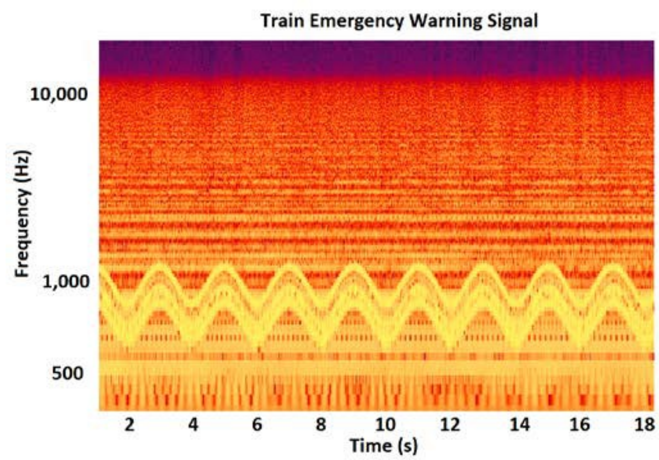
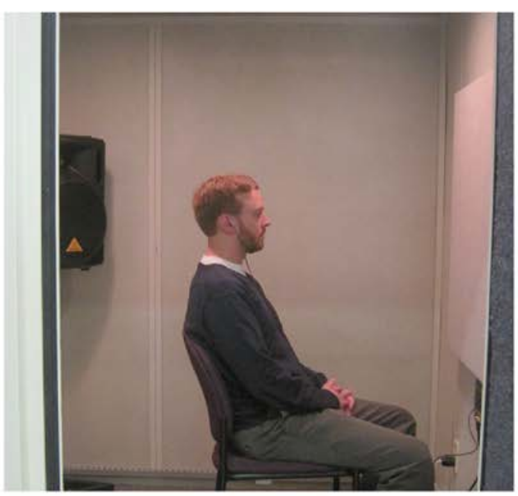
U.S. Department of Transportation

Federal Railroad Administration

Acoustical Warning Devices as Emergency Warning Signals (EWS), Phase 3: Performance Evaluation on a Locomotive

Office of Research, Development, and Technology
Washington, DC 20590





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Tom Campbell*, Basant Parida*, Jason Ross**

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
* QinetiQ North America
360 Second Avenue
Waltham, MA 02451

** VHB
101 Walnut Street
Watertown, MA 02471

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13. ABSTRACT (Maximum 200 words)
Emergency warning signal (EWS) sounds have been developed to improve safety for railroad workers and warn trespassers. Researchers conducted a literature review that addresses the need for a new EWS sound, the types of warning sounds used in railroad and non-railroad settings, and fundamental principles of human hearing as it relates to signal detection and masking effects from headphones and music. Preliminary EWS sounds were developed and their effectiveness evaluated with a listening survey. The survey measured the detectability, sense of urgency, identification/association of the sound with a train and the startle effect of various EWS sounds. Candidate EWS sounds were optimized and tested in an audio booth where participants listened to music with headphones while warning signals were reproduced to simulate a train approaching. Two candidate EWSs and a typical train horn sound were tested on board a moving locomotive on TTC tracks. The EWS sounds were reproduced using an acoustical warning device speaker system and the response times of participants wearing hearing protection or headphones were measured. This research shows that an EWS could maintain its association/identification of a train approaching, improve detectability, and provide more time to persons wearing headphones to vacate the tracks.

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Emergency warning sound, train horn, yelp, wail, trespassers, music masking sounds, reaction time, detectability, urgency, acoustic warning device

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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

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 CONVERSIO

°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

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Executive Summary

From the original "steam trumpet" built for locomotives in 1832 by the Leicester and Swannington Railway to modern air pressure horns, the warning signals used on trains have not changed significantly. The focus of this research is to improve safety for railroad workers in the right-of-way and warning levels for trespassers wearing headphones and listening to music. The authors have investigated new train horn technologies based on electronic acoustic sources and have developed and tested new candidate emergency warning signals.

The research team conducted a literature review of existing research on emergency warning signals (EWS). The review supports the need for a new locomotive EWS, evaluates the human hearing process, and explains how EWS can be designed to improve detectability and effectiveness. It also investigates how headphones and music affect the human ability to detect audible warnings, the methods used to develop and test EWS, and the amount of time typically needed for trespassers to vacate the tracks.

The team developed a listening survey to assess the ability of listeners to associate the source of the warning signals with a train, the detectability of the warning signal with and without music masking, the annoyance of the warning signals, and the sense of urgency to move away from the train. This survey showed that only certain new EWS maintained an association with a train event. Varying the acoustic parameters can easily affect the association of the sound sources with a train and that care must be taken to maintain proper source identification. The survey showed that some EWS could create a greater sense of urgency than a standard train horn. While some new EWS were detectable at a level 5 dB lower than the standard train horn, the police/fire wail and "yelp" signals were significantly more detectable at a level 8 to 10 dB lower than the train horn. This shows that a new EWS can perform better than a standard train horn sound. However, most importantly, this showed that maintaining characteristics of the police/fire wail and yelp in a new train EWS could further improve effectiveness.

Researchers then optimized candidate EWS based on the findings from the listening survey and tested them in an audio booth where participants listened to music with headphones while warning signals simulated an approaching train. Audio booth testing was conducted in two phases which included variations in the type and tempo of music, music level amplitude, and whether participants responded when they could hear the signal in addition to when it caused a sense of urgency to vacate the tracks.

The first phase of audio booth tests reproduced the warning signals over a period of 120 seconds, simulating a train approaching at 45 mph with a maximum output of 110 dBA at 100 feet forward of the locomotive. Test results showed that participants typically responded with sufficient time to vacate the tracks. The second phase, which included music listening levels up to 90 dBA and a shorter (20 second) EWS pattern, showed that a greater percentage of responses provided less than 7.5 seconds of remaining warning time for trespassers' action. This testing also showed that new EWS sounds could increase the amount of warning time provided.

Building on the literature review, listening survey, and audio booth tests, researchers tested two candidate EWS and a standard train horn sound on board a moving locomotive in the field at the Transportation Technology Center in Pueblo, Colorado. The EWS sounds were reproduced using an acoustical warning device (AWD) speaker system, and the response times of participants

wearing hearing protection and headphones were measured wayside near the tracks. Note that the AWD system sound level output was within FRA-regulated limits (96 to 110 dBA), but was substantially lower than the output used during audio booth tests calibrated to output levels relative to 110 dBA at 100 feet. Music listening levels were reduced 80 to 85 dBA to account for the lower warning sound output. The field tests showed a significant percentage of responses provided less than 7.5 seconds of warning for action, particularly for the standard train horn signal and over-ear headphones and ear buds. The team found that the EWS with yelp signature provided up to 4 seconds more time than the standard train horn on average, and the EWS with wail signature provided up to 2 seconds more time.

This research has shown that an EWS that includes acoustic characteristics of police/fire wail and yelp signatures can maintain its association/identification of a train approaching, improve detectability, and provide more time for those wearing headphones to vacate the tracks.

1. Introduction

The primary focus of this research is to improve safety for railroad workers in the right-of-way (ROW) and warning levels for the trespassers wearing headphones and listening to music. The authors investigated new train horn technologies based on electronic acoustic sources and developed and tested new candidate emergency warning signals (EWS). Background

A review of fatalities and injuries of trespassers on railroad ROWs over the past several years revealed that a large percentage of them involved wearing some kind of personal listening devices (PLD), which might have been responsible for masking the warning sound emitted by the conventional air pressure horn of the locomotives. The tragic consequence of a trespasser on the ROW who is unmindful of an approaching train from behind while listening to loud music through a PLD is that by the time he or she becomes aware of the presence of a train in close proximity, it is too late to vacate the track and move to safety. The Federal Railroad Administration (FRA) Office of Research, Development, and Technology is keen to assess the ways and means of saving more trespassers' lives, and through this FRA-sponsored program, QinetiQ North America and VHB carried out the research and development of alternative EWS. The effectiveness of the new system was evaluated through laboratory scale tests and field evaluation test on a locomotive.

1.1 Objectives

The objectives of this research were to 1) evaluate the need for and feasibility of using new EWS sounds to improve warning safety for railroad workers and trespassers, 2) design candidate EWS sounds, and 3) measure the effectiveness of new EWS sounds through listening surveys, audio booth testing and on-board locomotive field tests.

1.2 Overall Approach

The approach to achieving the objectives was to first conduct a literature review of existing research on EWS. The research also included testing the auditory effects of wearing circum-aural and supra-aural headphones with and without active noise cancellation and listening to music, the design of new candidate warning signals, and testing to evaluate the effectiveness of the warning signals..

Researchers then developed a listening survey to assess the ability of listeners to associate the source of the warning signals with a train, the detectability of the warning signal with and without music masking, the annoyance of the warning signals, and the sense of urgency to move away from the train. Candidate EWS sounds were then optimized and tested in an audio booth where participants listened to music with headphones while warning signals were reproduced to simulate a train approaching. Two candidate EWS and a typical train horn sound were tested on board a moving locomotive. The EWS sounds were reproduced using an acoustical warning device (AWD) system, and the response times of participants wearing hearing protection or headphones were measured.

1.3 Scope

This research included a relatively small sample of test subjects who had prior Institutional Review Board approval, to evaluate the feasibility and effectiveness of new EWS sounds. A broader survey to assess public perception of the potential introduction of new warning signal to the railroad environment has not been included. EWS sounds, including verbal messages, were not evaluated in the context of this study. This research did not evaluate specific circumstances from previous accidents or incidents involving railroad workers or trespassers.

1.4 Organization of the Report

This report summarizes the literature reviewed on emergency warning signals, the development approach, and the reaction time needed for trespassers to vacate the tracks in Section 2. Section 3 presents the preliminary EWS sounds developed and tested using a listening survey. Optimization of candidate EWS sounds and audio booth test results are presented in Section 4. Section 5 describes the equipment, testing procedures, and results of the onboard locomotive field tests. Conclusions outlining primary findings from the research are presented in Section 6, and references used in support of the present research can be found in Section 7.

2. Emergency Warning Signal Literature Review

This section presents the findings from a literature review on the need for new EWS sounds; existing EWS; human hearing and psychoacoustic effects related to detecting warning signals; headphone masking effects; methods to measure noise reduction and masking provided by headphones; the influence of listening to music; documented approaches to developing EWS sounds; and findings on the typical reaction time needed for railroad workers or trespassers to vacate the track once they detect an approaching train.

2.1 Need for a New Locomotive EWS

From the original "steam trumpet" built for locomotives in 1832 by the Leicester and Swannington Railway to modern air pressure horns, the warning signals used on trains have not changed significantly. 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, B4, and D#5 notes – which is a G-sharp minor 7 chord. While the chord and the timbre that train horns produce has a distinct sound that people identify as a train, this sound may not be the most effective way to alert 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 and do not take advantage of time-varying sounds with specific content designed for human detection.

Most people are familiar with the sounds of sirens on ambulances, fire engines, and police cars – and the attention they demand. Some trains such as light rail and heavy rail trains have a range of audible warning devices including bells, gongs, low horns, and high horns. Standard air-pressure train horns on FRA-compliant trains, however, do not take advantage of modern technologies such as sirens or electronic acoustic sources and the latest in EWS design.

With the use of electronic acoustic sources[1] on locomotives, an effective EWS can be generated to more effectively alert railroad trespassers and railroad workers of oncoming trains and save lives.

While the number of incidents, accidents, and fatalities at highway-rail grade crossings has decreased in recent years, there are still approximately 500 railroad trespasser fatalities in the U.S. per year (Cadle). A recent study has analyzed injury data from 2004 to 2011 to understand the role that headphone use by pedestrians has played in train-pedestrian accidents (Lichenstein). There were 116 reports of death or injury to pedestrians wearing headphones. Researchers found that 74 percent of case reports involving trains 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 had 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 is one of the most troubled rail lines for 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. Some of these accidents have involved pedestrians

[1] Electronic acoustic sources include speakers and other devices that can reproduce sound.

wearing ear buds and headphones (Nguyen). It is critical that a locomotive EWS effectively alert pedestrians including those wearing headphones listening to music.

