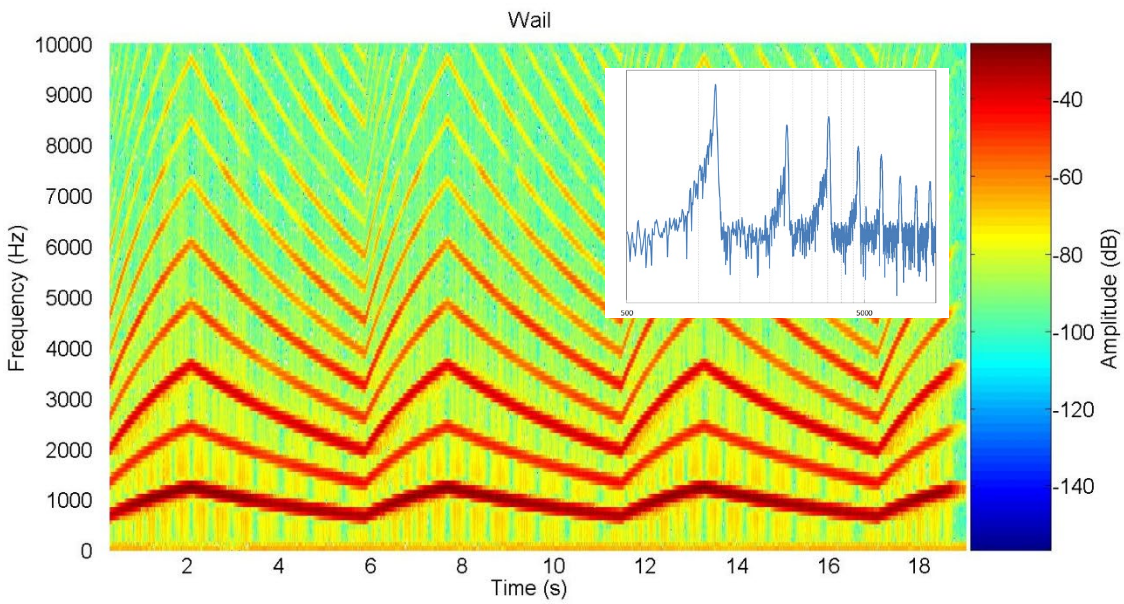


Figure 1. Wail Spectrogram and Spectrum

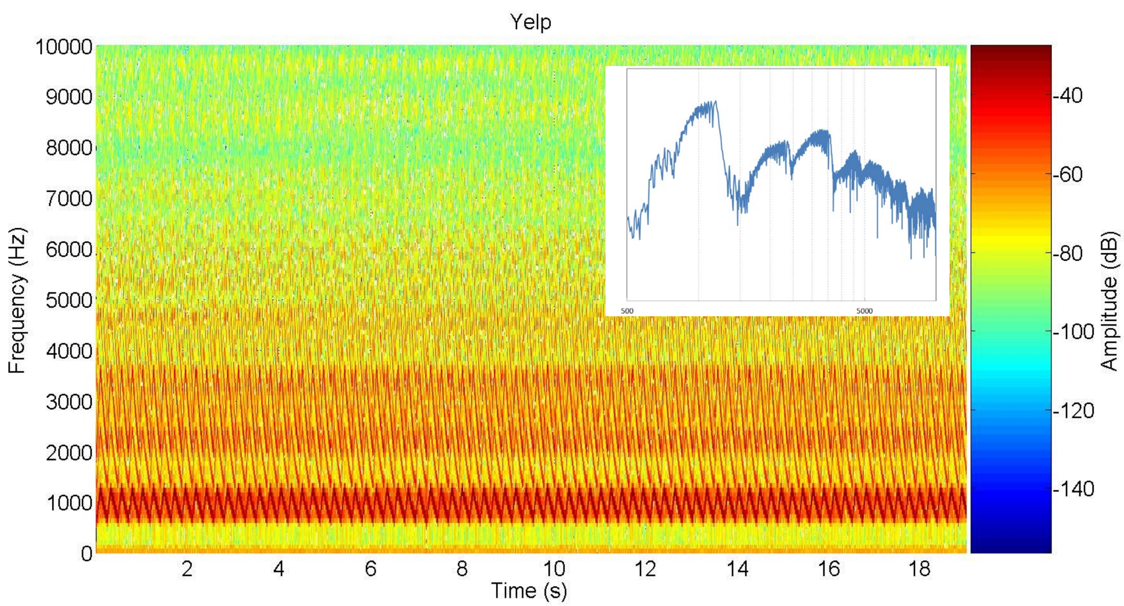


Figure 2. Yelp Spectrogram and Spectrum

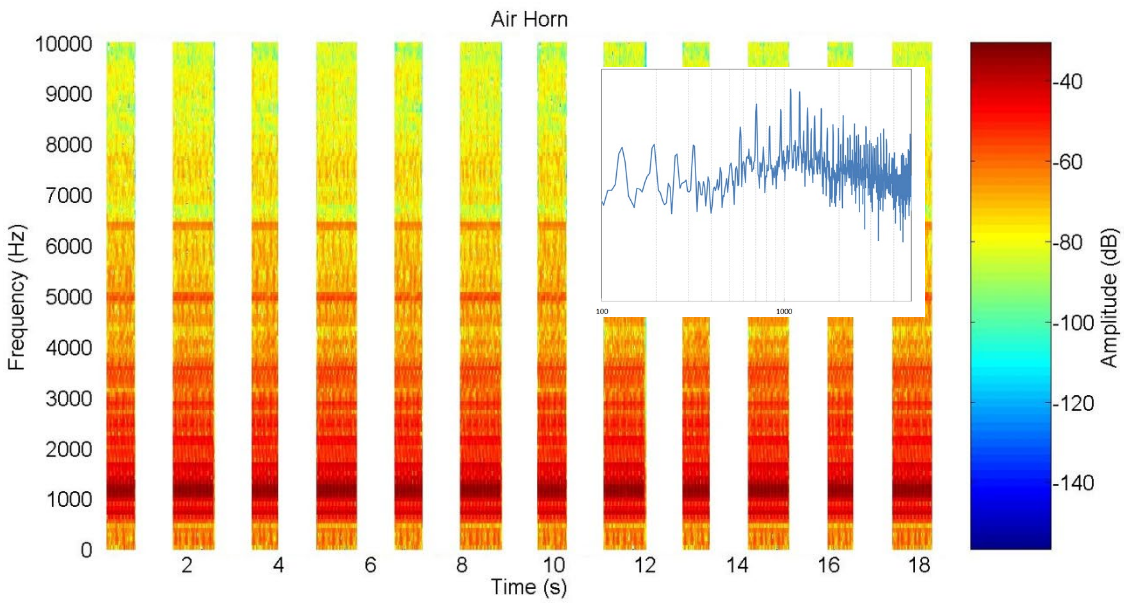


Figure 3. Air Horn Spectrogram and Spectrum

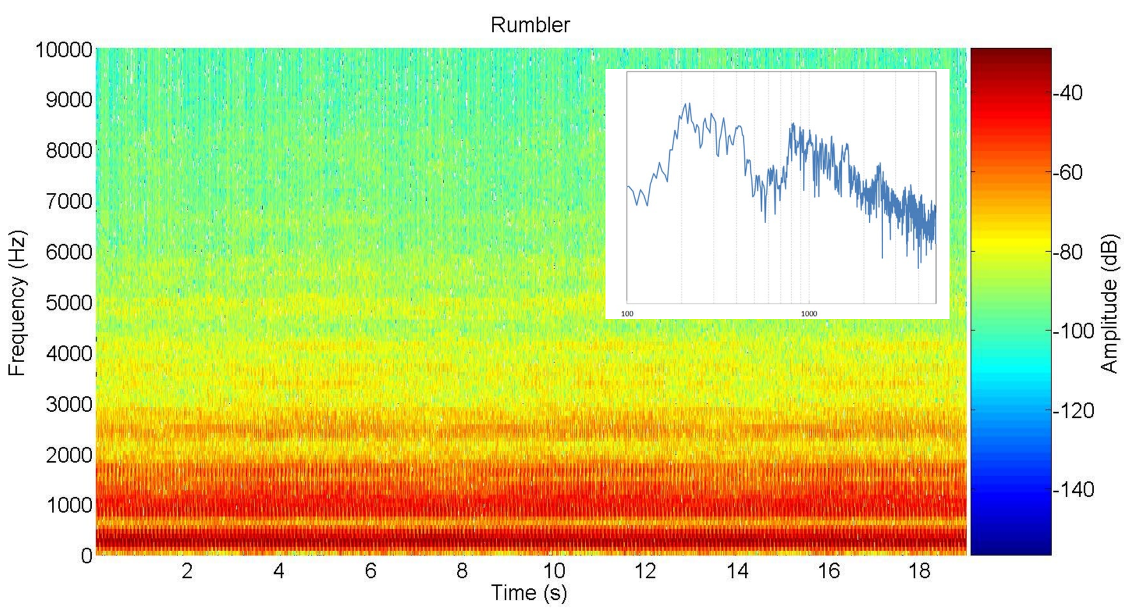


Figure 4. Rumbler Spectrogram and Spectrum

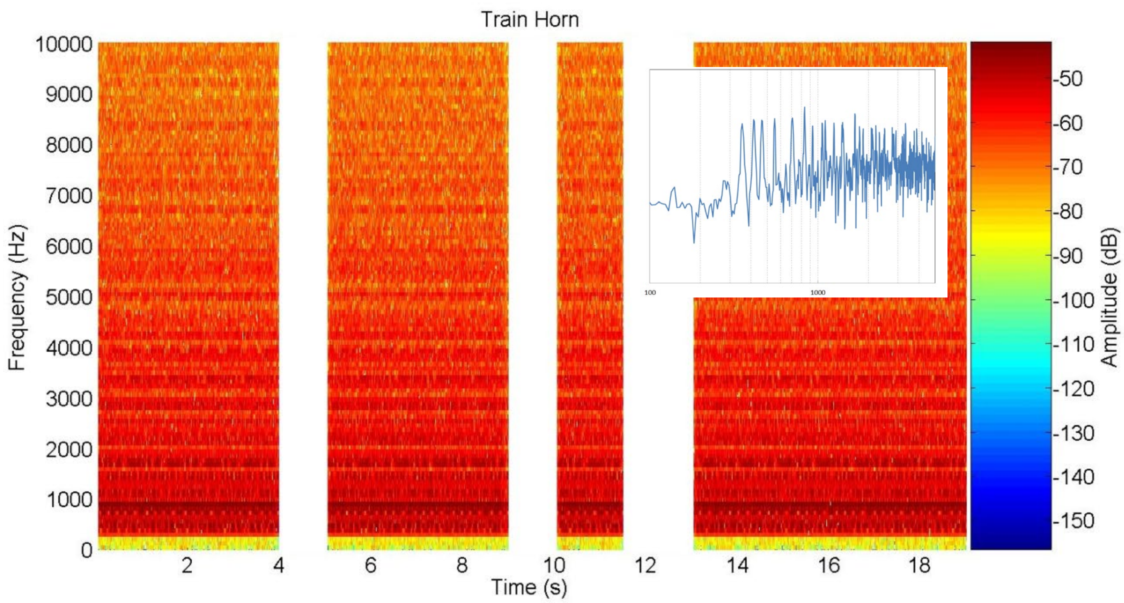


Figure 5. A Typical Train Horn Spectrogram and the Spectrum

Occupational noise exposure is an important issue for those who are exposed to EWSs (such as train engineers, policemen, firemen and ambulance drivers). To minimize the risk of noise-induced hearing loss, the United States Occupational Safety and Health Administration (OSHA) regulates (29 CFR 1910.95) general workplace noise exposure based on long-term exposure. OSHA requires employers to implement a hearing conservation program if exposure exceeds an 8-hour time-weighted average (TWA) sound level of 85 dBA. If 8-hour TWA levels exceed 90 dBA, employees must wear hearing protection.

Studies (Wagner, 2000) have shown that it is important to mount sirens as far forward on emergency response vehicles to minimize noise exposure to the driver. Mounting the siren in the grille reduced noise levels in the driver compartment by 16 to 22 dB compared to sirens mounted on the roof of the vehicle. The FRA has similar regulations to OSHA specified in 49 CFR 227. If an emergency warning device is mounted on the locomotive, similar considerations should be taken. Currently, railroads mount their air-pressure horns in the middle of the locomotive to increase the distance between the source and the locomotive cab (and engineer). When the amplitude of a locomotive EWS is determined, the long-term noise exposure of railroad engineers should be taken into consideration. Improving the effectiveness of the signal may facilitate using lower amplitude while also improving detectability/safety.

2.3 Human Hearing and Psychoacoustic Effects

The physiology of human hearing and human response to different sounds is a primary consideration in the design of a locomotive EWS. If an EWS creates a loud, rough, sharp and fluctuating sound, it would be the most detectable, create a great sense of urgency, and most effectively cause the desired action - avoidance of an oncoming train. Also, humans must easily identify the EWS as that of a moving train and localize its position. The fundamentals of these psychoacoustic phenomena are presented in this section.

The anatomy of a human ear is shown in Figure 6. The human ear detects acoustic signals when sound waves are focused into the auditory canal by the external part of the ear (pinna) resonating the ear drum (tympanic membrane). The ear drum moves three small bones (anvil, hammer and stirrup) in the inner ear which transmit vibration to the cochlea and then to the cochlear nerve where the acoustic signals are transmitted to the brain and processed. It is important to recognize that the entire human head influences sound propagating to each ear and the auditory canals. This "head-related transfer function" (HRTF) affects the time that sound reaches each ear as well as the amplitude and frequency content. Humans use their HRTF to localize sound sources.

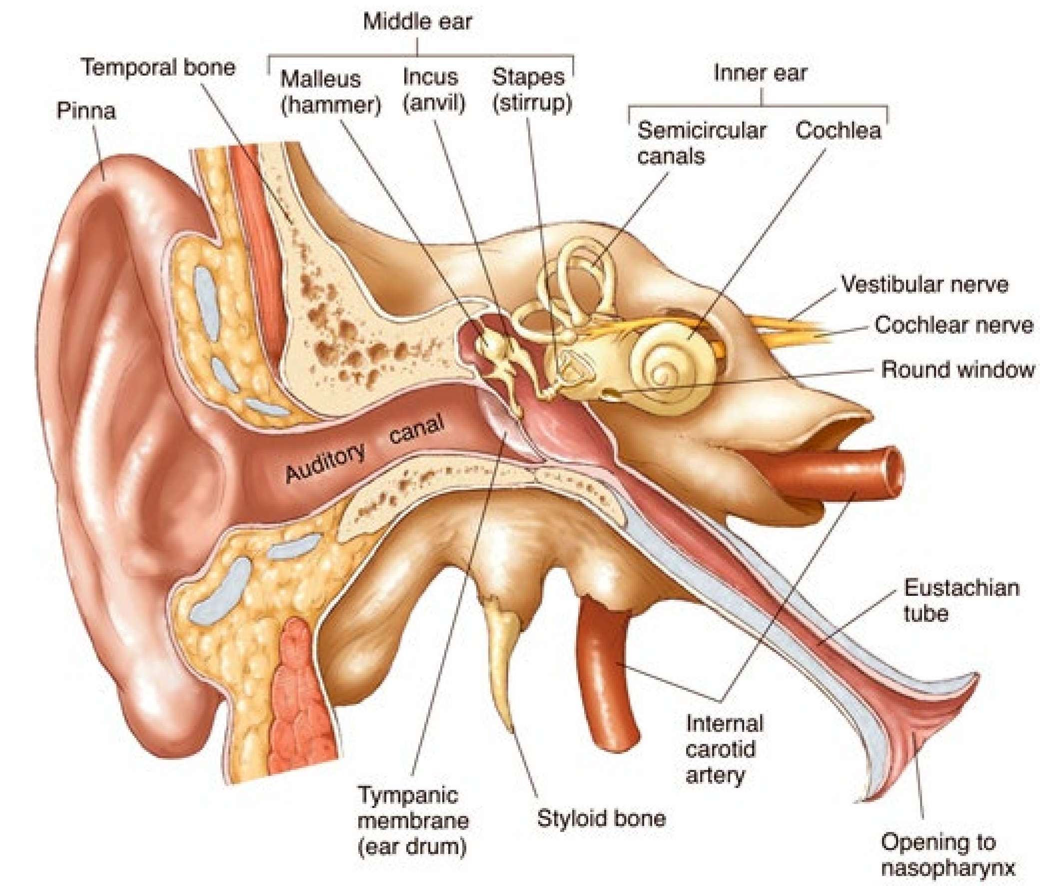


Figure 6. Human Ear Anatomy

As shown in Figure 7, the range of human hearing extends over amplitudes between the threshold of hearing (approximately 0 decibels) and the threshold of pain (approximately 140 decibels) and a range of frequencies nominally between 20 and 20,000 Hertz.

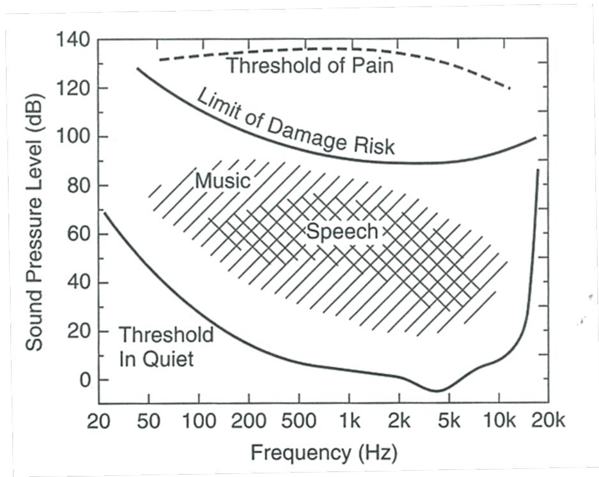


Figure 7. Audible Range for Humans (Crocker, 2007)

Humans do not hear all sounds within the audible range equally. The *loudness* of sound is defined (American National Standards Institute, 1995) as "that attribute of auditory sensation in terms of which sounds may be ordered on a scale extending from soft to loud". Loudness level is measured in phons and is typically depicted as "equal loudness curves" as shown in Figure 8. This figure shows how humans do not hear low-frequency (e.g. below 200 Hz) sound as well as mid and high frequency sound. An effective emergency warning signal should not generate amplitude that would exceed the threshold of pain and should have frequency-content to optimize loudness.

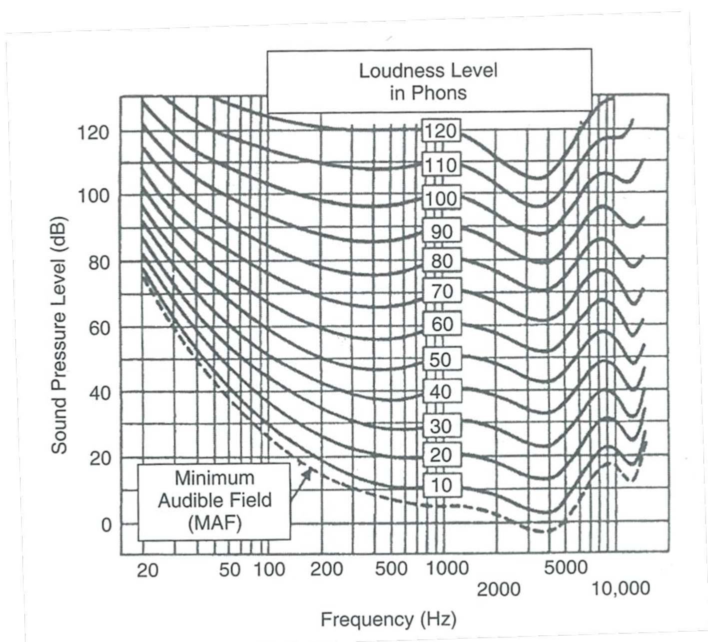


Figure 8. Equal Loudness Curves (Crocker, 2007)

The duration of an impulsive sound affects the perceived loudness. Loudness has been found to increase as a function of duration up to approximately 200 milliseconds (1/5th of a second). The perceived loudness of a sound does not increase for durations longer than 200 millisecond (Figure 9).

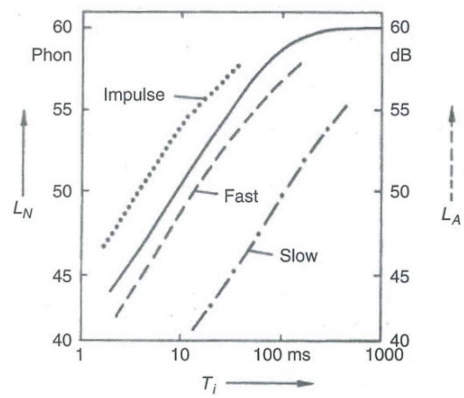


Figure 9. Perceived Loudness versus Sound Duration (Crocker, 2007)

The human ear acts as an "auditory filter." As shown in Figure 10, when a human is exposed to a pure tone it will mask the ability to hear other sounds within a certain bandwidth. Within the critical bandwidth, two discrete tones close in frequency will create a *beating* sensation due to both frequencies exciting the same part of the basilar membrane. As the frequency difference of the tones increase (still within the critical bandwidth), the perceived *roughness* increases. When the frequency difference between two tones is greater than the critical bandwidth, they excite separate parts of the basilar membrane and are perceived to be separate and distinct tones.

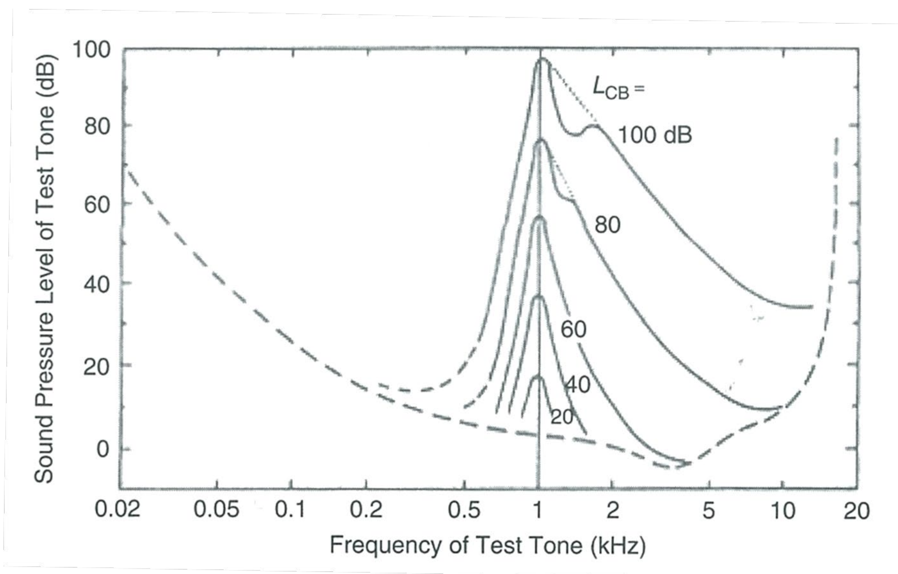


Figure 10. Critical Bandwidths of Human Hearing

Roughness or *harshness* is a psychoacoustic metric that relates to the subjective perception of rapid (15 to 300 Hz) amplitude modulation of a sound. For a tone with a frequency of 1000Hz or above, the maximum roughness of a tone is at a modulating frequency of 70Hz. Figure 11 depicts acoustic roughness. Roughness is often used to quantify the sound quality of products such as car engine noise and appliances. It has also been used in the calculation of an unbiased annoyance metric.

Fluctuation Strength is similar in principle to roughness except it quantifies subjective perception of slower (up to 20Hz) amplitude modulation of a sound. The sensation of fluctuation strength persists up to 20Hz then at this point the sensation of roughness takes over.

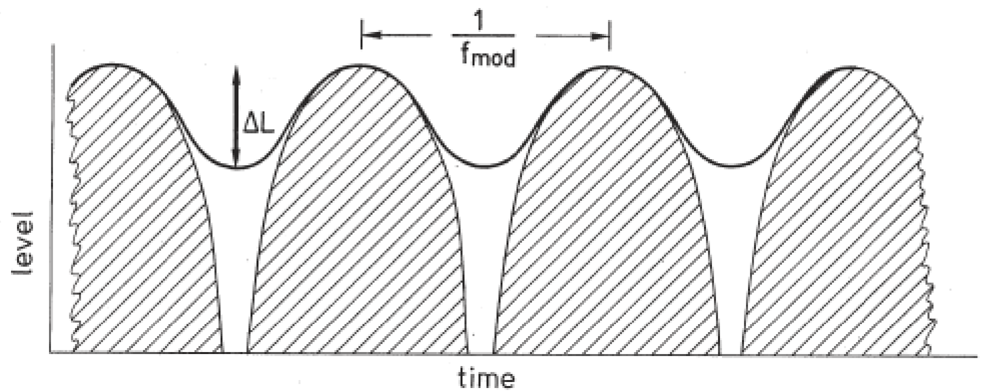


Figure 11. Depiction of Acoustic Roughness (Fastl et al., 2005)

An effective emergency warning signal should generate tones to increase perceived roughness.

Sharpness is a measure of the high frequency content of a sound; higher-frequency content relates to a 'sharper' sound. *Booming* is a measure of the low frequency rather than the high-frequency content of sound. Booming can be considered to be the opposite of the sensation of sharpness.

One approach to surveying human responses to different sounds, such as quantifying the sound quality of products, is to use a semantic survey. As shown in Figure 12, human subjects are exposed to different sounds and describe the sound by choosing between two opposing words on a seven point. Having human subjects choose between words such as "dangerous" or "safe" and "loud" or "soft" can indicate the relative perceived sense of urgency of different EWSs. Surveys can also be used to compare how effective different sounds are in regard to creating a sense of urgency.

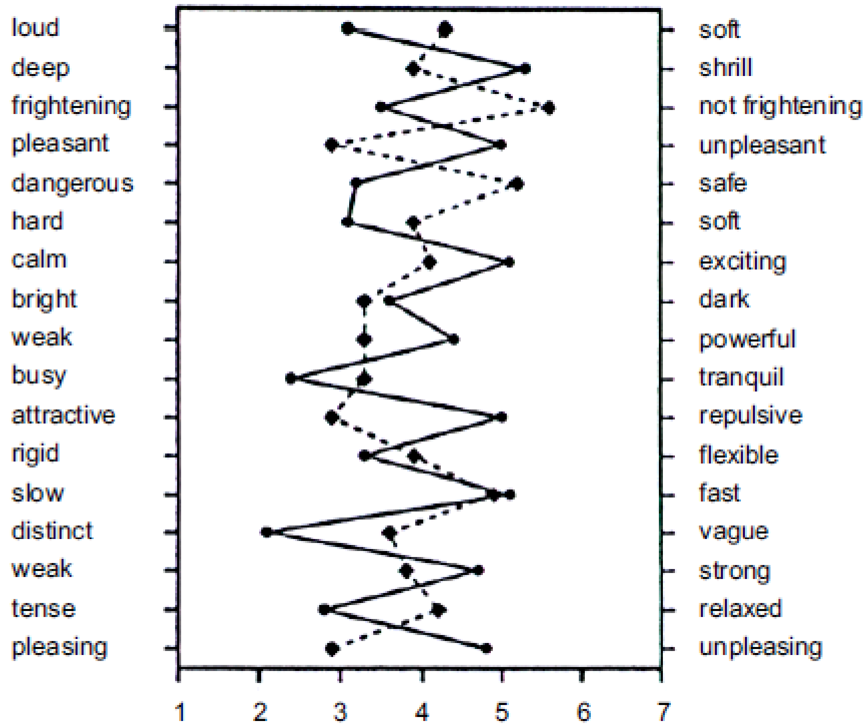


Figure 12. Semantic Difference Survey (Fastl et al., 2005)

2.4 Masking Effects from Headphones

Headphones act in several ways to reduce human's ability to detect oncoming trains. They act as a physical barrier to external sound reaching the auditory canal. This passive noise reduction depends on the headphone design (e.g. ear bud, on-ear headphone or over-ear headphones). Some headphones also use active-noise cancellation technology to further reduce external sounds. Active noise cancellation headphones reduce external sounds by reproducing the same sound with an inverted phase. Since sound is the rapid fluctuation (compression and expansion) of air pressure, active noise cancellation generates a sound that is in compression at the same time and location as an intrusive sound is in expansion (or vice versa) to reduce the overall sound level. Additionally, when headphones channel music or speech into a listener's ears, it masks the listener's ability to detect other sounds (such as a locomotive EWS).

Many survey studies have determined the typical levels that listeners are exposed to while listening to music with headphones (Keith et al., 1999; Keith et al., 2008; Keith et al., 2011, Prasher et al., 1998; McNeill et al., 2010). Based on data from all of these studies, the overall range of music levels that are reproduced with headphones is generally between 55 and 107 dBA with average levels generally between 55 and 85 dBA.

Also, the railroad environment, including other trains and nearby highways and roads, can generate an array of sounds that can mask the ability to detect an on-coming locomotive.

Locomotives and rail cars typically generate sound levels up to 90 and 93 dBA at 100 feet, respectively (40 CFR 201.12(b) and 49 CFR 210).

There are a wide range of headphone manufacturers, models, output levels and noise reducing characteristics as shown in the photo below of a store that only sells headphones. Types of headphones can be classified as follows:

- “Circumaural” headphones surround the entire ear.
- “Supra-aural” headphones rest against the ear.
- “Ear buds” are small devices typically placed inside the outer ear.
- “In-ear monitors” are small devices typically placed directly into the ear canal similar to an in-ear hearing protection device (HPD).

The methods and results of the passive noise reduction provided by HPDs have been the subject of extensive research (Berger, 2005; Robinson & Casali, 2002), but fewer studies have documented the passive and active noise cancelling effects of headphones. One study (Kan et al., 2011) has shown that the maximum elevation of the auditory threshold without a headphone was about 25 dB for in-ear monitors, which have the largest amount of sound isolation compared to other headphone types. This 25 dB increase in the auditory threshold is similar to the capability of the noise reduction function in headphones. It has been shown (Hara et al., 2010) that auditory thresholds can shift as much as 70 dB, Including music playback, with “in-ear monitors” which can cause many external environmental sounds to be inaudible.

Figure 13 shows the effect of the passive noise reduction that is used by headphones as determined by a study (Perala et al., 2009) that compared two methods for quantifying the noise reduction of headphones. The Bose Quiet Comfort headphones (circumaural) are shown to provide up to 30 dB of passive noise reduction at higher frequencies. In the frequency range of most EWSs (e.g. 250 to 2000 Hz 1/3-octave bands), the circumaural headphones provide approximately 2 to 18 dB of passive noise reduction. The Sennheiser headphones (supra-aural) provided limited passive noise reduction at frequencies up to 2000 Hz.

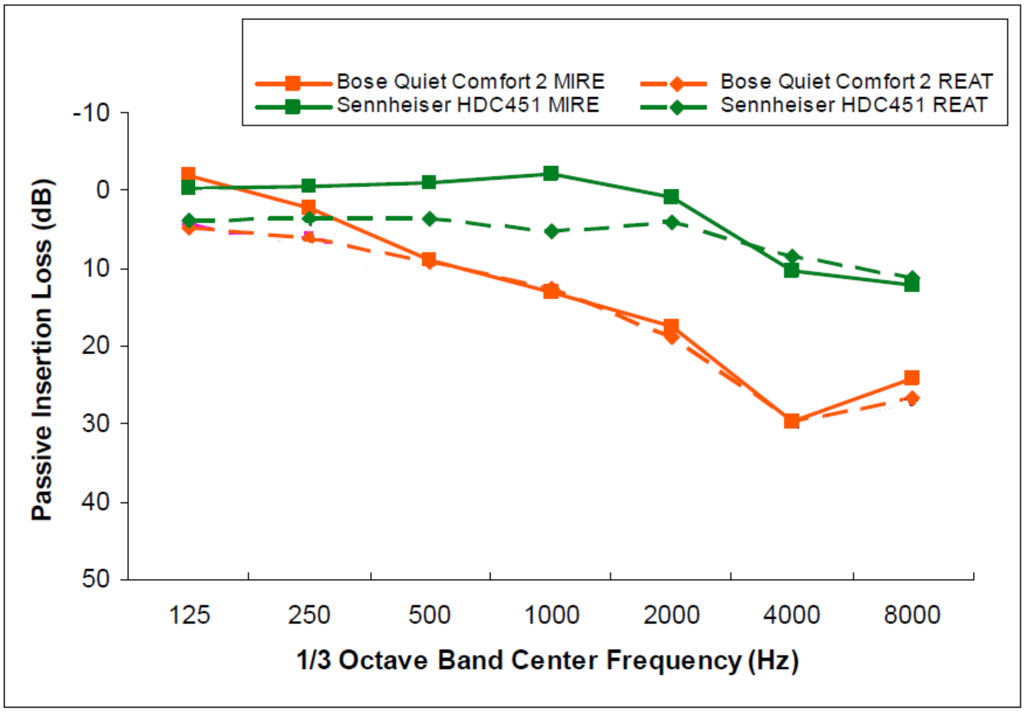


Figure 13. Measured Passive Noise Reduction of Headphones (Perala et al., 2009)

2.5 Methods to Measure the Effects of Headphones

There are two primary methods to measure human hearing and the effectiveness of HPDs. The real-ear attenuation at threshold (REAT) method (American National Standards Institute, 2008) involves testing human subjects at the threshold of audibility with and without HPDs. The REAT method is generally considered to be the gold standard due to the use of actual human subjects and their natural hearing mechanisms including sound which conducts through the bone surrounding the ear. The microphone-in-real-ear (MIRE) method (American National Standards Institute, 2010) utilizes human subjects acting as test fixtures with microphones positions in their ears. Similar tests can be conducted using an acoustic text fixture (ATF) such as a dummy head and dummy ear. This test method is most appropriate for circumaural hearing protection devices.

With some modification, the MIRE method can be used to physically measure the sound levels in the ear and determine the sound levels that humans are exposed to when they listen to music with headphones, the active and passive noise reduction characteristics of headphones, and the sound levels that humans are exposed to with different EWSs.

2.6 Effectiveness of Emergency Warning Signals

There is a substantial body of research into the effectiveness of EWSs and corresponding design recommendations. Some of the early research showed the relative ineffectiveness and limitations of EWSs to provide sufficient safety for emergency response vehicles. Since this early research, new approaches to EWS design aim to improve their effectiveness, and there have been many studies showing differences in the effectiveness of an EWS according to its sound pattern. In particular, this research has focused on hospitals and workplaces with various warning signals of that convey varying levels of urgency. There has been limited research into the design and effectiveness of EWSs for railroad applications.

2.6.1 EWSs on Emergency Response Vehicles

Early research (Ebata et al., 1969; Potter et al., 1977) examining the human detection process of audible warning devices on emergency vehicles showed that the audible warning devices typically have directivity pattern where sound is focused forward of the vehicle and the outdoor-to-indoor noise reduction and background noise levels inside automobiles are a significant factor. The study suggested that that the frequency content of the signal is important while the pattern of the EWS is not. A key finding of this research was that motorists should not rely on the current audible warning devices to warn them that emergency response vehicles are oncoming.

Detailed studies on emergency vehicle EWSs (Howard et al., 2011; Maddern et al., 2011; Catchpole & McKeown, 2007) have provided great insight into their effectiveness. Most of this work has been based on assessing the detectability of these signals for motorists inside vehicles. The research has shown that frequencies above 3000 Hz should not be relied upon for detection due to humans with hearing loss, an EWS should be a complex signal with many harmonics and a fundamental frequency below 1000 Hz, and that signals with significant sound energy below 1000 Hz should be used for outdoor alarms where a greater warning distance is required.