2.2 Existing Warning Signals

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

Emergency Response Vehicles

States typically regulate requirements for sirens on emergency vehicles including their use, mounting location, and sound emissions (CAC Title 13, Article 8). Audible warning devices on emergency response vehicles including police, fire, and ambulances are typically required to meet acoustical requirements in the Society of Automotive Engineers standard J1849:201210 (SAE, Wagner, GSA, CCR, NFPA). This SAE standard provides 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 maximum allowable fundamental frequency of 2,000 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 second). 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 maximum allowable fundamental frequency of 2,000 Hz.
- The sound bursts of the wail and yelp devices must generate amplitude no less than 111 dBA at its minimum and no greater 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 for yelp (GSA).
- The “air horn” is a signal with 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 1 to 2 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 second).

Federal Railroad Administration-Compliant Trains

Standard locomotive horns in the U.S. 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 point forward and some backward. 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 measured 100 feet forward of the locomotive. Additionally, the warning device may not be sounded beyond one-quarter 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.

Rule 14(p) in railroad operating procedures (49 CFR Part 222) requires 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).

Table 1. Summary of EWS Amplitudes at 10 and 100 Feet

Emergency Warning Device Standards	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 regulates train horns to generate a maximum sound level between 96 and 110 dBA at 100 feet forward of the locomotive and warning signals on emergency response vehicles to generate a maximum sound level up to 98 dBA (SAE standard) and 103 dBA (GSA ambulance standard) at 100 feet. To some extent, the higher amplitude of train horns corresponds to the need for motorists and pedestrians to be warned at farther distances for trains than for automobiles due to their relative stopping distances. Other reasons for this include the criticalness of a potential incident and the effectiveness of the different EWS. With the design of a more effective EWS, it may be possible to reduce the amplitude while improving safety.

Spectrograms of these existing EWS are presented in Figure 1 to Figure 5 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.