Jury tests have been conducted to compare the effectiveness of existing Wail, Yelp, two-tone and three-tone EWS with new signal designs that have modified sound burst cycles and fundamental frequencies (Balastegui et al., 2011). The jury compared their relative annoyance, loudness and sense of urgency. The Wail tones were perceived to be the least annoying and least urgent. The new Wail and Yelp tones improved the sense of urgency without increasing annoyance levels.

2.6.2 Designing Auditory Warnings

Research has shown that it is possible to design warnings to be more effective by manipulating measurable acoustical parameters. Tests on the human subjective response of auditory warnings (Hellier & Edworthy, 1989; Hellier et al., 1993; Hellier & Edworthy, 1999) has shown that the number of repetitions, the warning speed (fundamental frequency), the length of the signal and the harmonicity of the tones are all correlated with the "perceived sense of urgency". A set of experiments to quantify the effects of these three signal characteristics showed that large differences in the perceived sense of urgency can be achieved over a fixed period of warning time. The warning speed was found to have the greatest effect on urgency while harmonicity had the least effect.

In designing an EWS, research (Patterson et al., 1990) has shown that there are several other parameters that affect the perception of urgency, including delayed harmonics, amplitude envelope, rhythm, and musical structure. A guideline was recommended suggesting that the ideal amplitude of an EWS should be 15 dB above the human hearing threshold which includes ambient noise conditions. This research showed that humans do not hear a separate pitch for each peak of a sound spectrum that involves harmonics, but rather humans relate the harmonic series back to the fundamental frequency. This was an important finding; an EWS that includes a number of harmonic tones (four or more) across a broad frequency range will sound relatively simple, but will be resistant to masking from other environmental sounds. This research also showed that the pitch, intensity and speed of the bursts correspond to the perceived sense of urgency.

Designing urgency into auditory warnings by using pitch, speed and loudness has been investigated (Haas & Casali, 1995; Haas & Edworthy, 1996), and it was found that EWSs with a high-frequency, fast speed and high amplitude most effectively increased the sense of urgency and decreased response time. Specifically, perceived urgency increased as the fundamental frequency increased from 200 to 500 Hz, but did not increase further at 800 Hz. This research is most applicable for the workplace environment that requires a range of EWSs with a range of urgencies.

A study on the design and effectiveness of auditory warning signals in the work environment (Patterson & Mayfield, 1990) focused on flight aircrews that are exposed to relatively high ambient noise conditions and a large number of different audible warnings. It was found that there was a benefit in limiting the number of warning sounds bursts to six and that the warning signals should have a distinct and melodious character to identify and differentiate between them. One benefit of having quiet portions within an EWS is to allow communication within the warning event. Research (Suied, 2008) has indicated that temporal irregularity between pulses can capture a listener's attention.

There have been approaches to quantifying the effectiveness of EWSs using semantic surveys (Fastl et al., 2010). This research tested human subjects for varied duration and repetition rates of EWSs. This approach was able to identify an EWS that would be expected to greatest sense of urgency.

An international standard (ISO 7731:2003) specifies the physical principles of design, ergonomic requirements and the corresponding test methods for danger signals for public and work areas in the signal reception area and gives guidelines for the design of the signals. This standard may also be applied to other appropriate situations. It is stated that signal levels 6-10 dB above the masked thresholds will ensure 100% detectability, and that signal levels approximately 15 dB above the masked thresholds are recommended for ensuring rapid response from the listener.

Tonal sounds have been found to be harder to localize than broadband (e.g. white noise) (Catchpole et al., 2004); however, the tones increase perceived urgency. It has also been shown that the response accuracy and latency in identifying and localizing an auditory warning signal with complex tones was improved compared to a single tone.

Intelligent auditory alarm design has shown that it is critical to provide three types of information; how urgent the situation is, what is causing the alarm, and where is the event occurring (Hermann et al., 2011). One key failure of many auditory warnings is not providing a sufficient level of urgency.

The locomotive EWS design process should involve manipulating measurable acoustical parameters such as the number of repetitions, the warning speed (fundamental frequency), the length of the signal, harmonicity of the tones, timing of the pulses and/or the amplitude of the received signal.

2.6.3 EWSs on Trains

British Rail Research's auditory warnings were designed (Patterson & Mayfield, 1989) to be used by trackside maintenance crews to warn of approaching trains. The auditory warning design was to preserve the character of the warning that was currently generated by on-board locomotives and for the four EWSs to be audible in no fewer than 46 different ambient noise conditions.

2.6.4 EWS Effectiveness Across Cultures

The effectiveness of auditory warning signals for cultural differences across the world has been investigated (Kuwano et al., 2000; Langlois et al., 2008). This research has shown that there is similar influence of auditory warning design parameters in Germany, France, Great Britain and Turkey.

3. Design and Analyze Emergency Warning Signals

3.2 EWS Requirements

When a Secondary Emergency Warning System (EWS) is designed, it is critical that the EWS provides sufficient notice to trespassers to enable them to vacate the railroad right-of-way prior to the train arriving. The previous Phase 1 work assumed 2.5 seconds to notice and begin reacting (a commonly quoted time) to a warning signal, followed by 5 seconds to vacate the right-of-way. The 5 seconds time was the author's estimate for a healthy person to vacate a single track right-of-way.

Many of the EWS sound designs were based on the basic sound pattern from the Nathan K-5-LA train horns. While over 80 sounds were developed and assessed for levels of urgency , only twelve sound files were downselected for testing. EWS patterns had cycle rates that varied from 15 cycles per sec up to 8 seconds/ cycle; while they relied primarily on frequency modulations and some amplitude modulations, frequency modulations predominated.

To design an EWS sound that can penetrate a trespasser's headphones while he or she is playing music, the designer may want to increase noticeability by avoiding tempos that are associated with music. Table 2 shows the typical tempo for music that might be listened to by trespassers. The classic Wail sound has a tempo of 10 to 30 beats/min and the Yelp has a tempo of from 150 to 250 beats/min. As the designer attempts to increase noticeability, it may be prudent to avoid typical tempos that make a Wail more noticeable than a Yelp.

Table 2. Music Tempo for EWS Design Avoidance

Music Type	Tempo (Beats per Minute)
Ballads	50 – 80
Motown	80 – 100
Hip Hop	80 – 115
Rock	100 – 180
Polka, Reels	160 – 290
Marzucca, Tanatellas	210
Fast Waltz	300

3.3 EWS Sound Design Process

This section discuss how candidate on-board locomotive EWSs were designed to be more effective at alerting pedestrians wearing headphones listening to music. The first step to achieve this goal was to test the passive and active noise reduction, or *insertion loss*, of a range of typical headphones using the Microphone in Real Ear (MIRE) method to physically measure in-ear sound levels. The insertion loss results have been applied to the EWSs so that they have a spectral content that is optimized to combat the negating effects of headphones and music. Numerous EWS candidates have been created by varying several acoustical parameters such as the number of repetitions, the warning speed (fundamental frequency), the length of the signal, the harmonicity of the tones, the timing of the pulses and the amplitude of the received signal.

All EWSs are based fundamentally on a five-chime Nathan train horn with primary tones at 355, 415, 470, 555 and 710 Hz. The EWSs have been created using audio engineering software (Adobe Audition). The "analog baseline" train horn sound used, in the trade-offs, below is a calibrated recording of an actual Nathan train horn. Police, fire and ambulance warning signals include the *Wail* and *Yelp* and are also calibrated recordings of physical sirens. These standard warning signals, as described below, are considered to be a baseline for comparison of the new EWSs.

To create a new EWS, the designer must first generate a "digital baseline" version of the train horn sound. This was done by generating sine wave tones at the same frequencies and amplitudes as the physical horn. Although the actual train horn signal is more of a saw-tooth or square shape rather than sinusoidal, generating sine waves of each harmonic frequency at the correct amplitude more closely replicated the sound of the physical horn than generating saw-tooth or square waves. Sine waves were created at the lowest 100 frequencies of the primary tones and harmonics of the physical horn. These sine waves were combined to create a full range horn sound between 355 and 14,000 Hz. The resulting "digital baseline" is a sound that is nearly identical to the physical horn; however, it can now be modified using audio engineering software. Approximately half of the EWSs were based on this digital baseline version of the train horn sounds and half were based on the analog baseline.

Once the digital baseline has been created, the designer creates the new EWS by adding a Doppler effect of varying intensity to the digital baseline train horn. The Doppler effect is a phenomenon where the sound generated by an accelerating object will be heard by a stationary listener with gradually increasing or decreasing frequency depending on whether the object is accelerating towards or away from the listener. Therefore, gradually increasing the frequency of the horn signal creates a greater sense of urgency for the listener to respond to an object accelerating toward them. Increases in frequency between 5 and 100% (doubling) of the initial values were used in the various candidate EWSs. These increases in frequency must occur over a specific period or *cycle time.* Over longer-period cycle times, such as four or more seconds, the effect is more subtle suggesting that an object was accelerating slowly. Over shorter cycle times, the effect is more pronounced; however, the resulting signal was often found to be overly-electronic or "laser-like" and lose the association of the sound coming from a train.

Numerous candidate EWSs were generated with cycle times between 0.1 and 8 seconds. Since the warning signal must be able to sound for an extended period of time, the following options were investigated to continue the signal at the end of each cycle: 1) decrease the frequencies back down to their initial value over the same cycle time, 2) pause for a brief period of time (e.g. 0.05 to 0.2 seconds) to leave a gap in the signal and then restart the cycle from the beginning, and 3) repeat the cycle without a gap. After listening to these different options, the first resulted in a negative sense of urgency because decreasing the frequency created a sense of an object accelerating away from the listener. The second option of leaving a gap between cycles resulted in a discontinuous sound that sounded more like a malfunctioning acoustic device. The third option of repeating the cycle without a gap was found to be the most effective at maximizing the sense of an object accelerating towards the listener.

In simulating the Doppler-effect, a few different ways of increasing the frequency of the tones were investigated. Some of the EWSs had a simple linear increase in frequency (e.g. from 355 to 390 Hz). Some of the EWSs would "shake" or *modulate* each tone at the beginning and end of the cycle. For example, if a signal was modulated 1% in the beginning and 2% at the end of the cycle, it would shake between 352 to 359 Hz at the beginning of the cycle and between 381 and 399 Hz at the end of the cycle. How quickly EWSs were modulated is specified by the *modulation frequency*. For example, if a signal was modulated by 1% at a modulation frequency of 10 Hz, it would shake between 352 and 359 Hz ten times a second. This frequency modulation is expected to improve detectability of the signal because it is less likely that background noise, such as music, would mask all of the different frequencies that the EWS covers.

Some of the EWSs simulated the Doppler-effect to all of the fundamental tones and harmonics and some applied the Doppler-effect to only the higher harmonics while keeping the fundamental tones stationary. This approach was found to allow a balance of increased Doppler-effect while also maintaining the character and identification of a train horn.

A few of the candidate EWSs had a *beating effect* added to the signal. When two tones are close in frequency and within the auditory critical bandwidth, they will create a beating sensation due to both frequencies exciting the same part of the basilar membrane. This beating effect was included by adding a second set of tones at slightly different frequencies to the baseline tones.

A few candidate EWSs added additional tones below the lowest fundamental (355 Hz) to extend the low-frequency content. This was done either by mixing in the standard Rumbler sound or by adding in "fractional harmonics" of the fundamental tones. For example, one EWS included tones at one-half and one-third the frequency of each primary tone. This extended the low frequency content of the signal down to 177 Hz while maintaining the original character of the train horn sound. Because many of these fractional harmonics are separated by approximately 20 Hz, a beating effect occurs.

All EWS candidates were required to maintain the signature of a train horn, which would assure that listeners identify the sound with that of a train. It is critical that trespassers and railroad workers understand the cause of the warning signal to elicit the desired response. As the intensity of the Doppler-effect increased, EWSs were found to sound less like a train horn. Therefore, a key design goal was to balance the severity of the Doppler-effect with the identification of the EWS source.

Physical train horns are typically sounded at constant amplitude. Some of the EWSs have been designed to include *amplitude modulation* where the sound level increases and decreases over a particular duration.

3.4 Results of Headphone Noise Reduction Tests

MIRE measurements were conducted on six common circumaural and supra-aural headphones to quantify their noise reduction from exterior sounds. Tests were conducted with and without active noise cancellation (ANC) turned on for headphones with such capabilities. Six headphones were tested including;

- Sennheisser PXC 25-II (with ANC),
- Bose QC2 (with ANC),

- Bose QC3 (with ANC),
- Bose Triport OE (no ANC),
- Creative HN-505 (with ANC), and
- Sony MDR-V150 (no ANC).

Tests were conducted by playing broadband pink noise through amplified speakers inside an audiometric booth as shown in Figure 14. The audiometric booth is a highly absorptive room that is well-isolated from outside sounds. The absorption reductions with frequency are shown in Table 3. The absorption in the room reduces reflections so that the primary direction of sound reaching the listener is directly from the speakers which were oriented approximately 30 degrees to the left and right behind the listener. No sound or music was played through the headphones. In-ear sound levels were measured using Bruel & Kjaer 4101 microphones with a Bruel & Kjaer 2250 sound level meter. The difference between the in-ear sound levels with and without the headphones resulted in the headphone insertion loss.

Table 3. dB Noise Reduction for Audiometric Booth

Hz	125	250	500	1000	2000	4000	8000
dBA	19	28	38	46	52	54	54

Figure 14. Audiometric Booth Testing

As shown in Figure 15, headphones without ANC are generally effective at reducing noise levels to the ear at frequencies above 800 Hz. Below 800 Hz, the headphones do not significantly reduce noise levels. In fact, the headphones are shown to slightly increase in-ear noise levels at certain frequencies below 800 Hz. This may be due to resonant properties of the chamber that is created between the headphones and the ear with circumaural and supra-aural headphones. The insertion loss varies 10 dB or more between headphones. On average, the passive noise reduction of the headphones is 10 dB at 2,000 Hz and 20 dB at 20,000 Hz.

Insertion loss levels from headphones with ANC are shown in Figure 16. Figure 17 shows the difference in insertion loss due to ANC. These figures show that ANC does not significantly affect insertion loss levels 800 Hz or higher. Below 800 Hz, ANC substantially increases the insertion loss of the headphones by 7 to 16 dB depending on the particular pair of headphones. ANC increases insertion loss between 50 and 800 Hz with the most significant increase near 200 Hz.

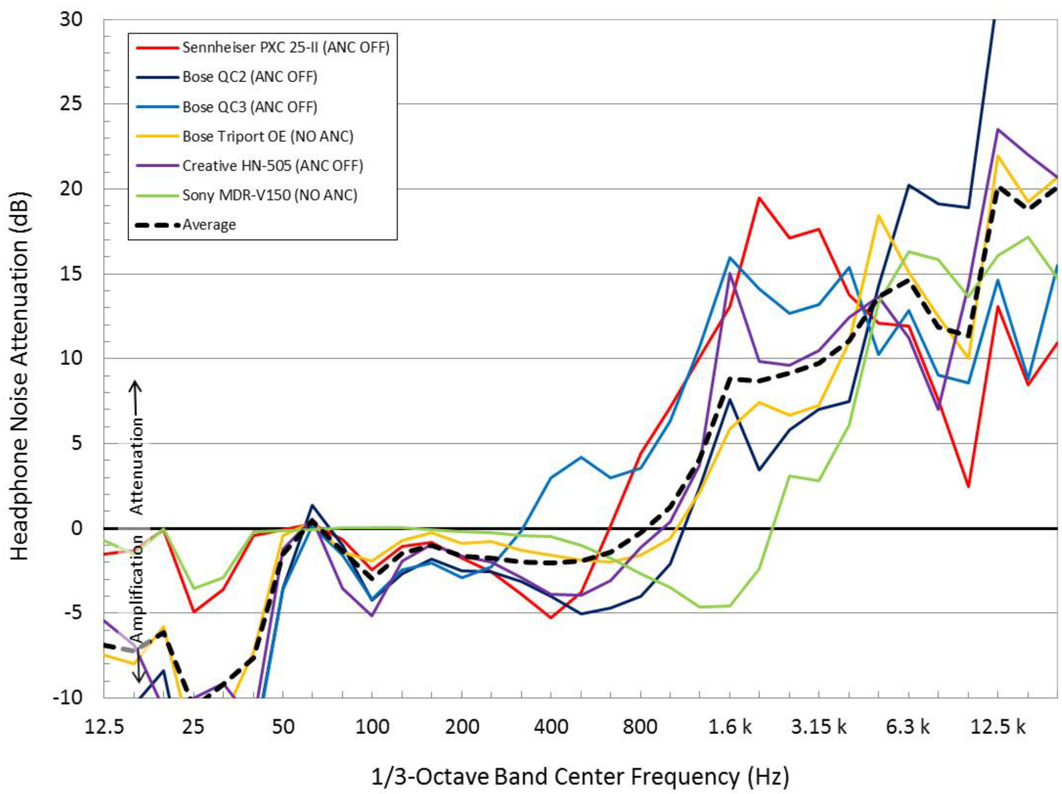


Figure 15. Insertion Loss of Headphones without Active Noise Cancellation

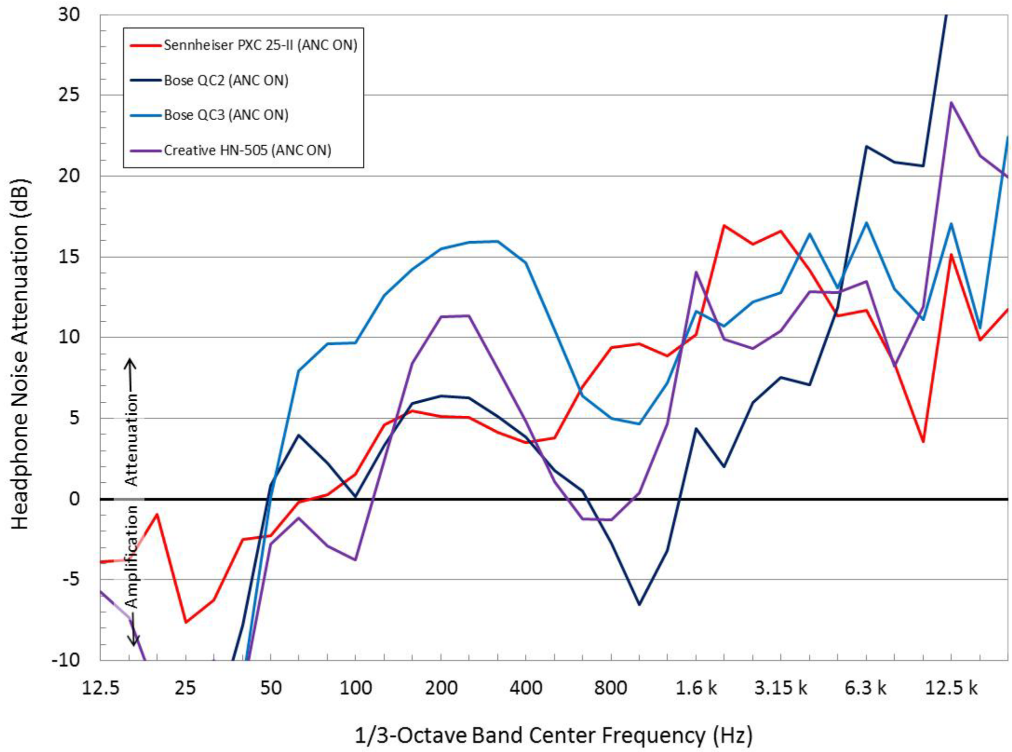


Figure 16. Insertion Loss of Headphones with Active Noise Cancellation

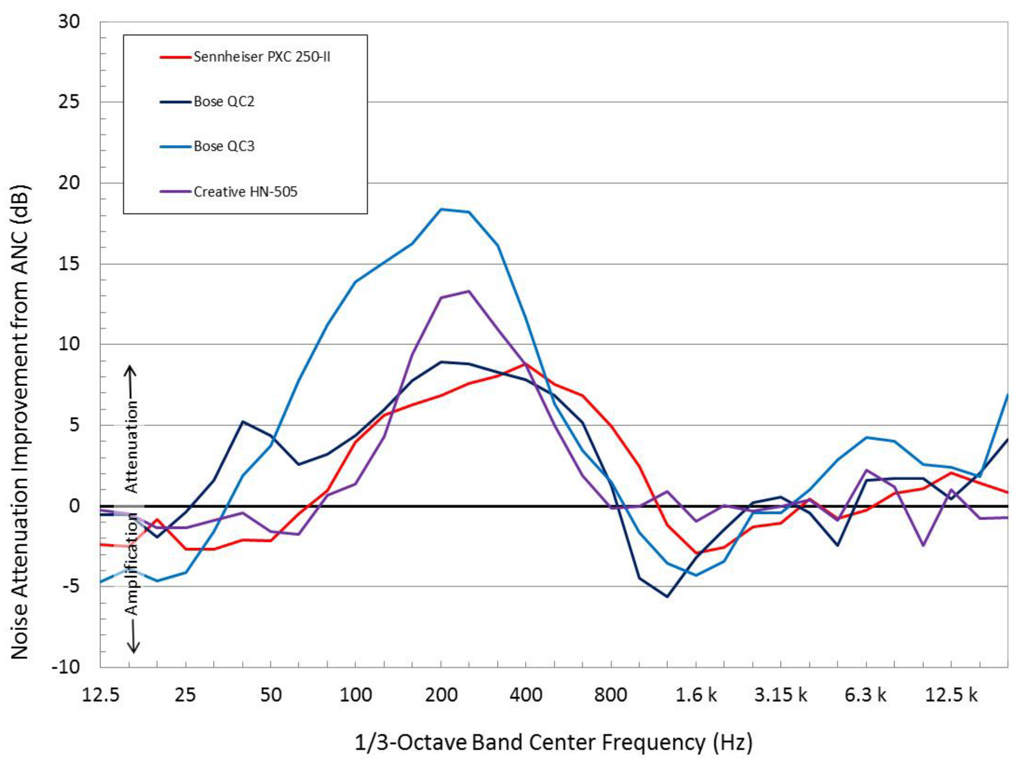


Figure 17. Noise Attenuation from only Active Noise Cancellation

3.5 Noticeability and Vacating the Right of Way

The EWS sounds generated must be urgent enough to encourage a trespasser to vacate the railroad right of way. If trespassers are slow to react, they may be struck by an approaching train. As an example, the d-prime noticeability of a Nathan K-5-LA has been determined from previous work as seen in Figure 18. The colored lines represent various distances along a crossing roadway where a crossing vehicle may be located. For a trespasser directly on the right of way, that distance is zero. For the case of the Nathan K-5-LA, a trespasser has a 95% likelihood of detectability when the approaching train is 500 to 550 ft feet away.

In the case of a trespasser, it is supposed for discussion purposes at this point that a typical trespasser will have a 2.5 sec reaction time to an audible stimulus like an EWS. More work is required to better define these reaction times, however 2.5 sec is often quoted. It is also supposed that 5 sec is a reasonable estimate of the time for a startled person to locate the train and vacate the right of way. Again, more work is required to better define these times.

But given the above assumptions, the plot in Figure 19 indicates the distance a constant speed train will travel in the total time available to the trespasser (7.5 sec). Thus, for the 500 to 550 ft that a trespasser has once he or she has heard the standard train horn, a trespasser has a reasonable chance of vacating the right of way safely when an approaching train is traveling at speeds of 50 mph or less. This speaks to the importance of producing an urgent signal from the approaching train to provide as much time as possible for a trespasser to vacate the tracks. Of course, the train will be decelerating once a trespasser is noticed, which will provide additional time, but the risks are much greater if the trespasser is wearing headphones or ear buds that significantly reduce noticeability.

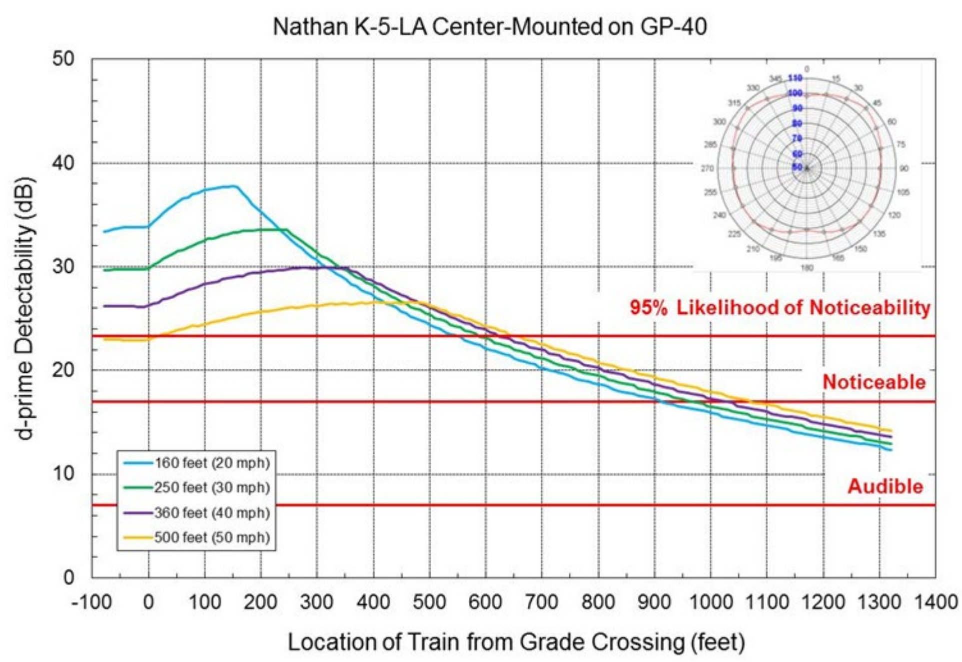


Figure 18. Nathan K-5-LA Noticeability

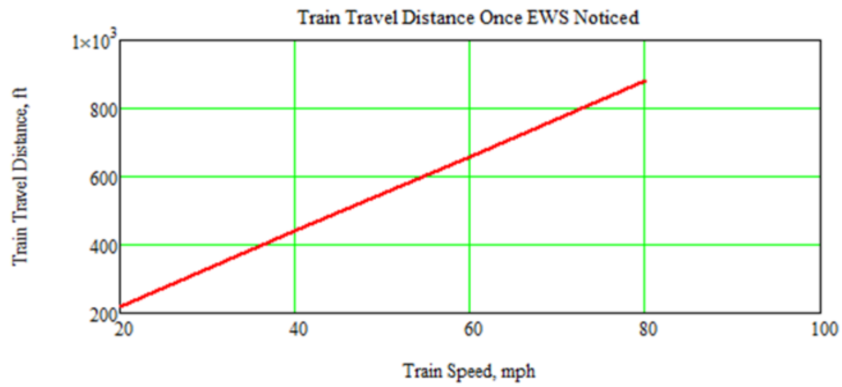


Figure 19. Train Travel Distance Once EWS Noticed

4. Conduct Static Tests of Emergency Warning Signals

Twelve candidate EWSs which represented a range of different design features and the standard warning signals (Wail, Yelp, Rumbler and baseline Nathan train horn) were tested and evaluated to quantify their effectiveness. Participants were given a survey to complete as they listened to calibrated playbacks of the different EWSs with headphones. Each survey includes six candidate EWSs and the four standard warning signals. The goal of this testing and evaluation was to identify specific features of the more-effective EWSs and reduce the group of effective EWSs for further refinement and evaluation.

All EWSs were reproduced with an in-ear amplitude of 80 to 85 dBA. Participants had an opportunity to adjust the amplitude so that it would be at a reasonably comfortable listening level. The background pink noise signal was reproduced at amplitude of 80 to 85 dBA and the EWS slowly ramps up to a maximum level of 90 dBA. The music used during the survey was an upbeat popular song with strong vocals; "Treasure" by Bruno Mars.

The first part of the survey asks demographic questions including age, sex, known hearing loss, dominant hand and how often participants wear headphones outdoors. The second part of the survey is repeated for each signal. The survey plays a typical outdoor noise environment with passing automobiles and other natural sounds for 10 seconds to provide a sense of location and to break up the repeated listening of EWSs. Each EWS is then played for 10 seconds and asks the participant the following questions:

- "Does this sound cause you to feel a sense of urgency to move away from the noise source?" (5-point rating scale; no urgency, slight urgent, moderately urgent, very urgent, highly urgent)
- Please identify the source of the sound? (5 options; train, police, fire engine, car stereo, other)
- "How certain are you about the source of the sound?" (5-point rating scale; not certain, slightly certain, moderately certain, very certain, highly certain)
- "Does this sound startle you?" (5-point rating scale; not startling, slightly startling, moderately startling, very startling, highly startling)
- "Is this sound annoying?" (5-point rating scale; not annoying, slightly annoying, moderately annoying, very annoying, highly annoying)

The survey then quantifies how efficiently the listeners can detect each signal by playing a calibrated recording where each signal slowly increases in amplitude while either 1) broadband pink noise or 2) music is played as masking background noise. The listeners are asked to press a button when they are first able to hear the sound to assess audibility of the EWS and to press a second button when the EWS is loud enough to "cause a need to take action (move away from the source)". Based on the time they press each button, a "d-prime" detectability level, which is a comparison of the EWS signal to the masking background noise, is measured. This study focused on the results obtained when music was played as masking background noise.

The second part of the survey includes 10 A/B comparisons between different EWSs. The listener is able to switch back and forth listening to two different signals. They are asked to compare signals for:

- A sense of urgency
- Certainty in identifying the source of sound
- A startling effect

4.2 Candidate Signals

The following describes the twelve EWS sounds that were tested and evaluated during the survey. Spectrograms of the candidate signals are shown in Appendix A.

EWS #1: This signal is the digital baseline train horn sound with Doppler-effect increasing all tones 20% over a cycle time of 0.2 seconds. The signal is repeated without any gaps. This EWS sounds fairly electronic and fast.

EWS #2: This signal is the digital baseline train horn sound without any Doppler-effect. Instead over a cycle time of 1 second, all of the tones are modulated 2% at a modulation frequency of 15 Hz (both beginning and end of the cycle). Additionally, the entire signal is amplitude modulated +/- 6 dB 10 times a second. The EWS sounds like an electronic train horn with a significant amount of warble.

EWS #3: This signal is the digital baseline train horn sound with Doppler-effect increasing all tones 5% over a cycle time of 1 second. The tones are modulated 1% at a modulation frequency of 8 Hz at both the beginning and end of the cycle. Additionally, the entire signal amplitude is ramped up 3 dB over the 1-second cycle. The signal is repeated without any gaps.

EWS #4: This signal is the digital baseline train horn sound with Doppler-effect increasing all tones over a cycle time of 1 second. Each tone is increased in frequency 25% of the auditory filter critical bandwidth of that tone. So, for example, the 355 Hz tone has an auditory critical bandwidth of 109 Hz and 25% of that is 27 Hz. Therefore, the tone is increased from 355 to 380 Hz (or 8%). All tones were increased approximately 4 to 8 percent. Additionally, the signal included 15% modulation at a modulation frequency of 4 Hz (beginning) and 20 Hz (end). Overall, this signal is very electronic and fast.

EWS #5: This signal is the digital baseline train horn sound with Doppler-effect increasing all tones 5% over a cycle time of ¼ second. This signal sounds like a "thumping" train horn as it maintains more of the train horn character than other candidate EWSs.

EWS #6: This signal is the digital baseline train horn sound with Doppler-effect increasing all tones 5% over a cycle time of 1 second. This signal is similar to EWS #5 with a slower "thumping" characteristic.

EWS #7: This signal includes both an analog baseline train horn sound (for the primary tones) and the digital baseline train horn sound for all harmonics. For the harmonic tones (700 Hz and above), the signal is similar to EWS #2 which does not include a Doppler-effect, but frequency modulation or "shaking" of the tones. Additionally, the Rumbler was added in for additional low-frequency content. The overall signal sounds like a fairly electronic train horn.

EWS #8: This signal is the analog baseline train horn sound including the primary and all harmonics. The Rumbler has been added in for additional low-frequency content. The overall signal sounds more like the standard train horn warning signal than many other candidate EWSs.

EWS #9: This signal is similar to EWS #7 which is a mixture of the analog baseline and digital baseline sound; however, this signal does not include the Rumbler. The overall signal sounds like a standard train horn signal with additional high-frequency content.

EWS #10: This signal is similar to EWS #9; however, instead of keeping just the primary tones in the analog baseline stationary, the primary tones and their first two harmonics are kept stationary. Upper harmonics (i.e. 3rd harmonics and above) are based on the digital signal that includes frequency modulation or "shaking" of the tones. The overall signal sounds more like the standard train horn warning signal than many other candidate EWSs.

EWS #11: This signal is similar to EWS #9; however, instead of modifying the harmonics with just frequency modulation, they have simulated Doppler-effect which increases these harmonics 20% over a cycle time of 0.2 seconds. The overall signal sounds highly-electronic and thumping.

EWS #12: This signal is the analog baseline train horn sounds including the primary and all harmonics. Lower-frequency "fractional harmonics" including all ½ and 1/3 frequencies of the primary tones have been included. The overall signal sounds like a deep and rich train horn sound with a slight beating effect in the lower frequency.

4.3 Survey Results

A total of 21 participants completed the surveys. As shown in Figure 20, the source identification results indicate that the actual baseline train horn was identified correctly by all participants. Interestingly, only 2 of 21 participants correctly identified the Rumbler as a police warning signal. Of the candidate EWS sounds, #9 and #10 had the highest number of participants identify the source as a train. All nine participants identified #9 as a train and eight of nine identified #10 as a train. As shown in Figure 21, participants responded that they had the highest level of certainty in the source of the sound for EWS #9.

The sense of urgency that each signal caused is shown in Figure 22. This figure shows the average rating, as well as plus and minus one standard deviation. Measuring the sense of urgency is one of the most important metrics for assessing the effectiveness of the EWS, since the primary purpose of the EWS is to cause the listener to take action and move away from the tracks. This figure shows that there is not a significant difference among most of the EWSs. The Rumbler, in fact, is shown to be one of the least effective signals. EWS #2, #3 and #12 are shown to cause a relatively low sense of urgency compared to the train horn. EWS #1, #4 and #6 are slightly higher than the train horn. EWS #9, which was one of the better performing signals for identification as a train source create a slightly higher sense of urgency than the train horn.

Figure 23 displays the level of startlement caused by the EWSs. Being startled can have both positive and negative effects regarding safety. Listeners that are startled have had a quick and rapid response to the EWS, which is desirable; however, it also could indicate a sense of confusion and hinder any efforts to respond (i.e. leaving the tracks). Results for the sense of urgency compared to the evidence of startlement show that listeners provided very similar responses to these two questions.

The detectability of the different signals over music masking is shown in Figure 25. Relative differences in detectability compared to the baseline train horn are shown in Figure 26. For reference, if a particular EWS can be heard or the need to take action occurs 6 dB lower than the standard train horn, this means that the EWS would be effective when the train is twice the distance away. Therefore, if the standard horn was audible when the train was 400 feet away, the new EWS would be audible when the train was 800 feet away. Doubling the distance of the train will also double the amount of time trespassers and railroad workers have to vacate the tracks. The Wail and Yelp standard warning signals are shown to be audible at the lowest d-prime levels. The Wail could be heard at a level approximately 8 dB lower and the Yelp could be heard at a level approximately 10 dB lower than the standard train horn. Many of the candidate EWSs that were adaptations of the baseline train horn improved audibility by 5 dB or more compared to the standard train horn. In regard to the amplitude needed to take action, many of the EWS candidates were effective one to three dB lower than the standard train horn.

The most effective EWS candidate must be able to 1) be correctly identified as a train, 2) create a high sense of urgency and 3) be detectable at relatively low signal-to-noise ratios. Figure 27 plots the percentage of correct source identification versus the urgency rating for all candidate signals. Signals near the upper right hand corner are more effective because they create a sense of urgency while maintaining high source identification. This figure shows that EWS #9 and EWS #10 perform well in regard to source both source identification and urgency.