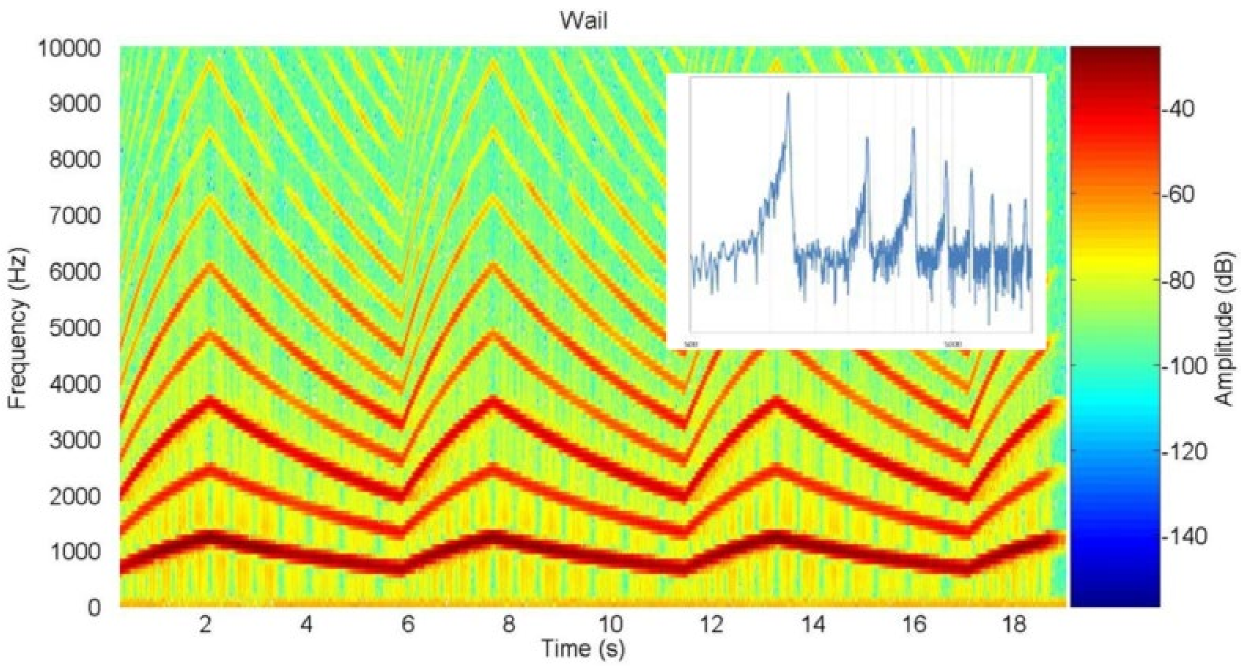

Figure 1. Wail Spectrogram and Spectrum

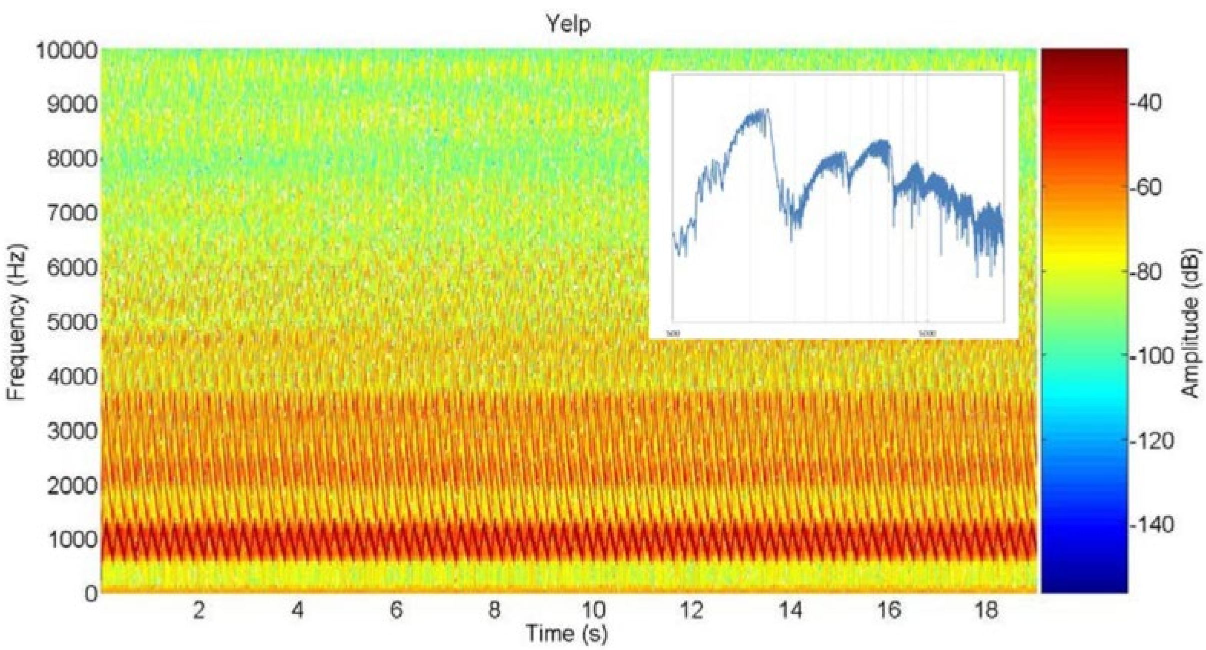

Figure 2. Yelp Spectrogram and Spectrum

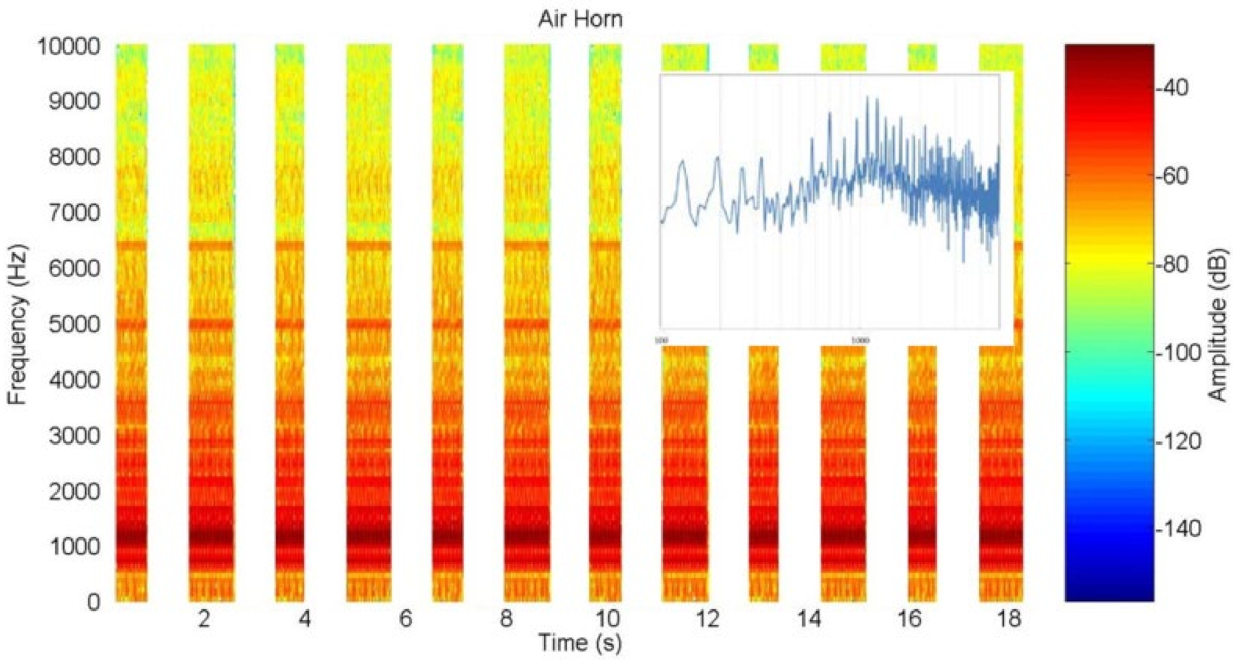

Figure 3. Air Horn Spectrogram and Spectrum

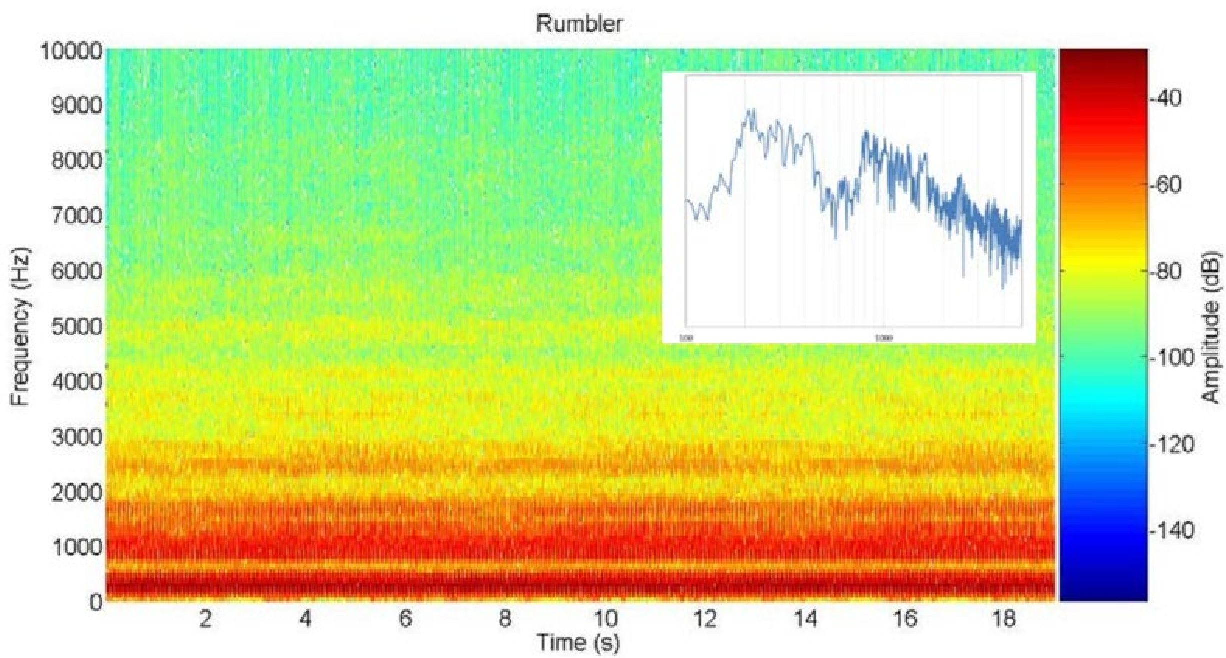

Figure 4. Rumbler Spectrogram and Spectrum

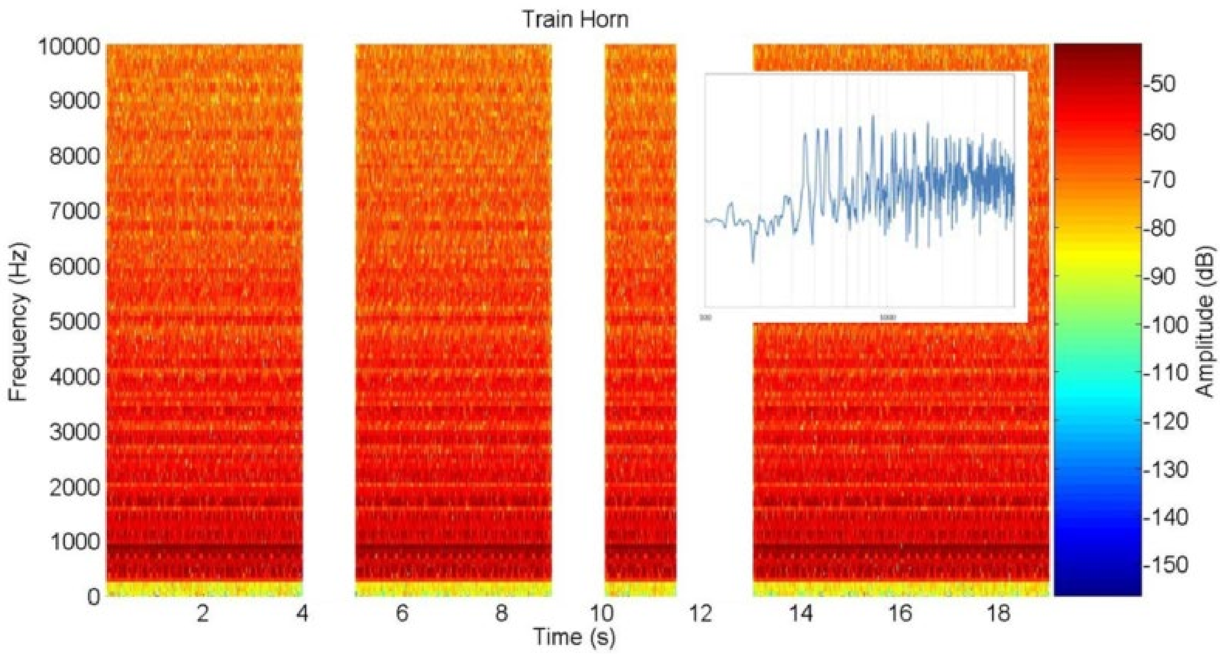

Figure 5. Train Horn Spectrogram and Spectrum

Occupational noise exposure for those exposed to EWS, such as train engineers, police officers, fire fighters, and ambulance personnel is an important issue. The U.S. Occupational Safety and Health Administration (OSHA) regulates (29 CFR 1910.95) general workplace noise exposure based on long-term exposure to minimize the risk of noise-induced hearing loss. 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) 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 was found to reduce noise levels in the driver compartment by 16 to 22 dB compared to sirens mounted on the roof of the vehicle. FRA has similar regulations to OSHA specified in 49 CFR 227. Similar considerations for the mounting location of an emergency warning device on a locomotive should be taken. Currently, it is common for railroads to mount their air pressure horns in the middle of the locomotive to increase the distance between the source and the locomotive cab/engineer. The amplitude of a locomotive EWS should be considered in the long-term noise exposure of railroad engineers. 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. An EWS that produces a loud, rough, sharp, and fluctuating sound is expected to be the most detectable, create the greatest sense of urgency, and most effectively cause the desired action – avoidance of an oncoming train. In addition to these psychoacoustic measures of human response to general sounds, 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 human ear detects acoustic signals when sounds 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 (hammer, anvil, and stirrup) in the middle 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.

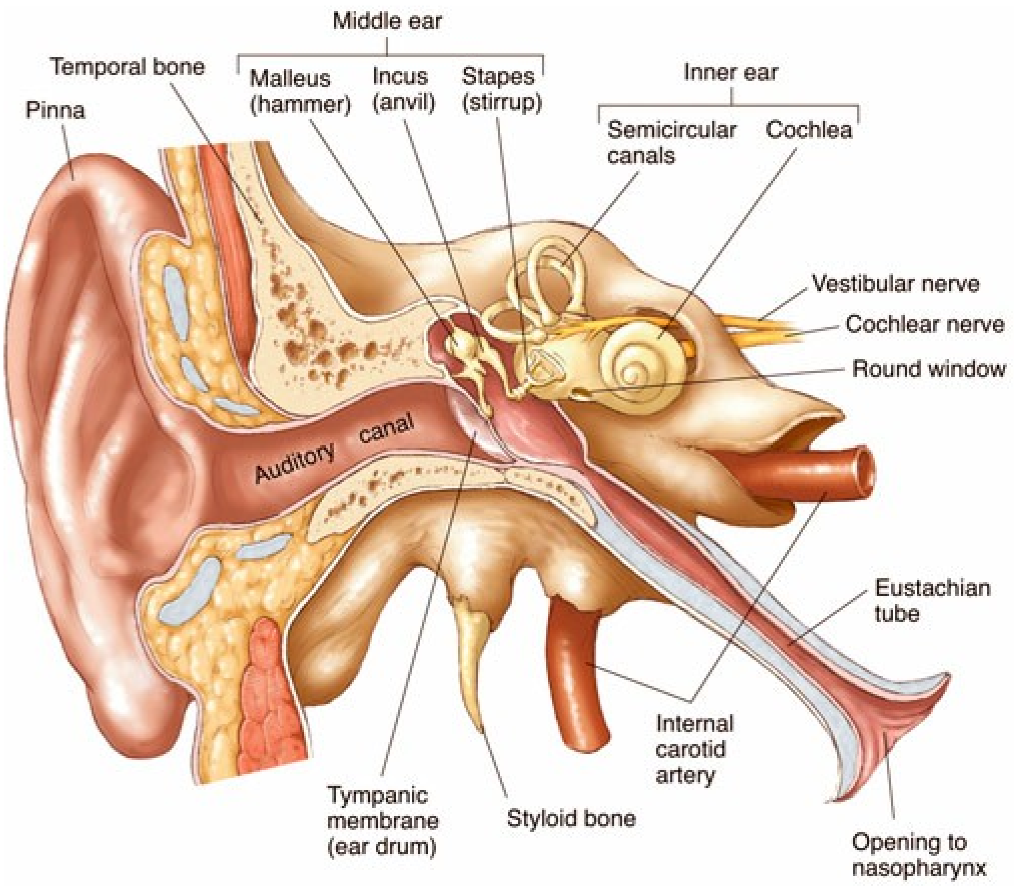

Figure 6. Human Ear Anatomy

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

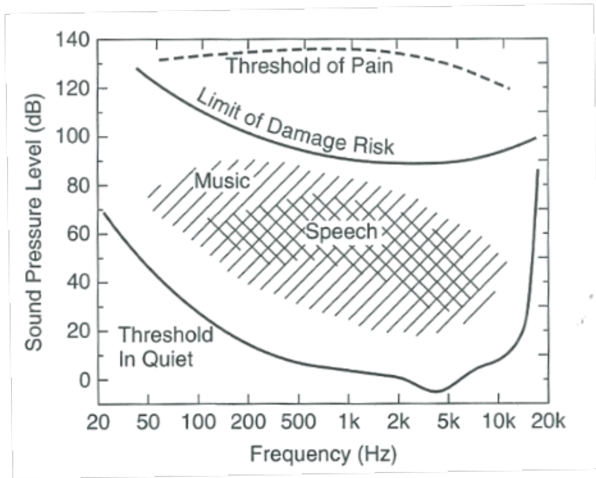

Figure 7. Audible Range for Humans (Crocker)

Humans do not hear all sounds within the audible range equally. The loudness of sound is defined (ANSI 3.20,1995) 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 the figure below. 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 EWS should not generate amplitude that would exceed the threshold of pain and should have frequency-content to optimize loudness.

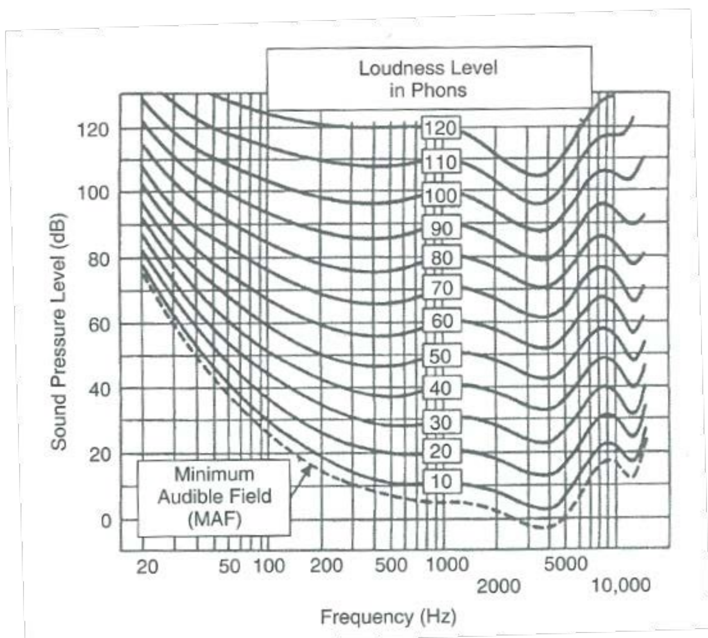

Figure 8. Equal Loudness Curves (Crocker)

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 (one-fifth of a second). The perceived loudness of a sound does not increase for durations longer than 200 milliseconds.

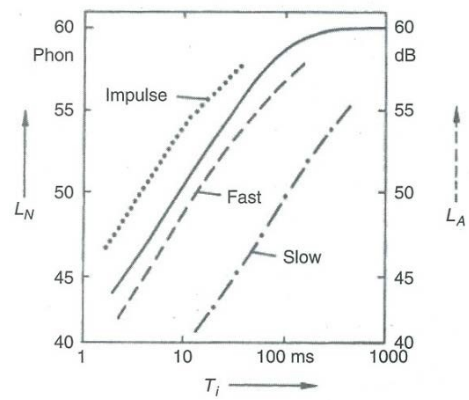

Figure 9. Perceived Loudness versus Sound Duration (Crocker)

The human ear acts as an "auditory filter," which is termed the "critical bandwidth." 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 increases (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.

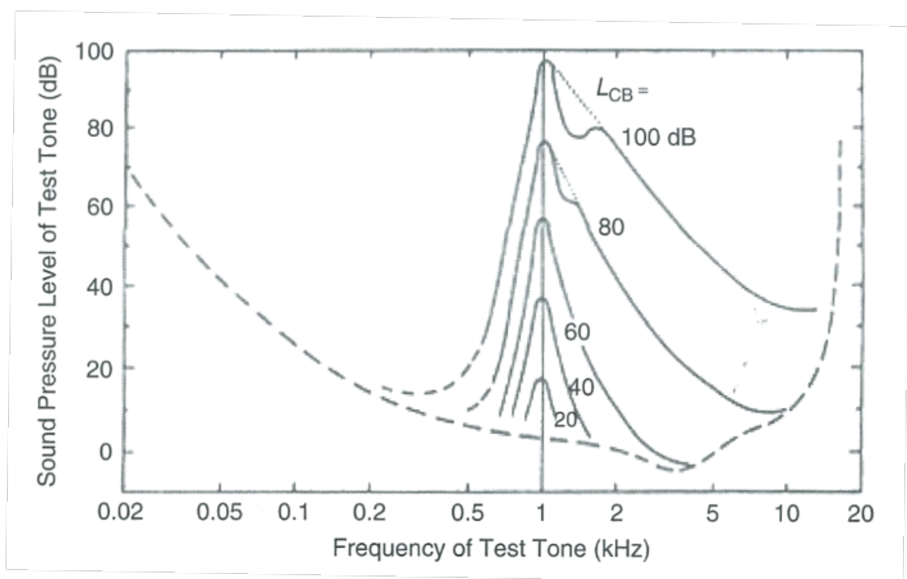

Figure 10. Critical Bandwidths of Human Hearing

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 1,000 Hz or above, the maximal roughness of a tone is found to be at a modulating frequency of 70 Hz.

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 20 Hz) amplitude modulation of a sound. The sensation of fluctuation strength persists up to 20 Hz then at this point the sensation of roughness takes over. The roughness and fluctuation levels of candidate EWS should be computed to determine if these psychoacoustic metrics correlate with perceived urgency.

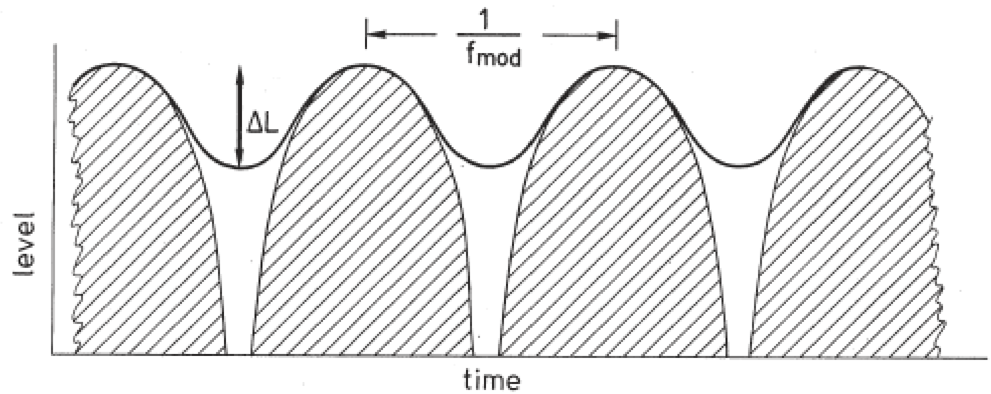

Figure 11. Depiction of Acoustic Roughness (Fastl)

An effective EWS 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 response to different sounds, such as quantifying sound quality of products, is to use a semantic survey. As shown in Figure 12, human subjects are exposed to different sounds and asked to judge their response 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 EWS. Semantic surveys can be used to compare candidate EWS to the existing train horn sound to quantify their perceived sense of urgency and annoyance.

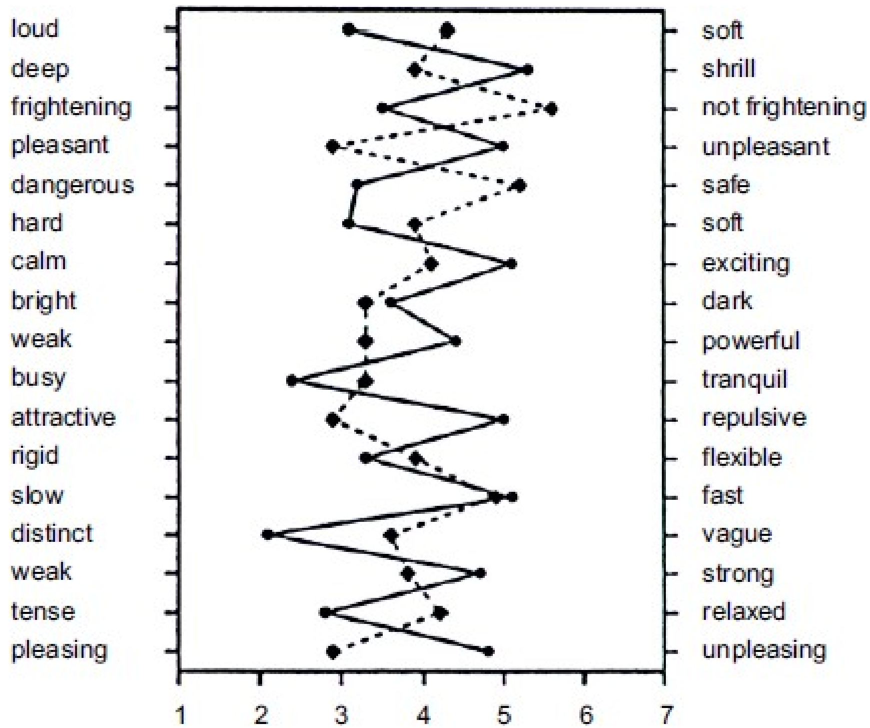

Figure 12. Semantic Difference Survey (Fastl, 2005)

The use of headphones has been identified as a critical factor in the detectability of trains because they act as a physical barrier to external sound reaching the auditory canal, and they reproduce music or other sound which masks the warning signal (Hara). The 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. Sound is the rapid fluctuation (compression and expansion) of air pressure. By reproducing sound that is in compression at the same time and location as the intrusive sound is in expansion (or vice versa), the overall sound level is reduced.

There have been many survey studies (Keith, 1999, 2008, 2011; Prasher; McNeill) undertaken to determine the typical levels that listeners are exposed to while listening to music with headphones. Based on data from all of these studies, the overall range of music levels reproduced with headphones is generally between 60 and 107 dBA, with average levels generally between 55 and 85 dBA.

There are other sounds in the railroad environment that can mask humans' ability to detect an on-coming locomotive including other trains and nearby highways and roads. Locomotives and railcars typically generate sound levels up to 90 and 93 dBA at 100 feet, respectively (40 CFR 201.12(b) and 49 CFR 210).

There is 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.

Figure 13. Commercially available headphones

Types of headphones can be classified as follows:

- "Circum-aural" 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).

There has been substantial research (Berger, Robinson) on the measurement methods and results of the passive noise reduction provided by hearing protection devices. Fewer studies have been conducted documenting the passive and active noise cancelling effects of headphones. One study (Kan) has shown that in-ear monitors provide the greatest sound isolation compared to other headphone types and can reduce hearing (increase our auditory threshold) by about 25 dB due to passive noise reduction alone. Including music playback through the headphones, it has been shown (Hara) that hearing can be reduced by as much as 70 dB with in-ear monitors, which can cause many external environmental sounds to be inaudible.

There are two primary methods to measure human hearing and the effectiveness of HPDs. The real-ear attenuation at threshold (REAT) method (ANSI S12.6:2008) involves testing human subjects at the threshold of audibility with and without HPDs. The REAT method is generally considered the gold standard due to its use of actual human subjects and their natural hearing mechanisms, including sound conducted through the bone surrounding the ear. The microphone-in-real-ear (MIRE) method (ANSI 12.42:2010) utilizes human subjects acting as test fixtures with microphones positions in their ears. Similar tests can be conducted using an acoustic text fixture such as a dummy head and dummy ear.

In this research, the MIRE method, which utilizes human subjects with microphones positioned in their ears, was used to measure the insertion loss of six circum-aural and supra-aural headphones with and without active noise cancellation (ANC). Tests were conducted by playing broadband pink noise through amplified speakers inside an audio booth with the primary direction of sound reaching the listener from behind.