Figure 28 displays the percentage of correct source identification versus the difference in detectability relative to the train horn for all candidate signals. Signals which are near the lower right hand corner are more effective because they are more easily heard while maintaining high source identification. EWS #9 and EWS #10 perform well in regard to these two categories.

Figure 29 displays the sense of urgency generated by the warning signals versus the difference in detectability relative to the standard train horn. Signals which are near the lower right hand corner are more effective because they are more easily heard and create a greater sense of urgency. EWS #1, EWS #6, EWS #9 and EWS #11 perform well in regard to these two categories.

The results in Figure 27 through Figure 29 indicate that EWS #9 is one of the most effective candidate EWSs as it performs well in the three most important categories. This EWS is a combination of both the analog and digital baseline which includes frequency modulation of the tones instead of a Doppler effect.

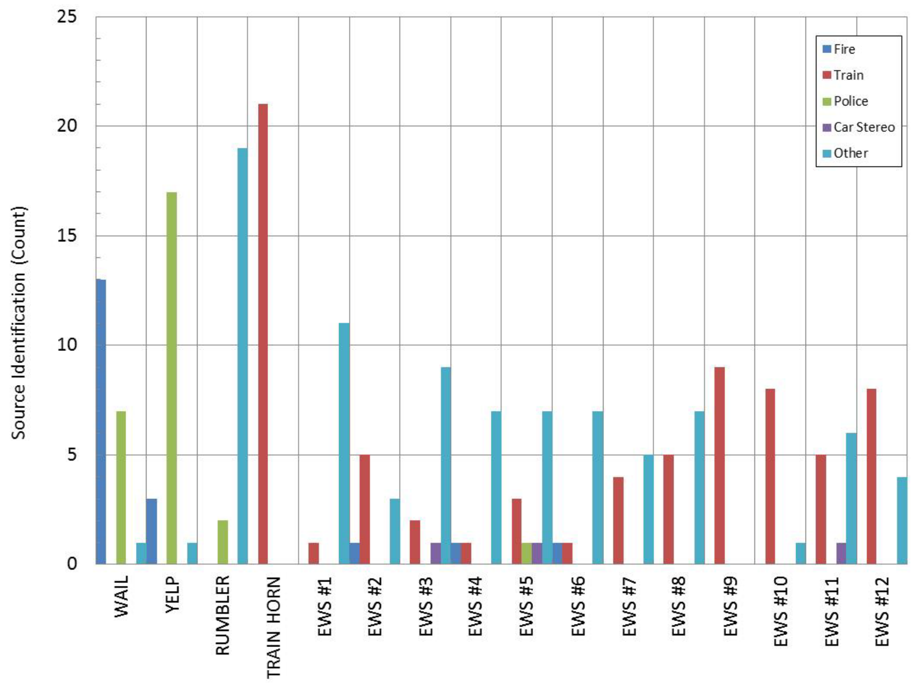


Figure 20. EWS Source Identification

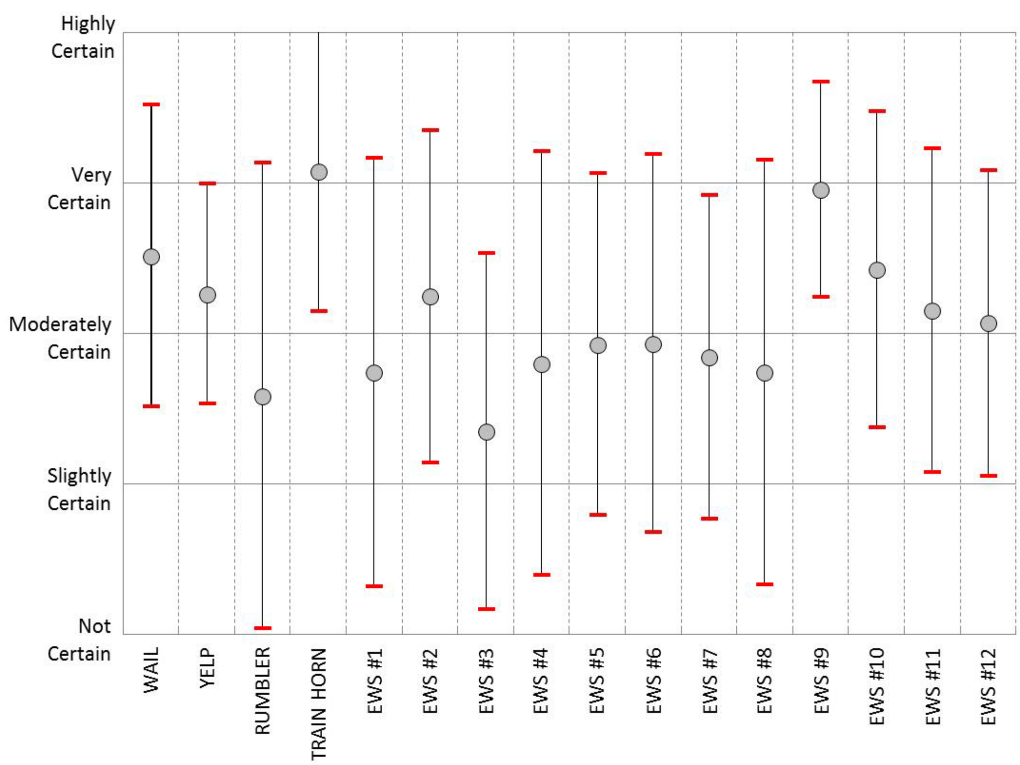


Figure 21. EWS Certainty of Source Identification Rating (Average +/- Standard Deviation)

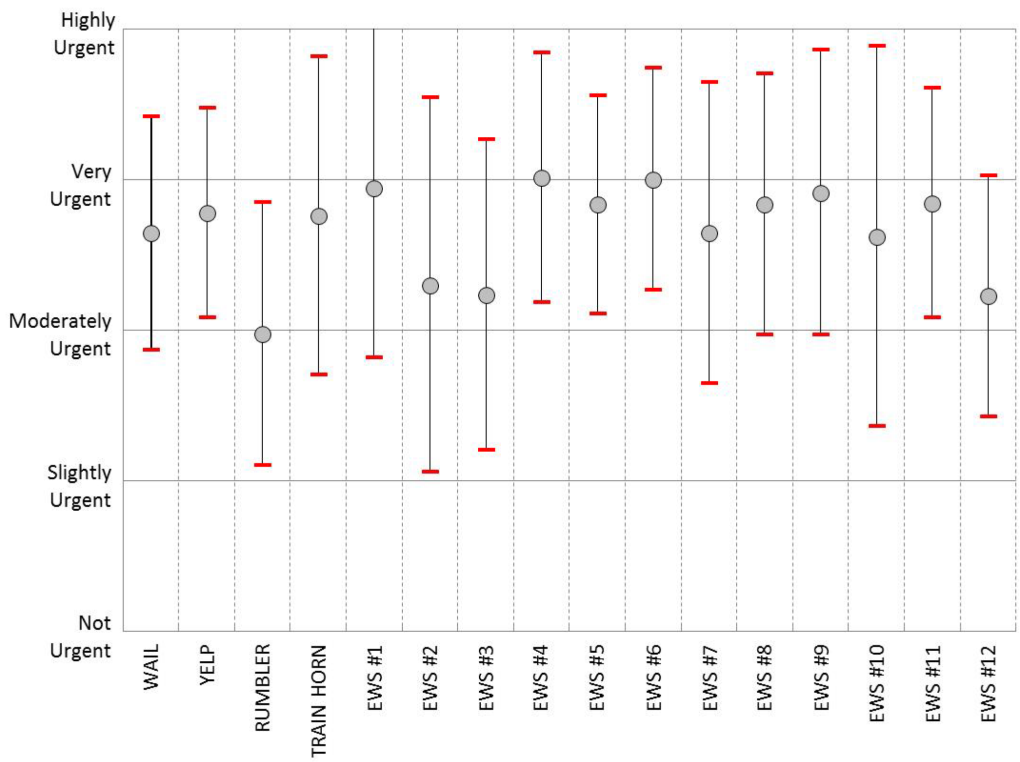


Figure 22. EWS Urgency Ratings (Average +/- Standard Deviation)

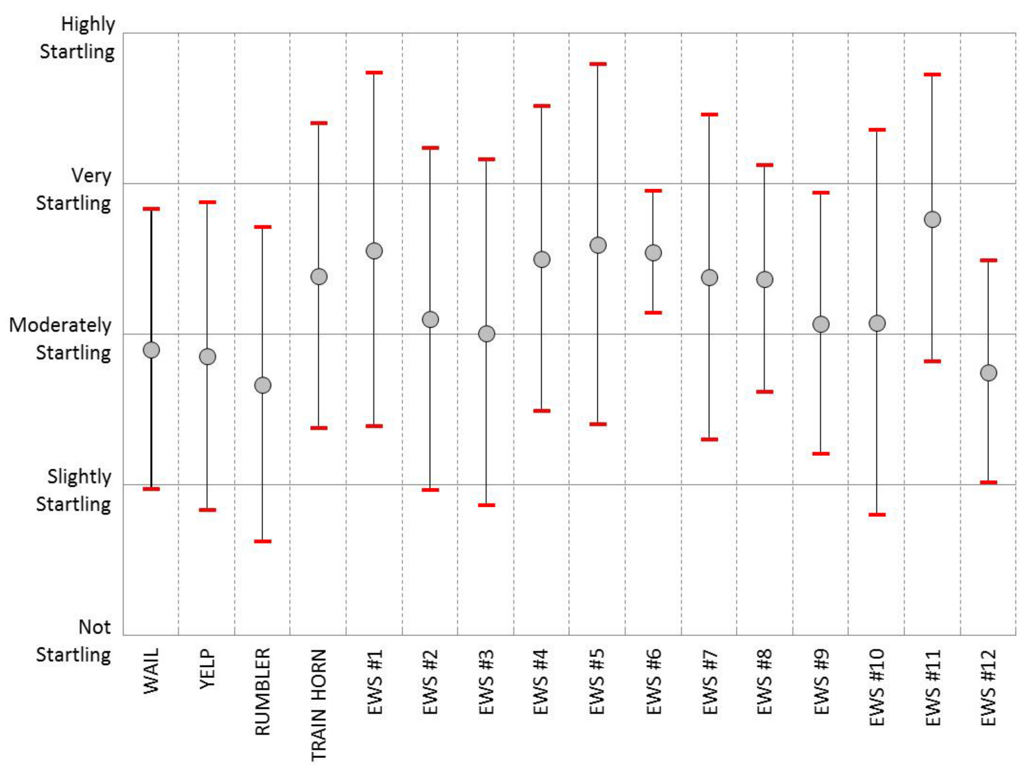


Figure 23. EWS Startling Effect Rating (Average +/- Standard Deviation)

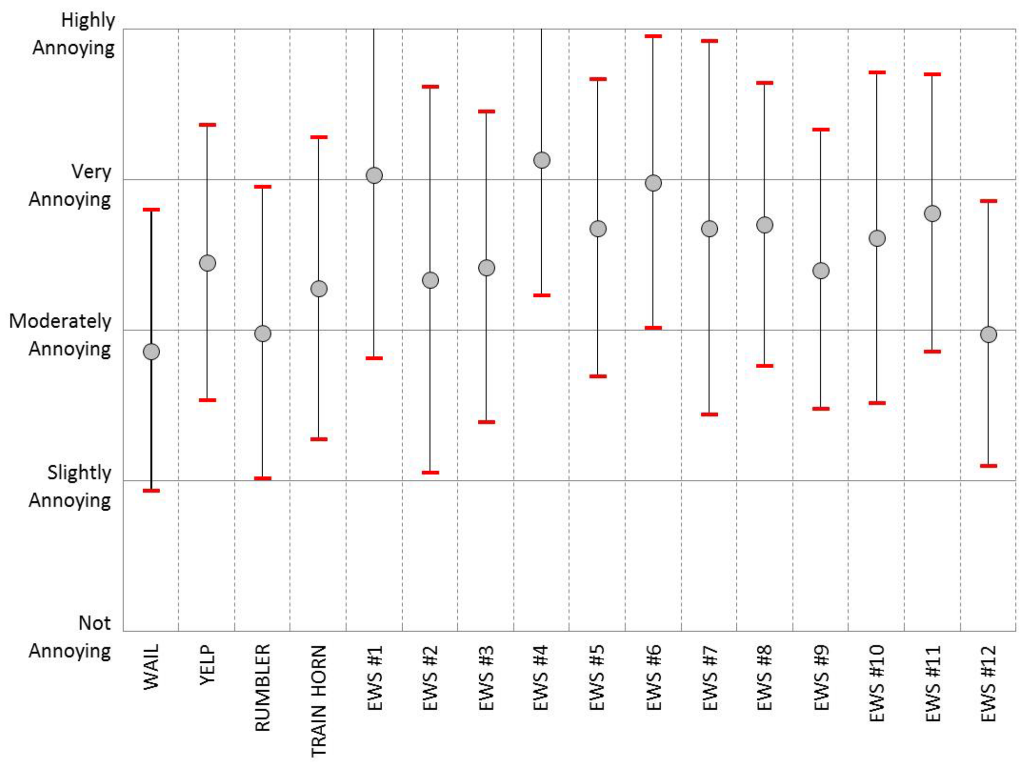


Figure 24. EWS Annoyance Rating (Average +/- Standard Deviation)

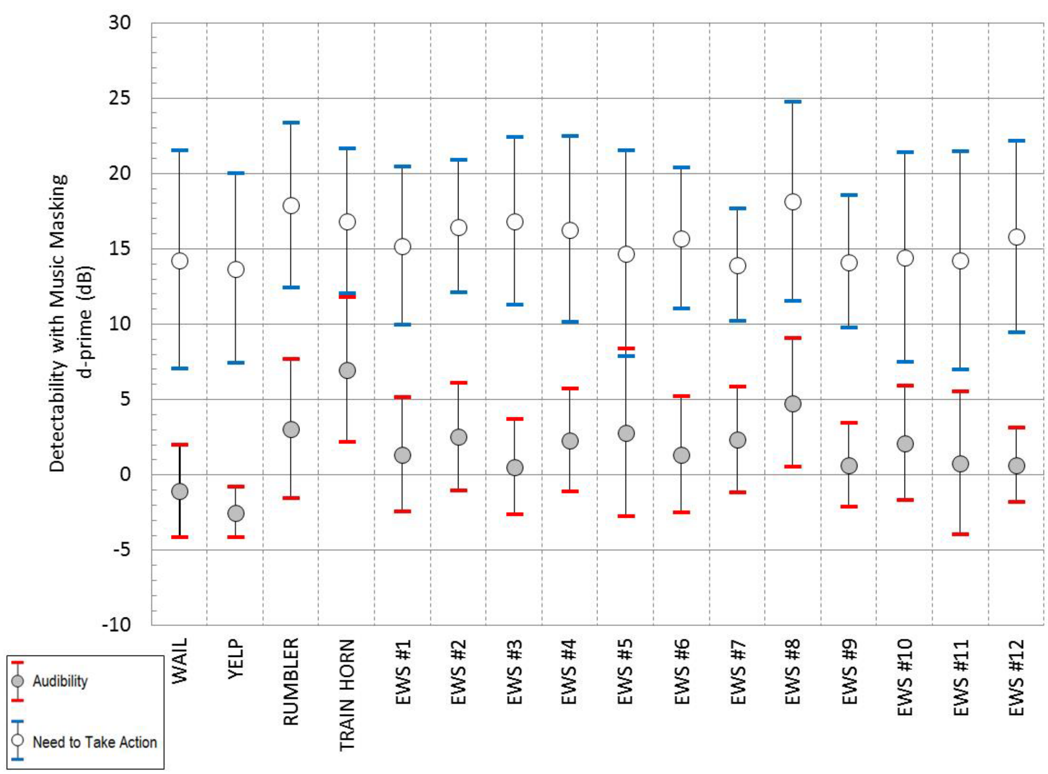


Figure 25. EWS Detectability with Music Masking (Average +/- Standard Deviation)

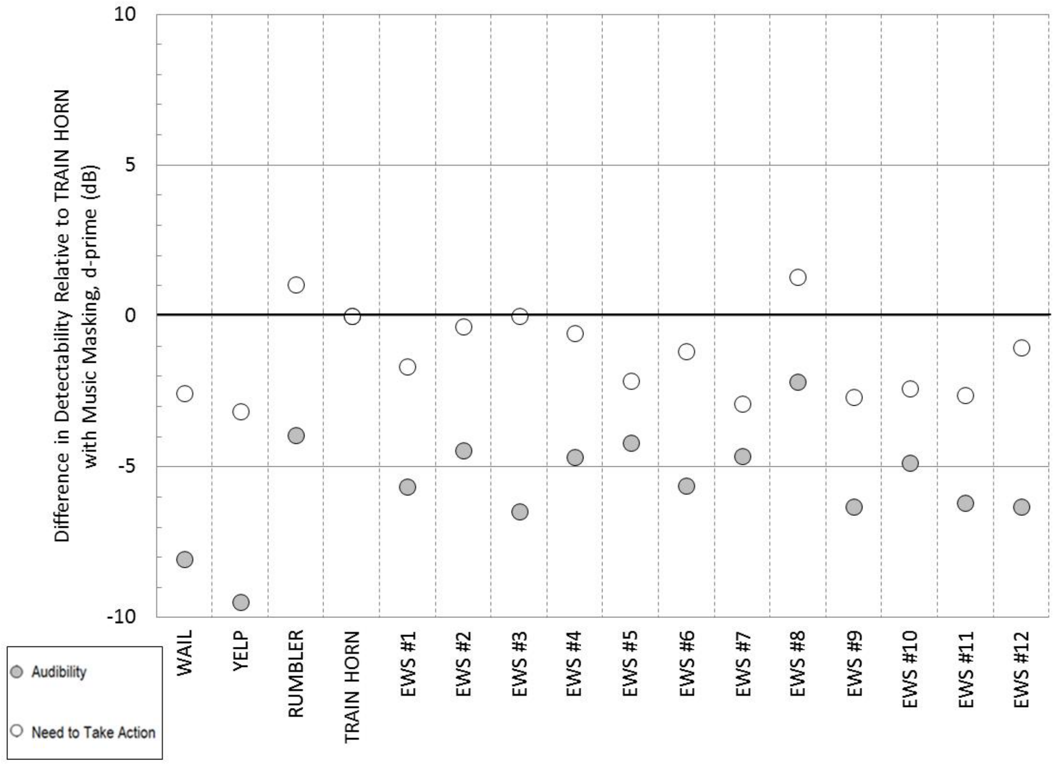


Figure 26. Difference in Detectability Relative to Train Horn with Music Masking

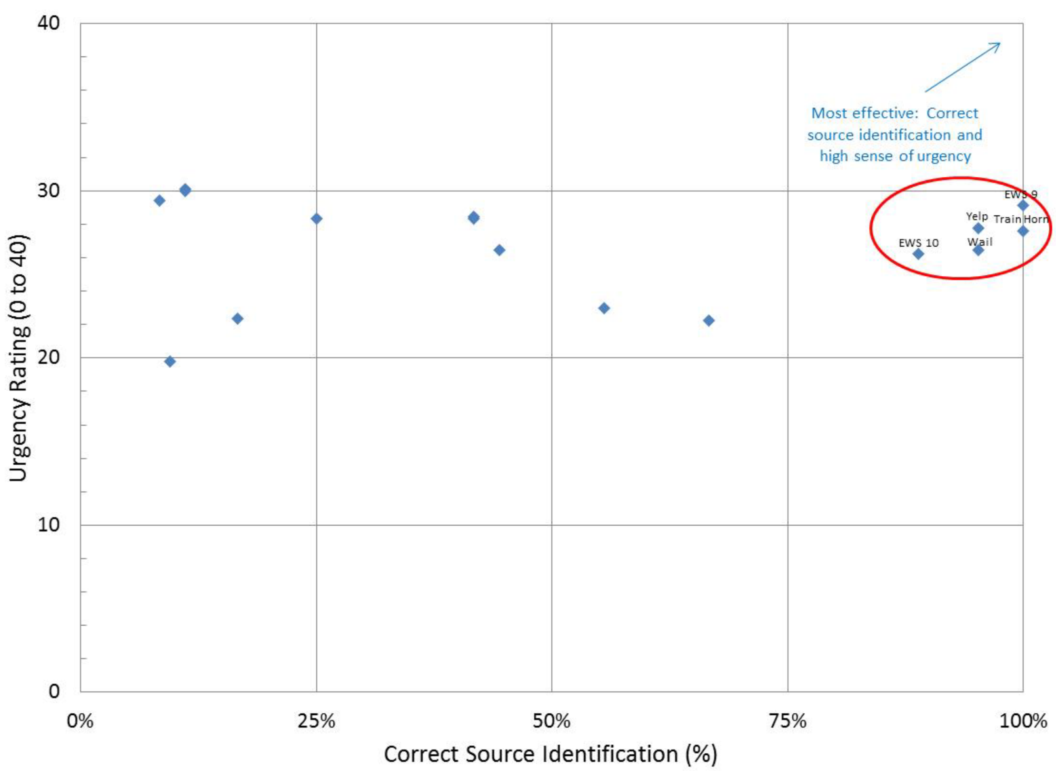


Figure 27. Correct Source Identification % vs. Urgency Rating

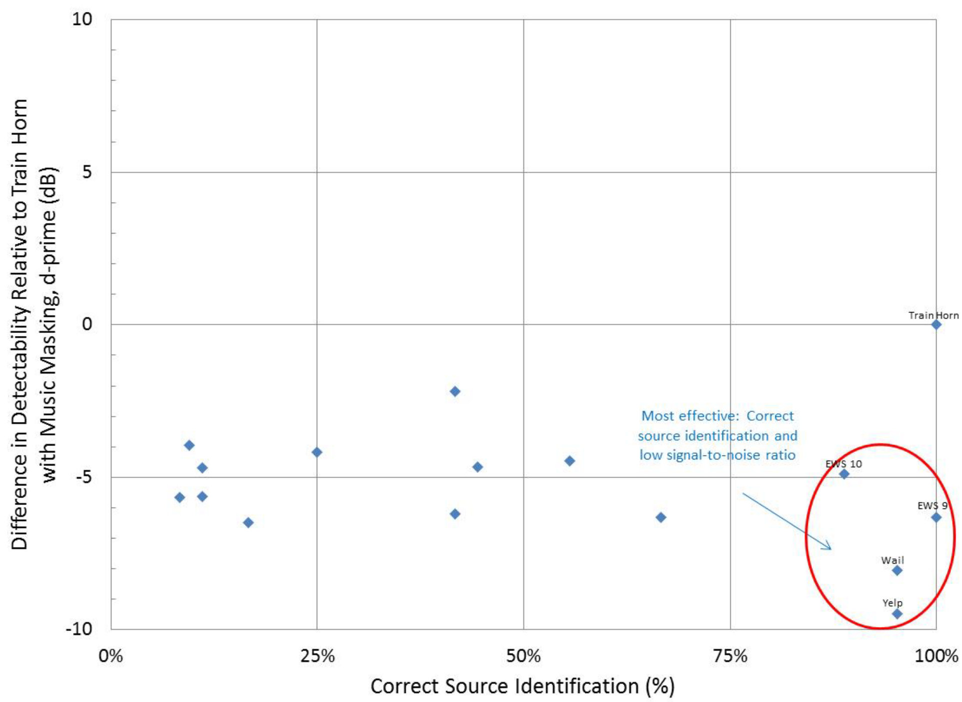


Figure 28. Correct Source Identification % vs. Difference in Detectability with Music Masking

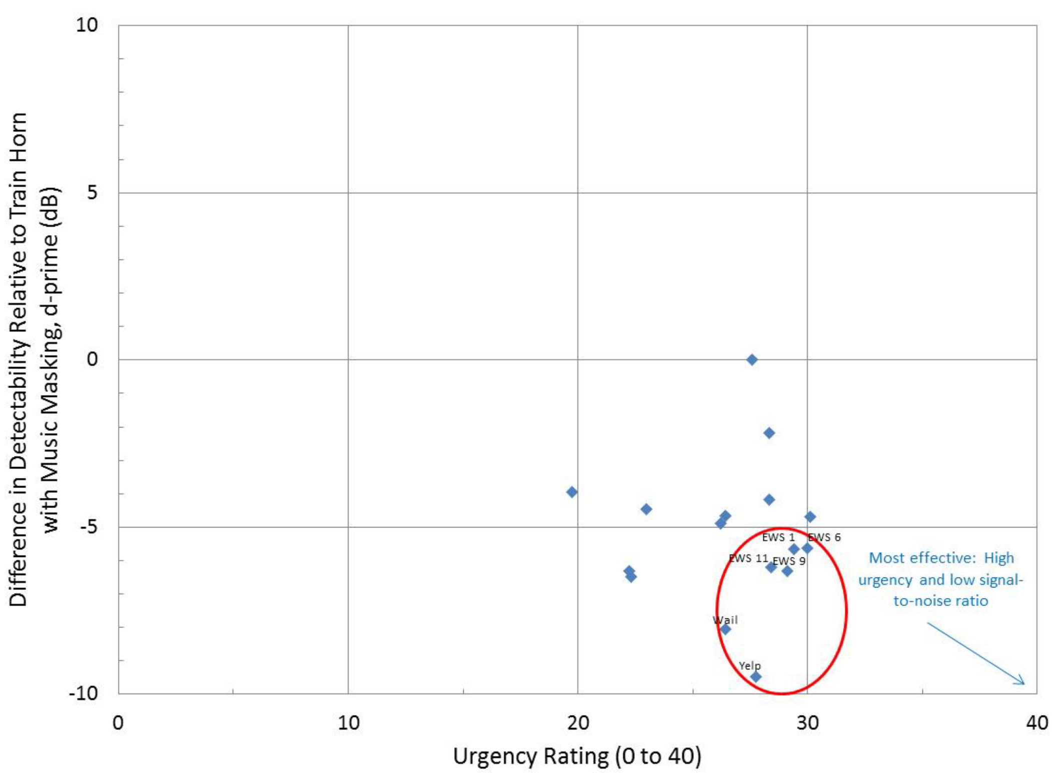


Figure 29. Urgency Rating vs. Difference in Detectability with Music Masking

5. Conclusion

This study indicates that it is possible to create a more effective EWS sound which can increase the sense of urgency in trespassers, reduce the signal-to-noise ratio at which detection occurs, and maintain the ability to identify the noise source and associate a EWS sound with a train.

The standard Wail and Yelp signals used on emergency response vehicles such as police cars and fire engines have been shown to perform better in several areas than the standard train horn signal. The Rumbler, which is a primarily low-frequency warning signal, was shown to perform poorly in source identification and creating a sense of urgency. As such, adding the Rumbler sound or extending the low-frequency content of candidate EWSs did not tend to improve effectiveness. Some of the more "electronic"-sounding versions of the train horn signals performed well in regard to creating a sense of urgency, but did not perform very well in regard to source identification.

The most effective candidate signal was shown to be a mix of the analog baseline standard train horn and digital baseline. It includes analog signal of the fundamental horn tones and digital versions of all of the harmonics which are modulated 2% at a modulation frequency of 15Hz. Additionally, amplitude modulation of +/- 6dB at 10Hz was applied to these harmonics.

Based on the findings of this initial study, next steps will include generating EWS sounds that are similar to EWS #9 but incorporate elements of a Wail and a Yelp to further improve its performance. Since an actual on-board locomotive EWS would be reproduced from a train that is moving and at times accelerating, the overall noise exposure will be different than what has been evaluated in this survey. Based on the actual distance of the train to the listener, the amplitude of the overall signal will increase or decrease and there would be a Doppler-effect when the train is accelerating or decelerating. To understand how this will affect the EWS, either audio engineering software can be used to replicate the anticipated rise and fall of sounds and the potential for additional Doppler-effect due to the accelerating train, or these EWS can be reproduced on an actual moving train. The latter option is preferred as this can also easily take into account the real-life effects such sound propagation over long distances.

Selected noise-cancelling headphones that may be used by right-of-way trespassers was found to greatly attenuate sounds greater than 2 kHz passively and below 800 Hz with a peak at 200 Hz actively. There is a band between 800 Hz and 1200 Hz which is minimally affected by these headphones, offering target frequencies for EWS sounds as heard by the trespasser.

Critical next steps include building on the EWS #9 approach and adding more characteristics from the Wail and Yelp sounds. Some of the changes may include longer duration rise and continuous fall in frequency for the signal. Signals in this test included abrupt drops in frequency versus the Wail and Yelp, which produce a continuous rise and fall. This is likely a more useful signal and less injurious to the speakers when volumes are increased. Larger frequency shifts are also more likely to be detected through music.

A next series of surveys will be conducted within the audiometric booth. This allows realistic assessment of the headphone attenuation with and without active noise cancellation. The external speakers in the booth that simulate the EWS will also increase in sound level appropriate for a constant speed approaching train. The sound level increase is roughly logarithmic with changes in frequency content. The higher frequencies are more attenuated with distance and including these effects provides a more realistic simulation. The booth testing will provide the final iteration prior to testing at the Transportation Technology Center, Inc. (TTCI).

TTCI testing will be with instrumented sound level meters wayside. A "trespasser" will be located near the tracks with in-ear microphones and headphones. All appropriate safety procedures will be in effect. The subject will record the realistic sense of urgency of the developed EWS sounds as well as the baseline sounds of a train horn, Wail and Yelp. These tests will guide the design of both the EWS and the sound system and sound pressure levels needed to provide sufficient time to vacate the tracks. Time to vacate the tracks will be tested with several individuals to assess that portion of the reaction time.

6. References

American National Standards Institute. (1995). *Bioacoustical Terminology*. American National Standards Institute, S3.20-1995.

American National Standards Institute. (2008). Methods for Measuring the Real-Ear Attenuation of Hearing Protectors. American National Standards Institute, S12.6-2008.

American National Standards Institute. (2010). Methods for Measurement of Insertion Loss of Hearing Protection Devices in Continuous or Impulsive Noise Using Microphone-in-real-Ear or Acoustic Test Fixture Procedures. American National Standards Institute, S12.42-2010.

Balastegui, A., et al. (2011). On the Power and Frequency of Auditory Signals on Emergency Vehicles. *Inter-Noise 2011*, Osaka, Japan.

Berger, E. (2005). Preferred Methods for Measuring Hearing Protector Attenuation, *Inter-Noise 2005*. Rio de Janeiro, Brazil.

Benthorn, L., and Frantzich, H. (1996). Fire alarm in a public building: How do people Evaluate information and choose evacuation exit? Unpublished report, Department of Fire Safety Engineering, Lund University.

Catchpole, K., McKeown, D., and Withington, D. (2004). Localizable Auditory Warning Pulses. *Ergonomics*, Volume 47.

Catchpole, K., and McKeown, D. (2007). A Framework for the Design of Ambulance Sirens. *Ergonomics*, Volume 50.

CAC Title 13, Article 8, 2010. Barclays Official California Code of Regulations, Title 13. Motor Vehicles, Division 2. Department of the California Highway Patrol, Chapter 4. Special Equipment, Article 8. Sirens, 2010.

Crocker, M. (2007). *Handbook of Noise and Vibration Control*, Wiley & Sons.

Ebata, M., and Baba, H. (1969). Detection of the Ambulance Siren While Driving. Institute of Noise Control Engineering.

Fastl, H. (2005). Psychoacoustics and Sound Quality, *Communication Acoustics*, Blauer, J., Springer.

Fastl, H., et al. (2010). Perceptive Aspects of Emergency Signals, *Inter-Noise 2010*, Lisbon, Portugal.

Federal Railroad Administration Office of Safety. Casualty Summary Tables Section 4.08. Retrieved from Office of Safety.

General Services Administration. (2007). Federal Specification for the Star-of-Life Ambulance, Report No. KKK-A-1822F, Washington, DC: U.S. General Services Administration.

Green, M. (2000). "How Long Does It Take to Stop?" Methodological Analysis of

Driver Perception-Brake Times. *Transportation Human Factors*, *2*(3), 195–216.

Haas, E., and Casali, J. (1995). Perceived Urgency of and Response Time to Multi-tone and Frequency-modulated Warning Signals in Broadband Noise. *Ergonomics*, Volume 38.

Haas, E., and Edworthy, J. (1996). Designing Urgency into Auditory Warnings Using Pitch, Speed and Loudness. *Computing and Control Engineering Journal*.

Hara, K., et al. (2010). Perceptibility of environmental sounds by earphone wearers listening to pop and rock music. *The Acoustical Society of Japan*, Volume 31.

Hay, W. W. (1982). *Railroad Engineering*. Wiley-Interscience.

Hellier, E., and Edworthy, J. (1999). "On using psychophysical techniques to achieve urgency mapping in auditory warnings," *Applied Ergonomics*, Volume 30.

Hellier, E., and Edworthy, J. (1989). Quantifying the Perceived Urgency of Auditory Warnings, *Canadian Acoustics*, Volume 17.

Hellier, E., Edworthy, J. ,and Dennis I. (1993). Improving Auditory Warning Design: Quantifying and Predicting the Effects of Different Warning Parameters on Perceived Urgency. *Human Factors*.

Hermann, T., Hunt A., and Neuhoff, J. (2011). The Sonification Handbook. *Logos Verlag*.

Howard, C., Maddern, A. and Privopoulos, E. (2011). Acoustic Characteristics for Effective Ambulance Sirens. *Acoustics Australia*, Volume 39.

International Standards Organization for Standardization (2003). Ergonomics – danger signals for public and work areas – Auditory danger signals. *ISO 7731*.

Kan, M., et al. (2011). Auditory thresholds for human subjects using a headphone, *Inter-Noise 2011*. Osaka, Japan.

Keith, S., et al. (1999). Sound Levels From Headphone/Portable Compact Disc Player Systems. *Inter-Noise 99*. Fort Lauderdale, FL.

Keith, S., et al. (2011). MP3 Player Listening Sound Pressure Levels Among 10 to 17 Year Old Students, *Journal of the Acoustical Society of America*, Volume 130.

Keith, S., et al. (2008). Evaluating the Maximum Playback Sound Levels From Portable Digital Audio Players, *Journal of the Acoustical Society of America*, Volume 123.

Kuwano, S., et al. (2000). The Timbre and Annoyance of Auditory Warning Signals in Different Countries, *Inter-Noise 2000*, Nice, France: *the 29th International Congress and Exhibition on Noise Control Engineering*.

Langlois, S., et al. (2008). Cross Cultural Study of Auditory Warnings, *Proceedings of the 14th International Conference on Auditory Display*, Paris, France, 2008.

Lichenstein, R., Smith, D., Ambrose, J., and Moody, L. (2012). Headphone use and pedestrian injury and death in the United States: 2004-2011. *Injury Prevention*.

Maddern, A., Privopoulos, E., and Howard, C. (2011). Emergency Vehicle Auditory Warning Signals: Physical and Psychoacoustic Considerations. *Proceedings of ACOUSTICS*, 2–4 November 2011. Gold Coast, Australia.

Manion, M. (2012). *Operating Rules Book*, Norfolk Southern.

McNeill, K., et al. (2010). MP3 Player Listening Habits of 17 to 23 Year Old University Students, *Journal of the Acoustical Society of America*, Volume 128.

National Fire Protection Association. (2009) *Standard for Automotive Fire Apparatus.* National Fire Protection Association, NFPA 1901, Part 13.9, 2009.

Ngyuen, D. (2010). *Blue Line Keeps Grim Distinction*. The Associated Press.

Olson, P.L., and Sivak, M. (1986) Perception-response time to unexpected roadway hazards. *Human Factors*, *28*, 96–99.

Patterson, R., and Mayfield, T. (1990). Auditory Warning Sounds in the Work Environment. *Philosophical Transactions of the Royal Society of London*. Series B, Biological Sciences, *327*(1241), Human Factors in Hazardous Situations.