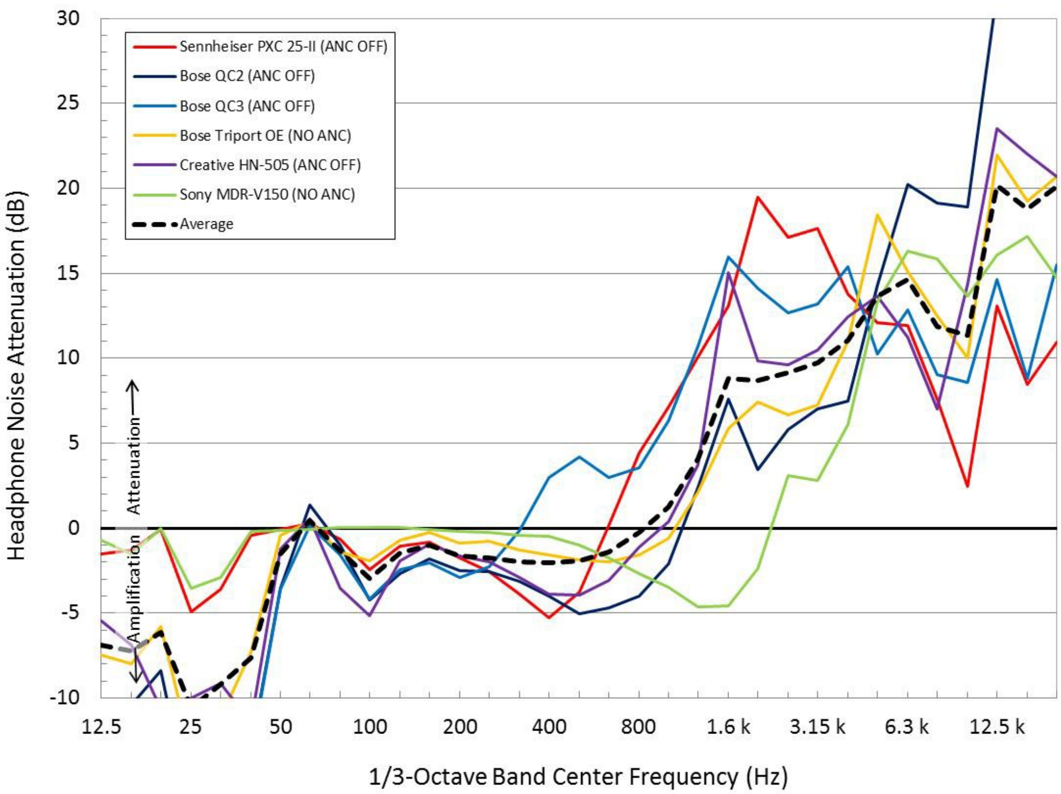

Figure 14. Insertion Loss of Headphones without Active Noise Cancellation

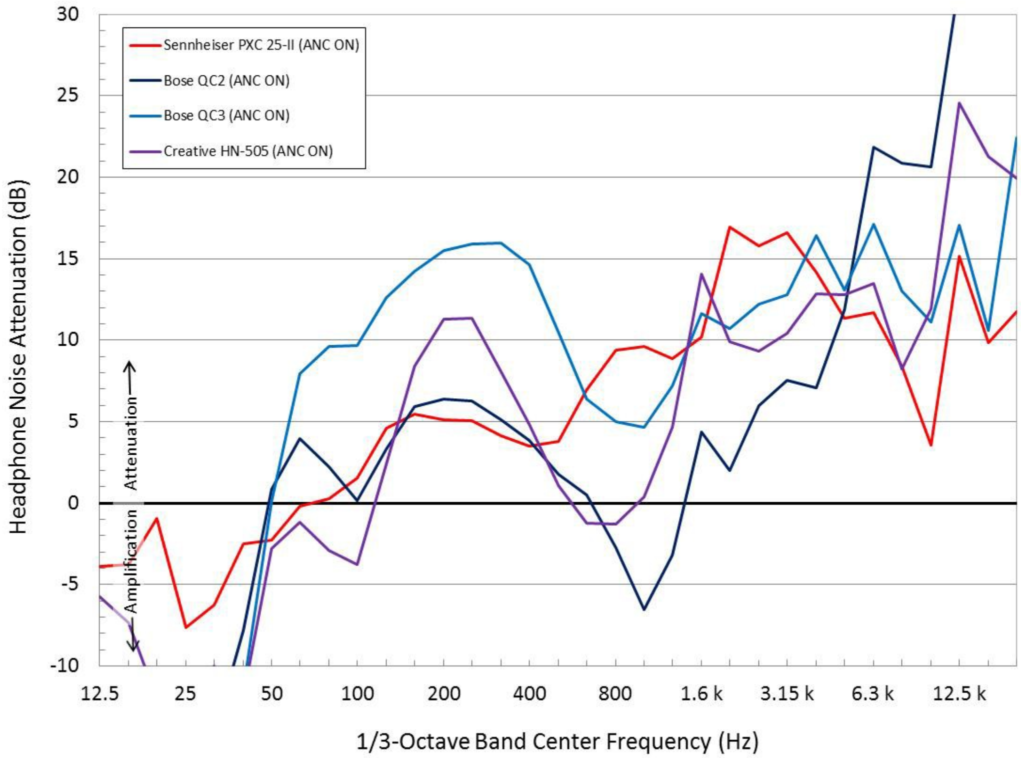

Figure 15. Insertion Loss of Headphones with Active Noise Cancellation

As shown in Figure 14, headphones without ANC were generally effective at reducing noise levels to the ear at frequencies above 800 Hz. Below 800 Hz, the headphones did not significantly reduce noise levels. In fact, the headphones were shown to slightly increase in-ear noise levels at certain frequencies below 800 Hz. This may have been due to resonant properties of the chamber that are created between the headphones and the ear with circum-aural and supra-aural headphones.

The insertion loss varied 10 dB or more between headphones. On average, the passive noise reduction of the headphones was 10 dB at 2,000 Hz and 20 dB at 20,000 Hz.

Insertion loss levels from headphones with ANC are shown in Figure 15. ANC did not significantly affect insertion loss levels 800 Hz or higher. Below 800 Hz, ANC substantially increased the insertion loss of the headphones by 7 to 16 dB depending on the particular pair of headphones. ANC increased insertion loss between 50 and 800 Hz, with the most significant increase near 200 Hz.

2.4 Music Influence on Warning Signals

Through this research, the acoustic characteristic of music has been observed to affect the detectability of EWS. The most important characteristics include the amplitude of music, frequency content, and the tempo. The frequency content of seven songs on the Billboard™ charts in 2014 in the rock, country, hip-hop, dance, electronic, pop, and rhythm and blues music categories has been measured.

These figures below show relative 1/3-octave band spectra for five statistical metrics (L01, L10, L33, L50, and L90). These statistical metrics represent the sound level which was exceeded for a certain period of time throughout the duration of the song. For example, the L10 spectra represents the sound levels which were exceeded only 10 percent of the time during the song and thereby represent the higher end of the range of sound levels during the song.

Most songs appeared to be mixed for a relatively equal (flat) frequency content up to 2,000 Hz, with higher frequency content dropping off typically 10 dB. These figures also show that most songs were mixed to include relatively similar amplitude throughout the song – demonstrated in the fact that there was only a 10 dB or less difference between the median sound levels (L50) and the higher sound levels (L10). This means that most music does not have significant periods of time when the amplitude is lower (and detectability of an EWS may improve). The tempos of these songs ranged from 95 to 160 beats per minute which correspond to a beat every 375 to 630 milliseconds. It has been observed that EWS with similar cycle times such as yelp (150 and 250 cycles per minute) can blend in with the music and decrease detection.

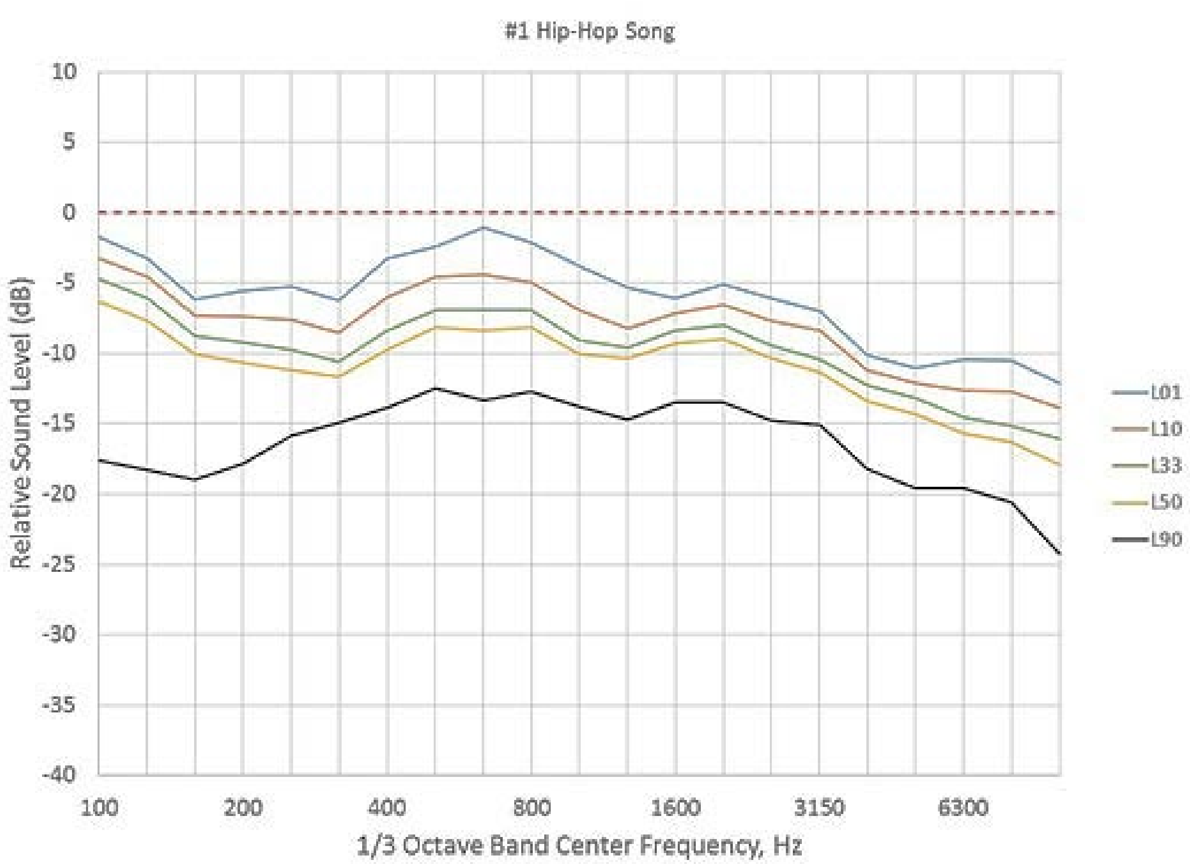

Figure 16. Hip-Hop Song Spectra (133 bpm)

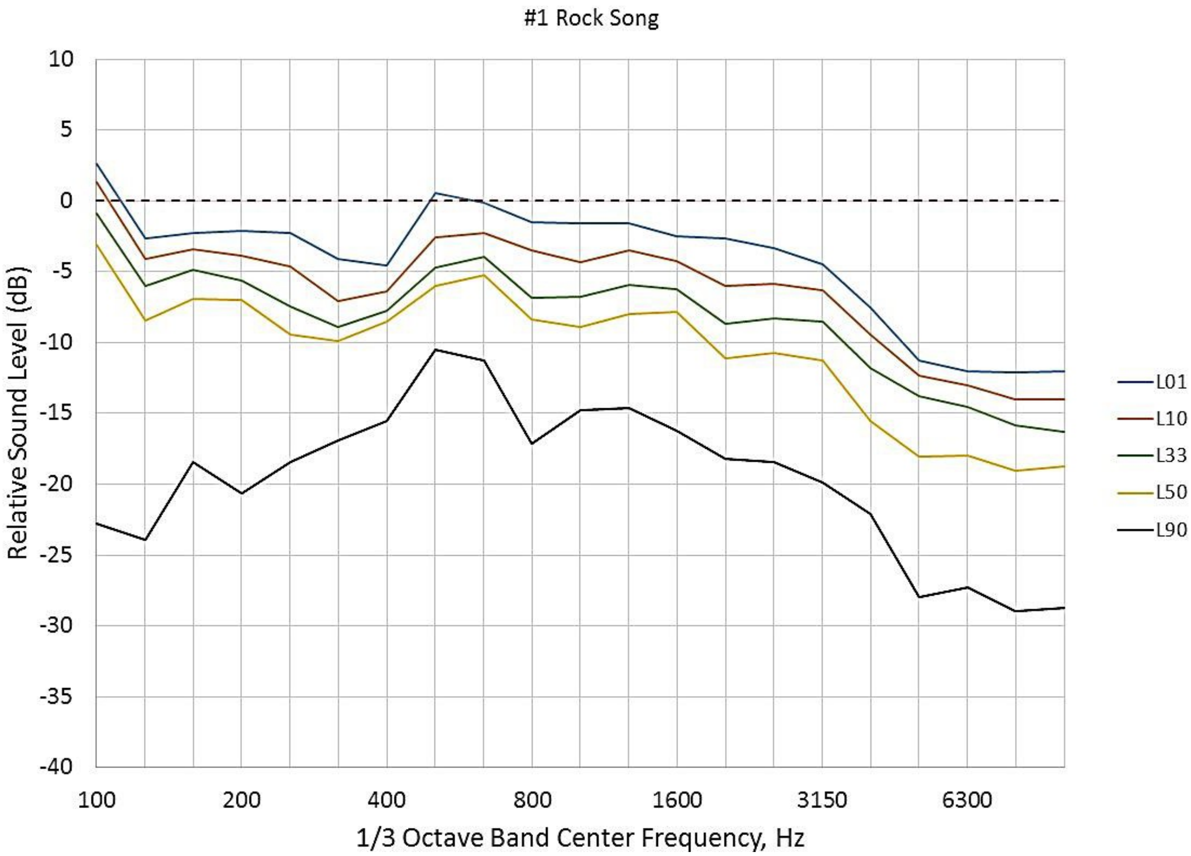

Figure 17. Rock Song Spectra (127 bpm)

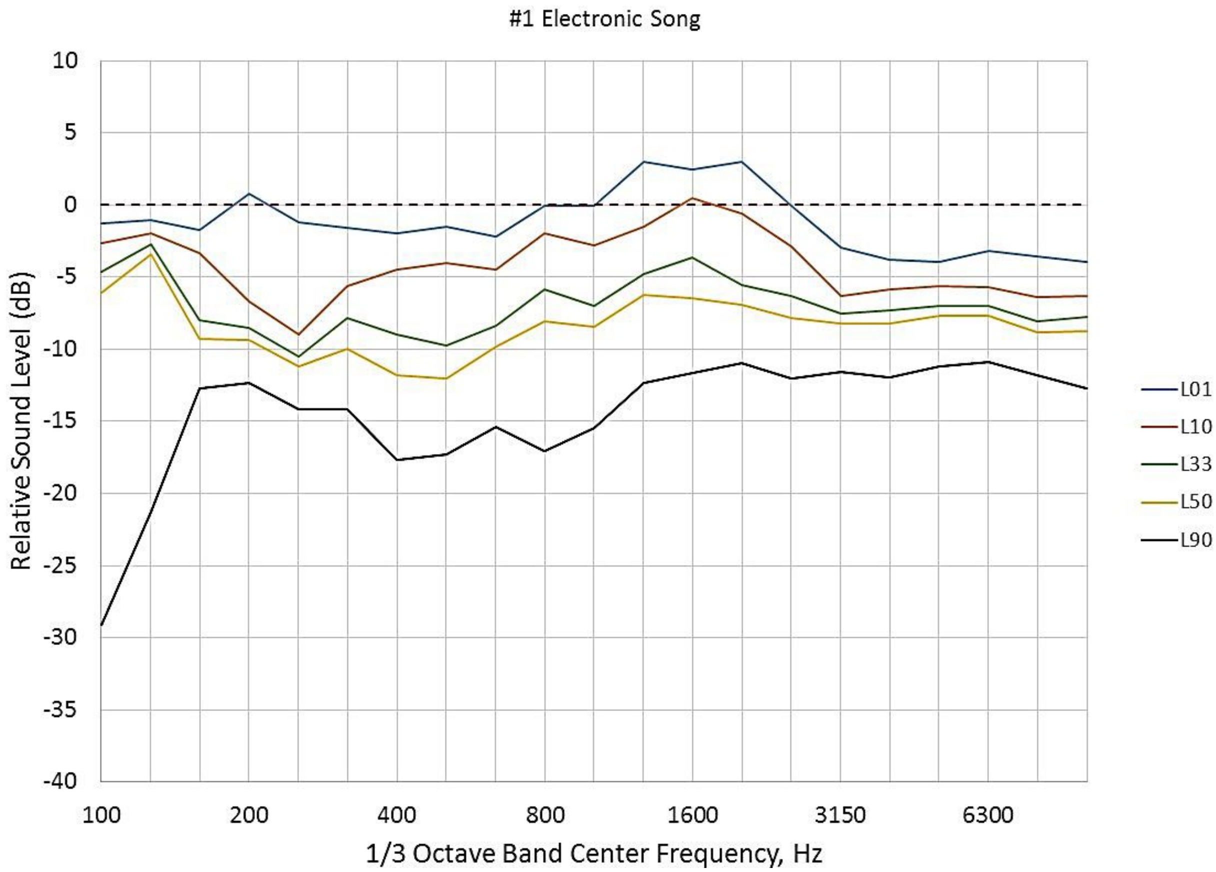

Figure 18. Electronic Song Spectra (100 bpm)

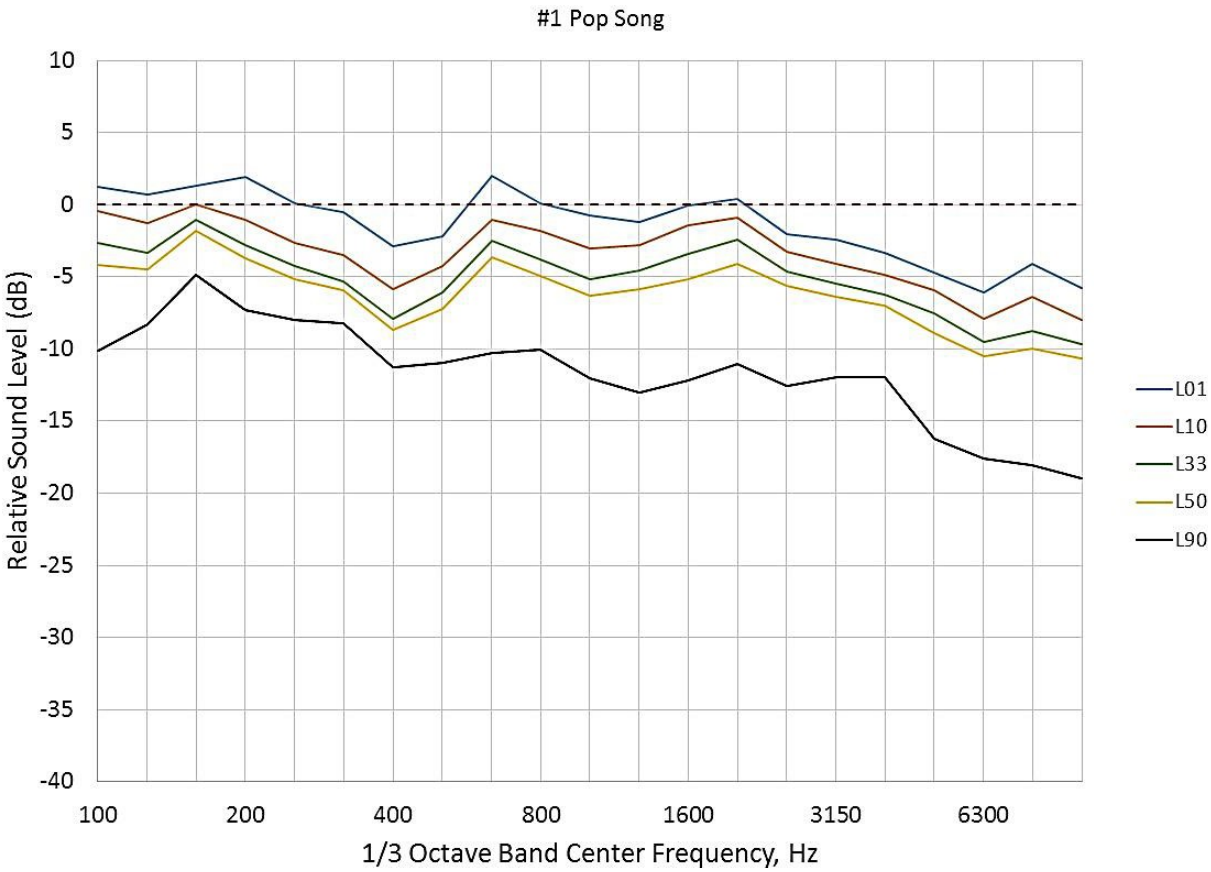

Figure 19. Pop Song Spectra (95 bpm)

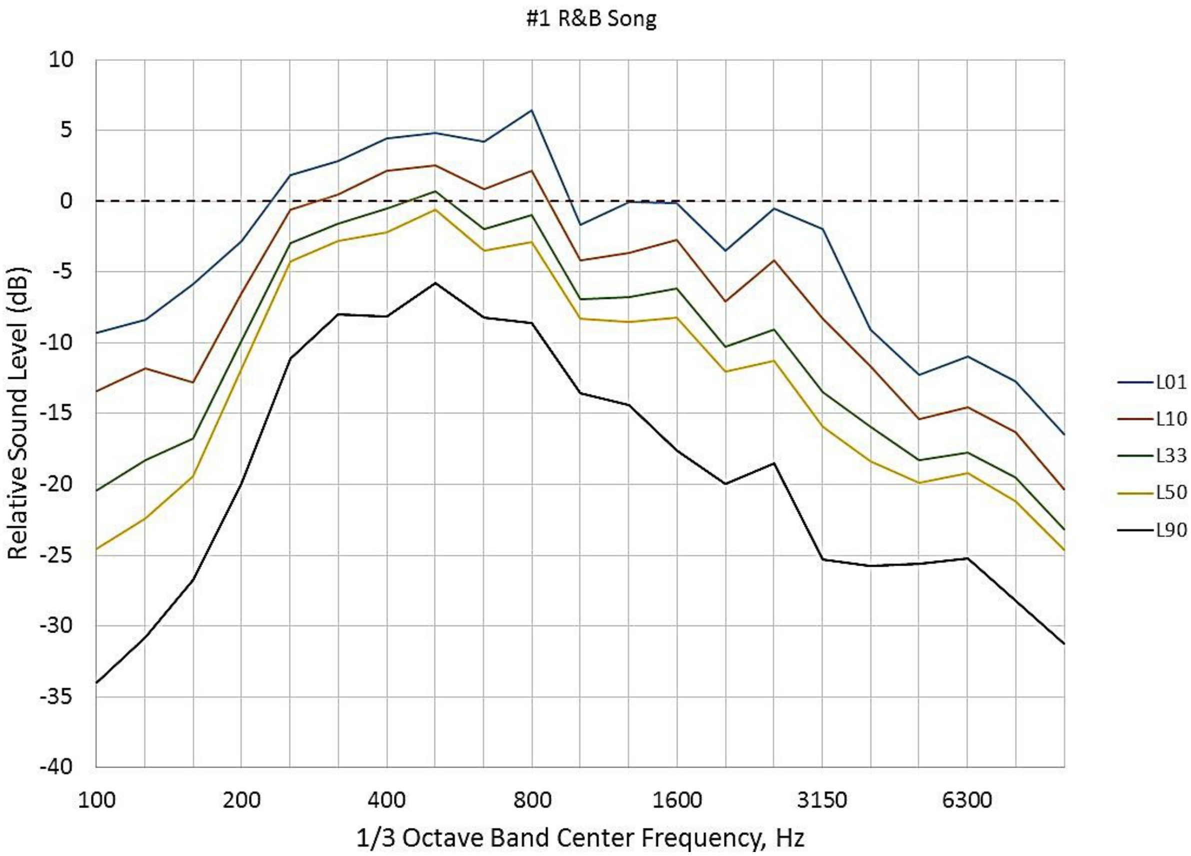

Figure 20. R&B Song Spectra (120 bpm)

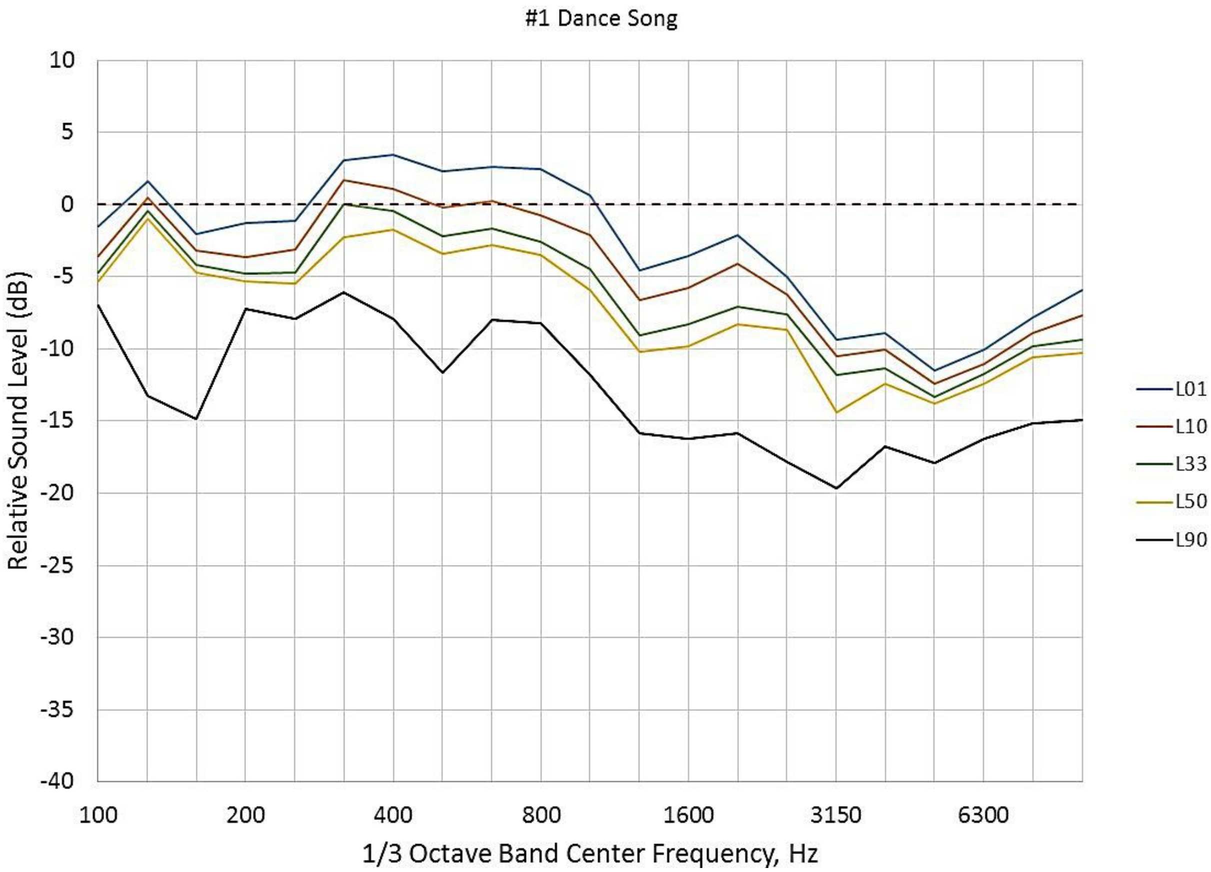

Figure 21. Dance Song Spectra (160 bpm)