Patterson, R., Cosgrove, P., Milroy, R. and Lower, M. (1989). Auditory Warnings for the British Rail Inductive Loop Warning System, *Proceedings of the Institute of Acoustics*.

Perala, C. H., and Casali, J. G. (2009). Human subject investigation of MIRE microphone location during insertion loss testing of Active Noise Reduction hearing protectors in active and passive modes. *Noise Control Engineering Journal*.

Portnuff, C., Fligor, B., and Arehart, K. (2011). Teenage Use of Portable Listening Devices: A Hazard to Hearing? *Journal of the American Academy of Audiology*, 22:663–677.

Potter, R., Fidell, S., Myles, M. and Keast, D. (1977). Effectiveness of Audible Warning Devices on Emergency Vehicles. Report No. DOT-TSC-OST-77-38, Washington, DC: John A. Volpe National Transportation Systems Center.

Prasher, D., et al. (1998). Advances In Noise Research Volume 2: Protection Against Noise, Chapter 11, Personal Cassette Players: A Hazard To Hearing? Whurr Publishers Ltd.

Proulx, G., and Pineau, J. (1996). Differences in the evacuation behavior of office and apartment building occupants. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 40*, 825–829.

Rapoza, A., and Fleming, G. (2002). Determination of a Sound Level for Railroad Horn Regulatory Compliance. Report No., DTS-34-RR397-LR1. Washington, DC: John A Volpe National Transportation Systems Center.

Robinson, G., and Casali, G. (2002). Signal detection and speech intelligibility in noise using nontraditional hearing protectors. *Inter-Noise 2002*. Dearborn, MI.

SAE. (2008). SAE J1849:2002 Emergency Vehicle Siren. *Society of Automotive Engineers Standard.*

Suied, C., Susini P., and McAdams, S. (2008). Evaluating Warning Sound Urgency With Reaction Times, *Journal of Experimental Psychology: Applied*, Volume 14.

Wagner R. (2000). Guide to Test Methods, Performance Requirements, and Installation Practices for Electronic Sirens Used on Law Enforcement Vehicles, Volume 500, Issue 0 of NIJ guide, U.S. Department of Justice.

Woodson, W., Tillman, B., and Tillman, P. (1992). *Human Factors Design*

Handbook, 2nd edition. McGraw-Hill Publishing.

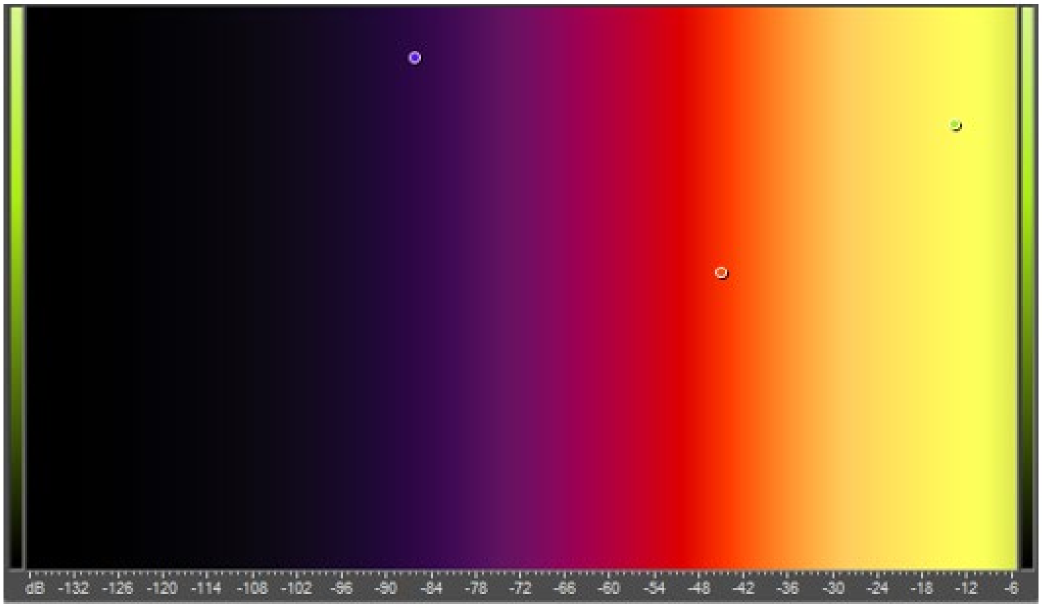
Suied, C., Susini, P., & McAdams, S. (2008). Evaluating warning sound urgency with Reaction times. *Journal of Experimental Psychology: Applied*, *14*(3), 201–212.

Abbreviations and Acronyms

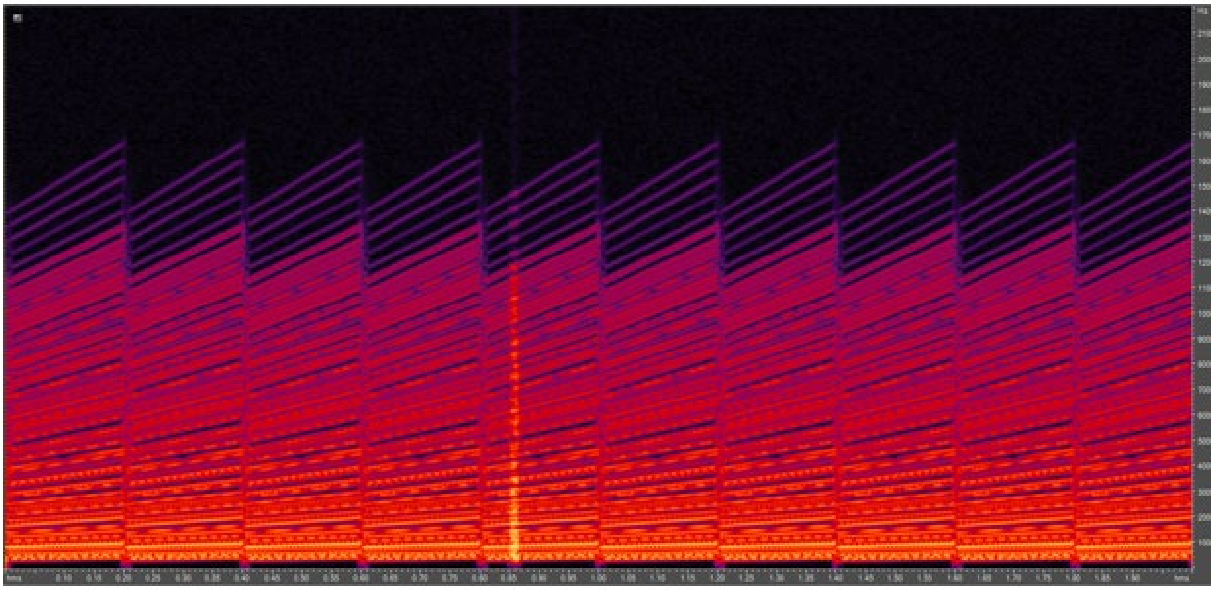
ANC	Active Noise Cancellation
AWD	Acoustical Warning Device
dB	Sound Decibel (Referenced to 20 micro-Pascals)
dBA	A-weighted Sound Decibel (Referenced to 20 micro-Pascals)
d-prime	Detectability Level
EWS	Emergency Warning Signal
FRA	Federal Railroad Administration
HMMH	Harris Miller & Hanson Inc.
Hz	Hertz (Cycles Per Second)
OSHA	Occupational Safety and Health Administration
QNA	QinetiQ North America
SAE	Society of Automotive Engineers
TTCI	Transportation Technology Center, Inc.
TWA	Time-Weighted Average

Appendix A. EWS Sounds Spectrograms

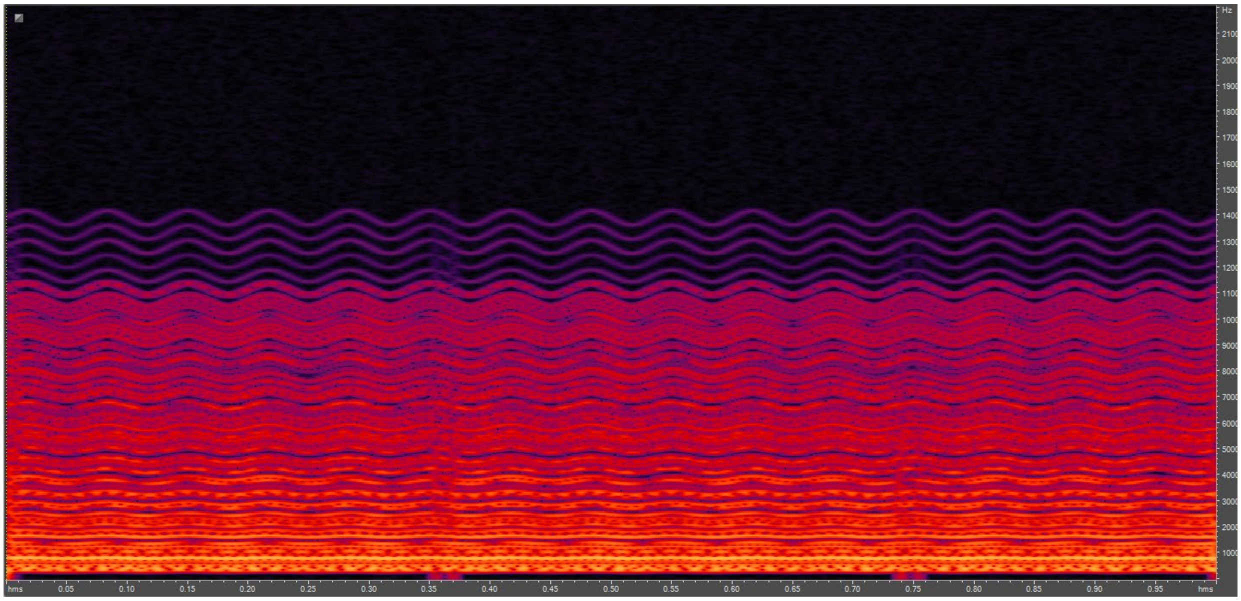
The following figures show the spectrograms of the candidates EWS sounds tested in Phase 1. Spectrograms illustrate the sounds by plotting the frequency content versus time. The amplitude of the sounds at a particular frequency is illustrated with the color. The color scale in Figure 30 shows that amplitude scale with yellows being the highest dB levels and scaling down to the purples and black for the lowest dB sound levels. Primary tones and their harmonics show as horizontal discrete bands.



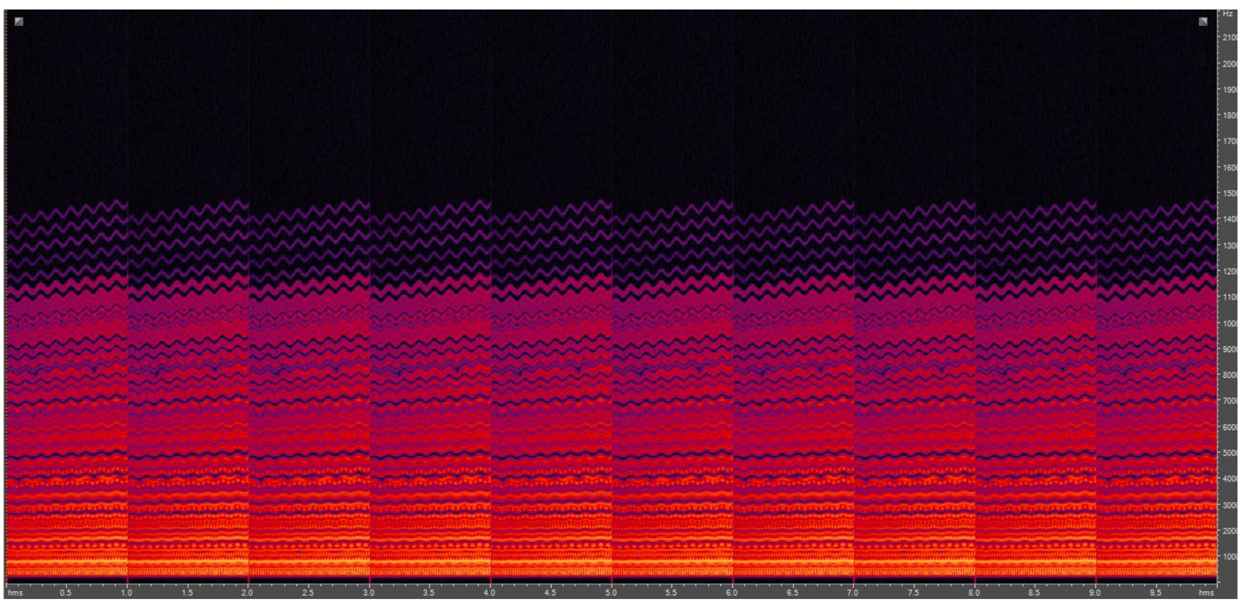
Spectrogram amplitude scale



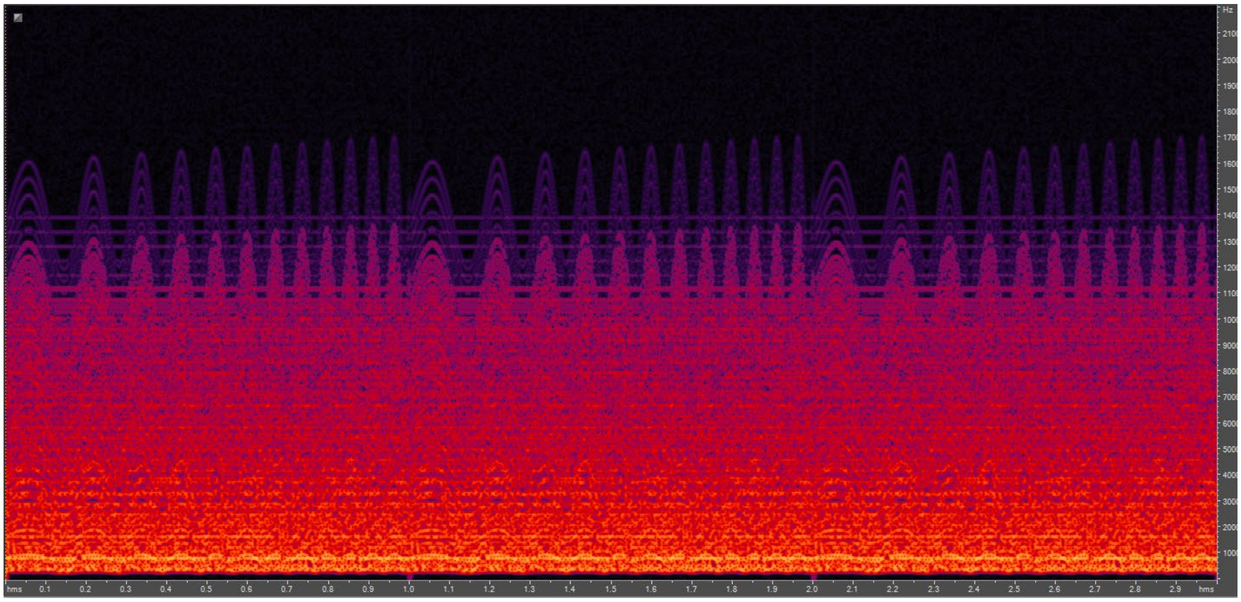
EWS #1, 2 sec sample, 0.2 sec Doppler increase of 20%



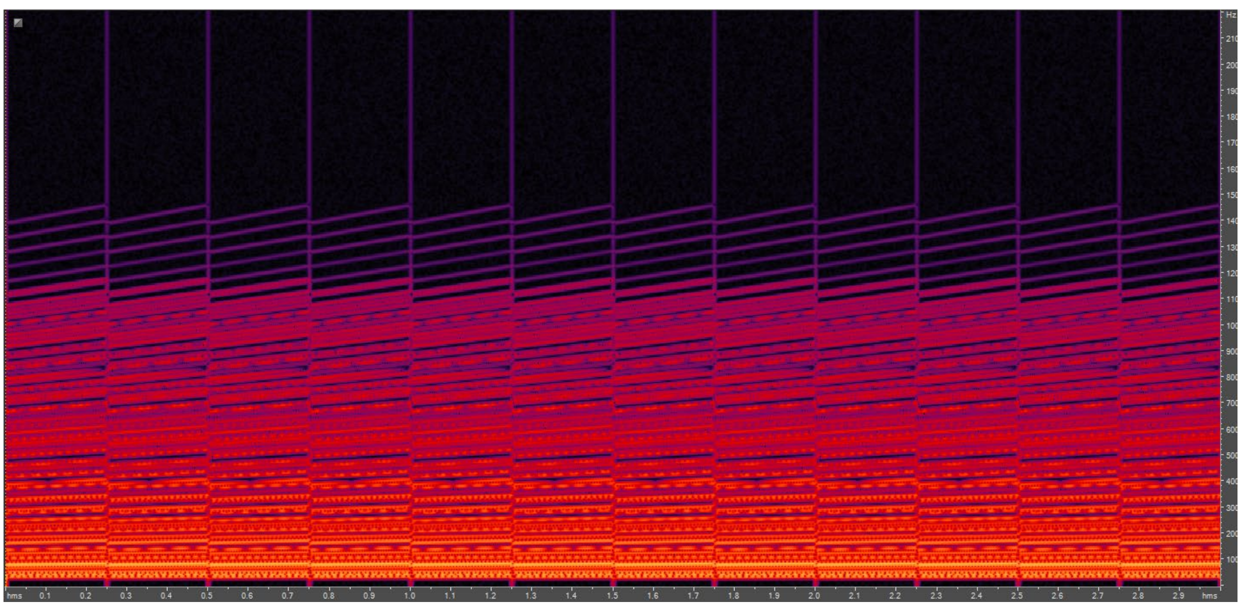
EWS #2, 1 sec sample, 2% frequency modulation 15 times/sec, 6 dB amplitude modulation 10 times/sec