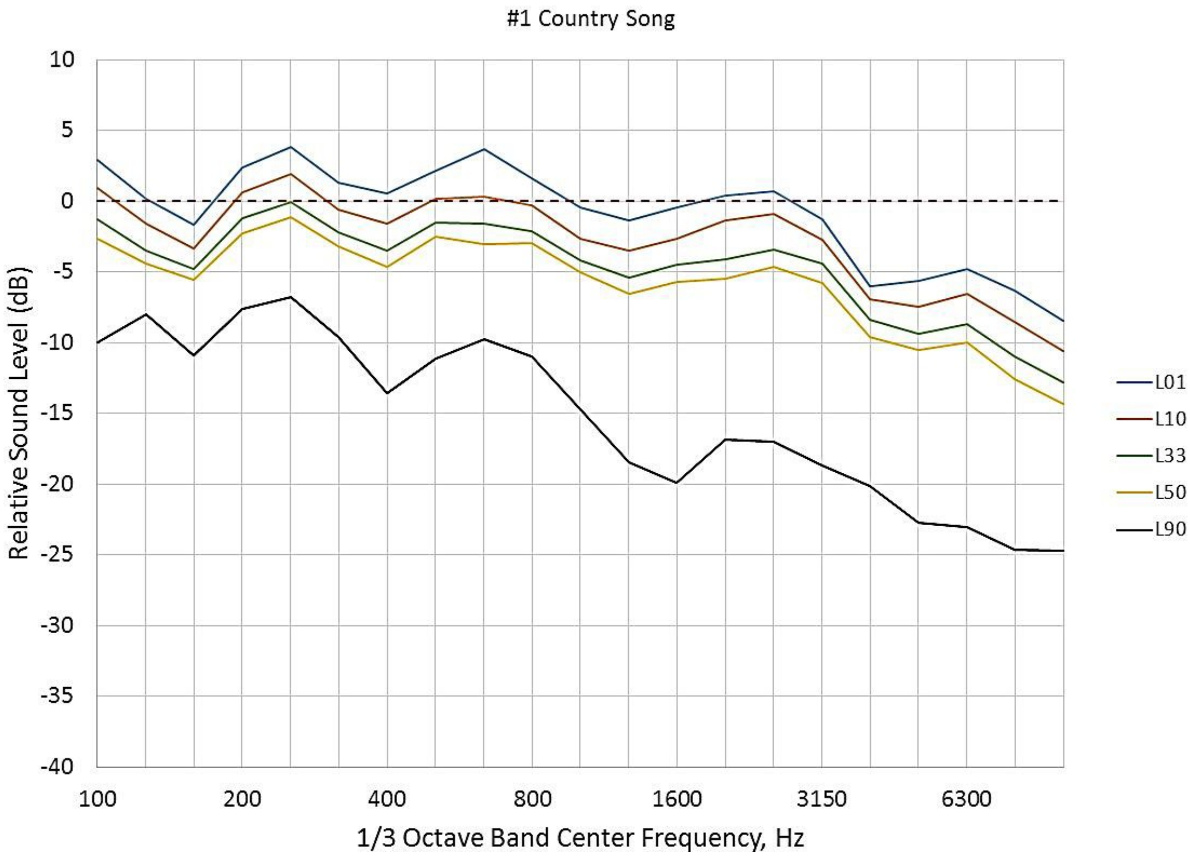

Figure 22. Country Song Spectra (144 bpm)

2.5 General EWS Development Approaches

There is a substantial body of research into the effectiveness of EWS and corresponding design recommendations. Some of the early research showed the relative ineffectiveness and limitations of EWS to provide sufficient safety for emergency response vehicles. Since then, new approaches to EWS design have been introduced to improve their effectiveness.

There have been many studies since this initial work 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 varying criticalness. There has been limited research into the design and effectiveness of EWS for railroad applications.

EWS on Emergency Response Vehicles

Early research (Ebata, 1977) examining the human detection process of AWDs on emergency vehicles showed that such devices typically have a 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 the pattern of the EWS is not important, but that the frequency content of the signal is. A key finding of this research was that motorists should not rely on the then-present AWDs to warn of oncoming emergency response vehicles.

Detailed studies on emergency vehicle EWS (Howard, Maddern, and Catchpole, 2007) have provided great insight into the effectiveness of these devices. A majority of this work has been based on assessing the detectability of these signals for motorists inside vehicles. The research has shown that frequencies above 3,000 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 1,000 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 designs of these signals that have modified sound burst cycles and fundamental frequencies (Balastegui). The jury was surveyed to compare 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.

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, 1989, 1993, 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 the harmonicity had the least effect.

In designing an EWS, research (Patterson, 1990) has shown that several other parameters 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 has been investigated (Haas, 1995, 1996) by using pitch, speed, and loudness. Researchers found that EWS 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 EWS with a range of urgencies.

The design and effectiveness of AWDs in the work environment (Patterson, 1990) has also focused on flight aircrews exposed to relatively high ambient noise conditions and a large number of different audible warnings. Researchers found that there was a benefit in limiting the number of warning sound 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) has indicated that temporal irregularity between pulses can capture a listener's attention.

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

An international standard (ISO 7731, 2003) specifies the physical principles of signal design, ergonomic requirements, and the corresponding test methods for danger signals for public and work areas. 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 percent detectability, and that signal levels approximately 15 dB above the masked thresholds are recommended for ensuring a rapid response from the listener.

Tonal sounds have been found to be harder to localize than broadband (e.g., white noise) (Catchpole, 2004); however, the tones increase perceived urgency. It has also been shown that the response accuracy and latency in identifying and localizing an AWS 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). One key failure of many auditory warnings is not providing a sufficient level of urgency.

This research shows that 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, the harmonicity of the tones, the timing of the pulses, and/or the amplitude of the received signal.

The intention is that a new EWS would be sounded only under emergency situations and not at all grade crossings. Therefore, annoyance to abutters is not as significant an issue as it is with typical train horn soundings.

EWS on Trains

At the request of the British Rail Research Division, auditory warnings were designed (Patterson, 1989) to be used by trackside maintenance crews to warn of approaching trains. The goals of the auditory warning design were to preserve the character of the warning generated on board locomotives and for the four EWS to be audible in no fewer than 46 different ambient noise conditions.

EWS Effectiveness across Cultures

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

2.6 Reaction Time to Vacate Tracks

A critical aspect of the design of a secondary EWS is to provide sufficient warning to trespassers to enable them to vacate the railroad ROW 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 ROW. The 5 seconds was the author's time estimate for a healthy person to vacate a single track ROW. Given those assumptions the minimum distance a train needs to be noticed can be calculated, as shown in Figure 23. For example, a 40-mph train needs to be noticed by a trespasser when it is 450 feet away in order for the trespasser to vacate the tracks prior to the train arriving, assuming the train is not slowing down.

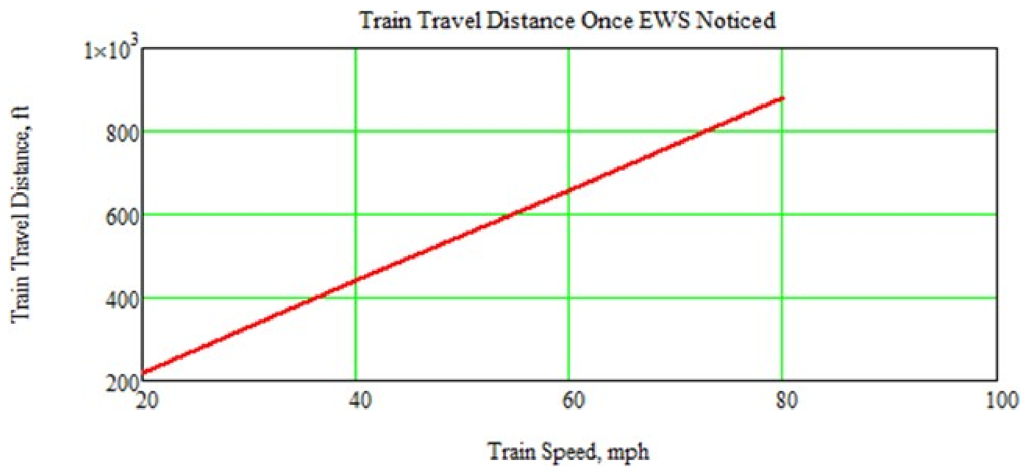

Figure 23. Minimum Train Distance Once Noticed for Trespassers to Vacate the ROW with a 7.5-sec Total Reaction Time

This distance calculation then determines the sound levels for the secondary EWS necessary to be noticed by a trespasser. FRA regulations require train horns to produce between 96 and 110 dBA at 100 feet forward of the locomotive. Initial assumptions are that the EWS must meet the same requirements. Referring to Table 2, an EWS that develops the maximum of 110 dBA at 100ft forward of the locomotive will attenuate to 96 dBA at 500 feet. An EWS developing 96 dBA sound level at 100 feet attenuates to 82 dBA at 500 feet away. These sound level reductions are based on standard spherical sound propagation, where sound in dB is reduced by $20log\frac{r2}{r1}$ where r2 is the new distance (500 feet) and r1 is the reference distance from the source (100 feet).

Table 2. EWS Sound Level Attenuation with Distance

Distance from trespasser, ft	Max Horn Sound level, dB	Min Horn Sound level, dB
100	110	96
200	104	90
500	96	82
1000	90	76
2000	84	70

Trespassers wearing earbuds or headphones can frequently be listening to music at 90 dBA. A recent study (Portnuff, 2011) showed that teenagers chose to listen to music at higher levels, with earbuds approaching 90 dBA at the highest selected levels. The mean listening levels for different ambient sound levels is shown in Figure 24. Examples of background sound levels are 50 dBA for light vehicle traffic, 70 dBA for normal street noise, and 80 dBA for a passing diesel truck at 10 m.