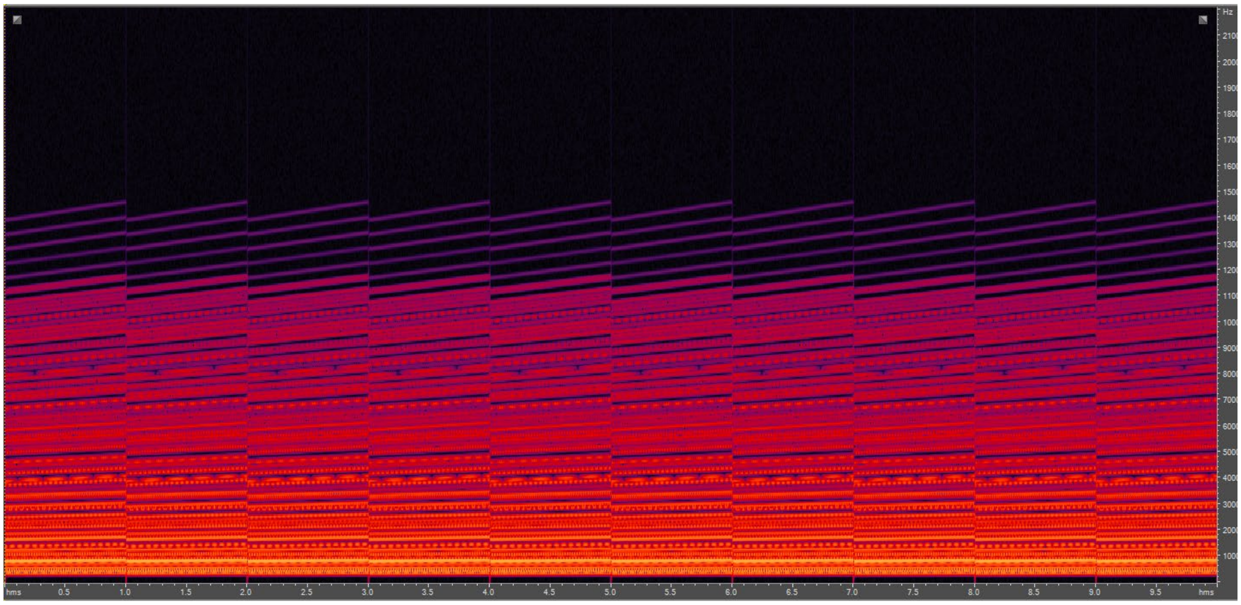
EWS # 3, 10 sec sample, 1 sec 5% Doppler frequency increase, 1% frequency modulation 8 times/sec, 3 dB amplitude modulation over 1 sec



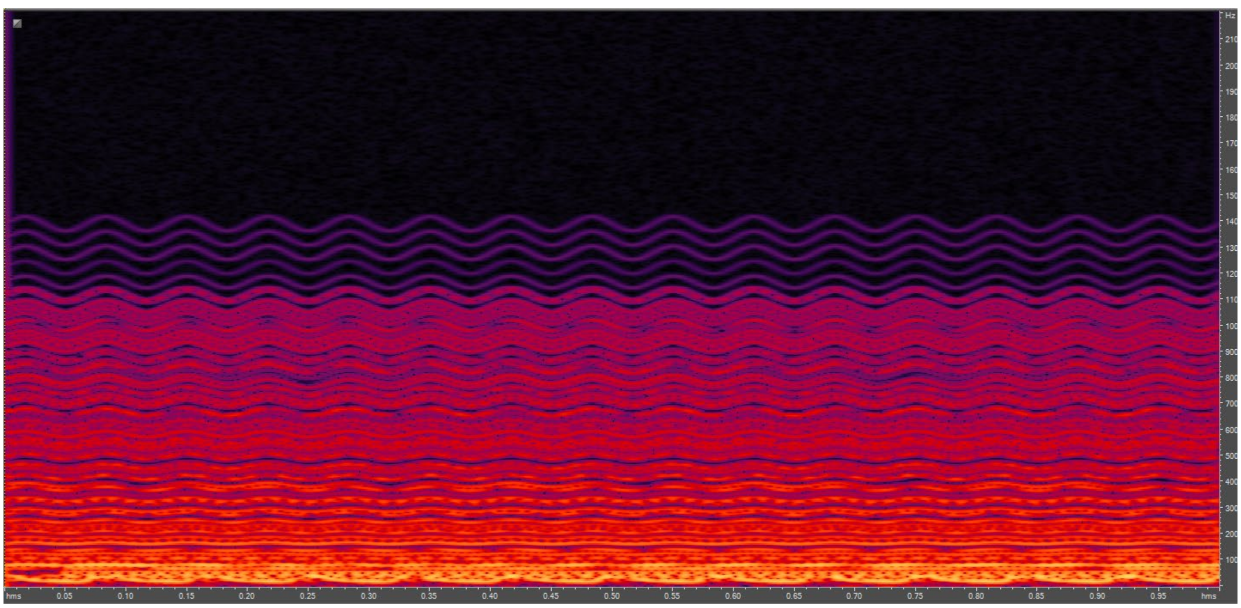
EWS #4, 3 sec sample, 1 sec Doppler increase of 4-8%, increasing 4 to 20 times/sec frequency modulation of 15% every second



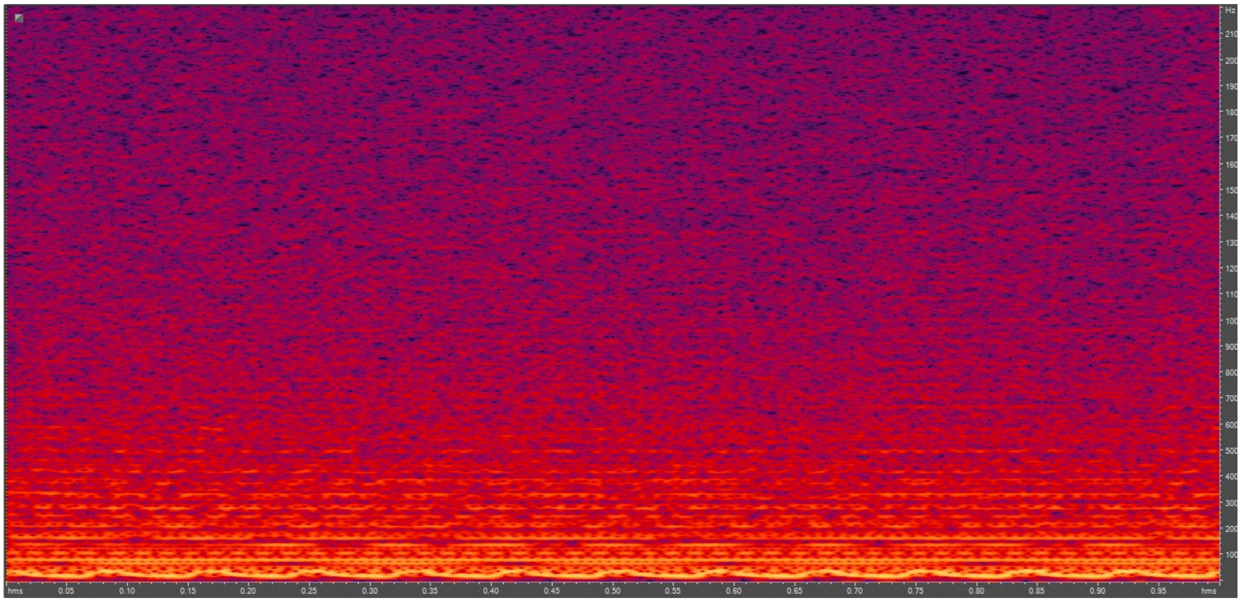
EWS #5, 3 sec sample, 5% Doppler 4 times/sec



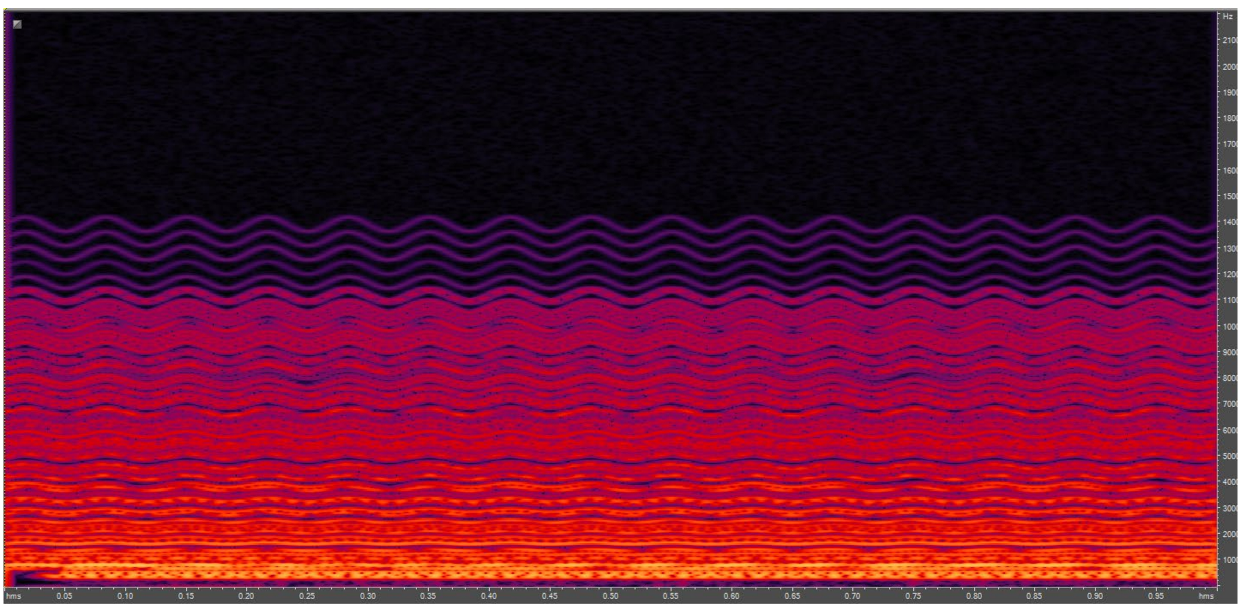
EWS #6, 10 sec sample, 5% Doppler every second



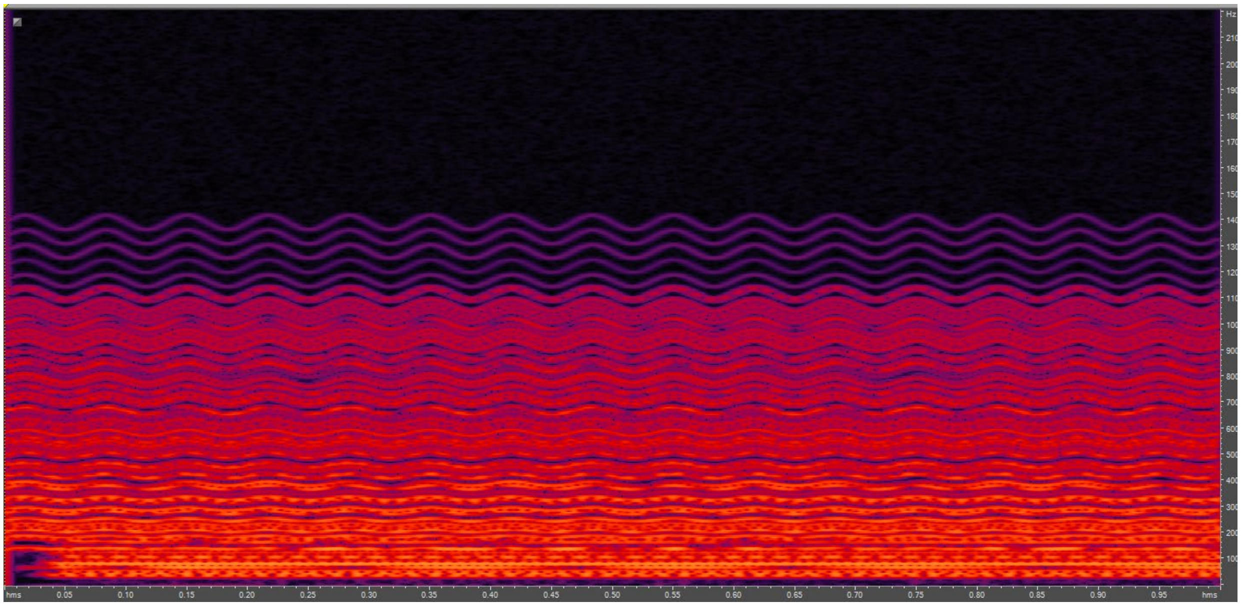
EWS #7, 1 sec sample, analog signal <700Hz, 2% frequency modulation 15 times/sec, Rumbler added at low frequencies



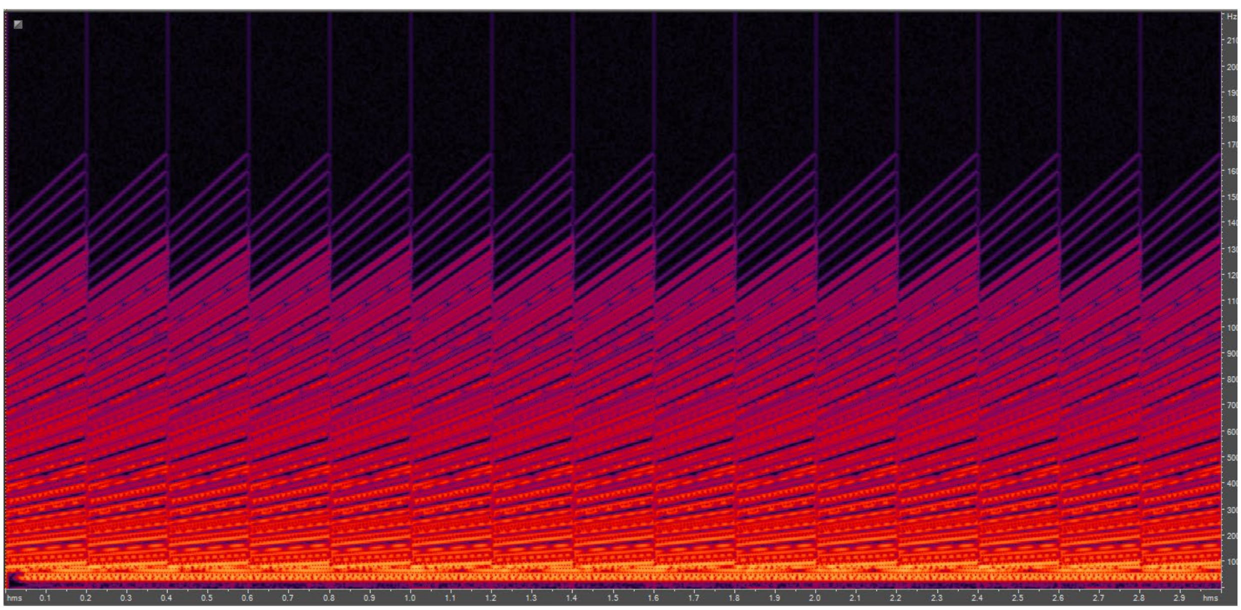
EWS #8, 1 sec sample, baseline analog horn with Rumbler



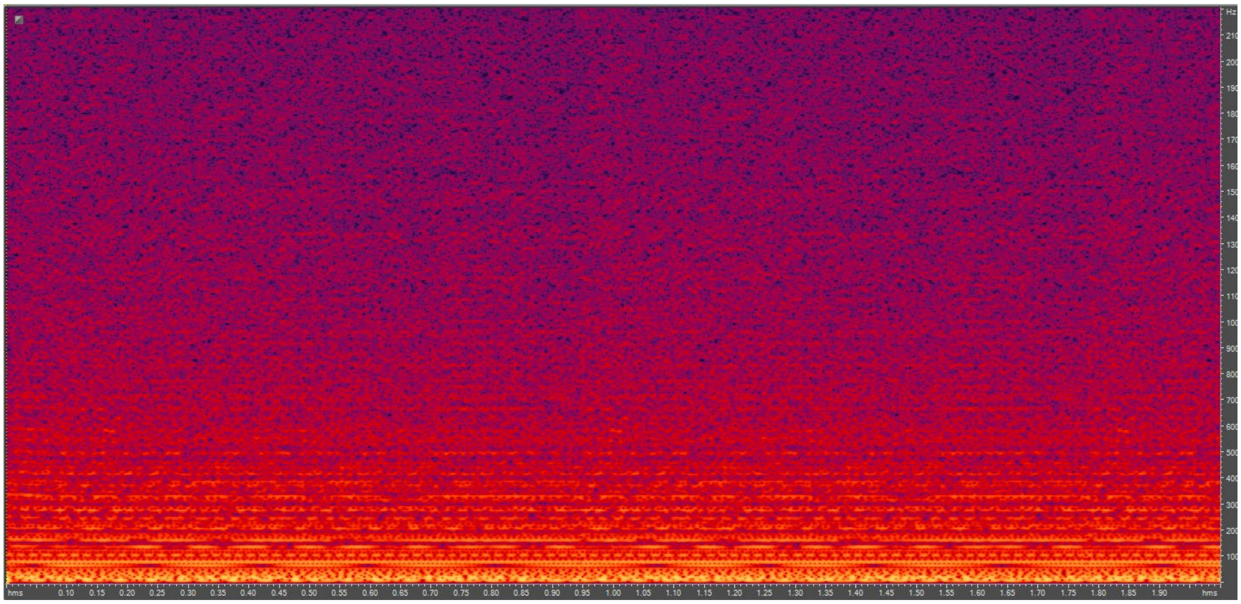
EWS #9, 1 sec sample, mix analog and digital horn, 2% frequency modulation 15 times/sec



EWS #10, 1 sec sample, 1st 3 harmonics are analog and stationary, higher harmonics with 2% frequency modulation 15 times/sec



EWS #11, 3 sec sample, 20% Doppler increase 5 times/sec



EWS # 12, 2 sec sample, all analog horn including ½ and 1/3 subfrequencies creating a low frequency beating effect