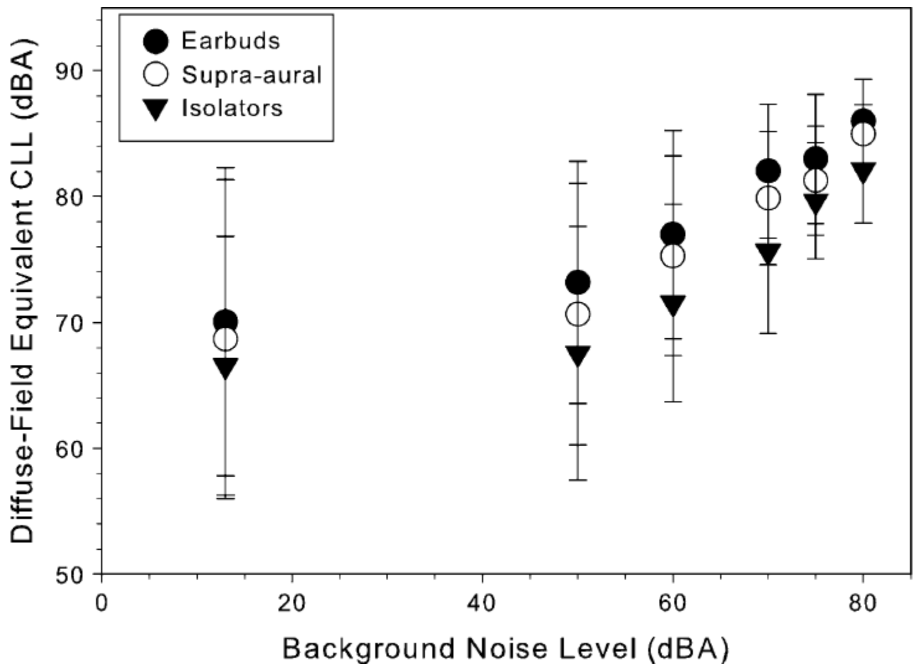

Figure 24. Chosen Listening Levels for 29 Teenagers as a Function of Background Noise (Portnuff, 2011)

For the EWS to be audible, the EWS sound level needs to be at least 5 dB above ambient. For a sense of urgency, the sound level should be 10 to15 dB above ambient. At the highest music listening levels, the EWS should be 95 dBA to be audible and up to 105 dBA to be very noticeable at the trespasser. At the highest 105 dBA level, a train horn with 110 dBA capability would be only 200 feet away when noticed. Only a 20-mph train or slower could be avoided, as shown in Figure 23. Alternatively, to achieve this sound level at 450 feet, the horn would need to generate 118 dBA at 100 feet. Said another way, referring to Figure 25, the time for a trespasser to vacate the tracks with a standard train horn at 110 dBA 100 feet forward of the locomotive is generally less than the available 7.5 seconds assumed in this report. To provide ample warning for trespassers, it may be necessary to increase the sound level for train warning sounds when the engineer becomes aware of a trespasser. This is based solely on the sound amplitude. Later work will show that the sound characteristics may play an important role in decreasing the times to notice the warning for EWS. Figure 26 shows the required train horn sound levels at 100 feet forward of the locomotive needed to provide a 7.5-second warning to trespassers prior to impact based solely on sound levels above 90 dBA music listening levels. So a 50-mph train would need the train horn to generate 120 dBA at 100 feet forward of the locomotive to provide the highest likelihood of notice and provide 7.5 seconds to vacate the track at the 90 dBA listening level. This is without consideration of sound attenuation through headphones.

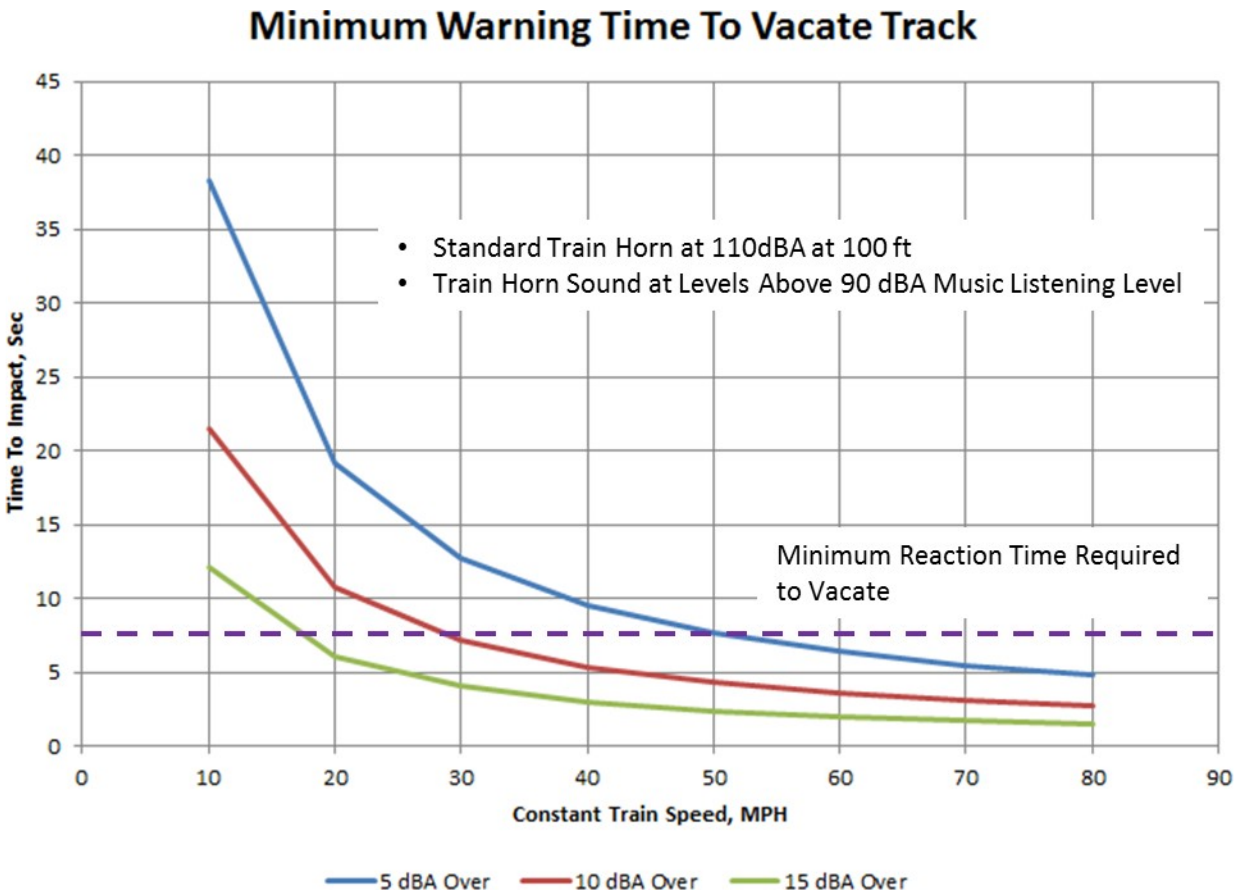

Figure 25. Minimum Time to Vacate Track for Warning Sound Levels over Ambient Level for a Standard Train Horn with 110 dBA at 100 ft Forward of the Locomotive

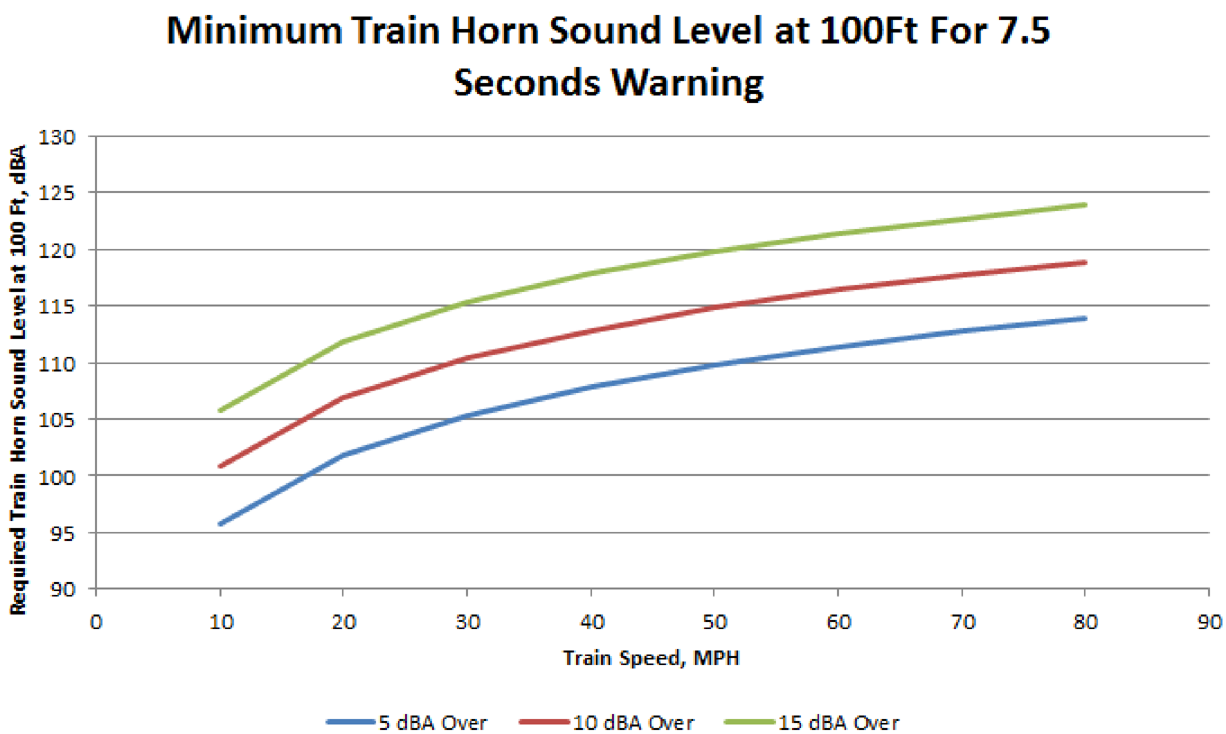

Figure 26. Train Horn Sound Levels Needed for 7.5-sec Warning to Trespassers for 90 dBA Music Listening Levels

So the issue of trespassers wearing earbuds or headphones while listening to music raises issues pertaining to train horn and EWS sound levels to allow safe egress from the ROW. A key aspect of that is the reaction time and physical egress time to vacate the ROW.

Researchers conducted a literature review was conducted to assess whether the assumed warning time of 7.5–2.5 seconds perception/reaction time and 5 seconds movement time is sufficient. The most applicable literature about warning time was reviewed, primarily from outside the railroad industry.

2.6.1 Components of Reaction Time

Generally speaking, according to Woodson, Tillman, and Tillman (1992), a basic reaction to an auditory stimulus can be produced in 150 ms, recognition time is a further 400 ms, decision-making time is up to 4 seconds, and motor response time is 6 seconds at minimum. They also noted that a simple reaction time to a surprising event was likely to increase the reaction time by around 0.5 second. Summed, this gives a reaction time of approximately 11.05 seconds; however, they also noted that this time may change, depending on how much time is required to assess response options, the number and familiarity of response options, and how much of the environment needs to be scanned in order to produce response options.

Conceptually, total reaction time can be broken apart into perception-reaction time and movement time.

2.6.2 Perception-Reaction Time

Mental processing time (also called perception-reaction time) is the time it takes for an individual to perceive that a signal has occurred and to decide on a response; movement time is the time the individual needs to perform the required movement – in this case, to leave the railroad ROW. The typically quoted value of 2.5 seconds is based on the brake reaction time of the 85th percentile driver in response to a visual obstacle in an urban environment (Wortman and Matthaas, 1983). The range for perception-reaction time in Hay's Railroad Engineering (1982) is given as 0.5–3 seconds, but the origin of those numbers is uncited; Olson and Spivak (1986) found a reaction time of about 1.6 seconds for drivers reacting to unexpected visual obstacles in optimal conditions.

Given that these numbers represent the reaction time of an active driver to a visual signal in performing a simple action with no real response selection, and the conditions at issue are the reaction of a pedestrian to an auditory signal that may well have to perform response selection in an unfamiliar environment, it is not a particularly close analogue.

Perception-reaction time can be further broken down into three stages, according to Green (2000):

1) Sensation is the period of stimulus detection. Auditory signals generally produce faster reactions than visual signals; greater signal intensity also decreases the reaction time in this stage.
2) Perception/recognition is the period for assigning meaning of the stimulus. Low stimulus probability, uncertainty, and surprise increase the reaction time in this stage.
3) Response selection and programming is the period for deciding whether and which action to make as well as for mentally programming the movement. A need to select among multiple responses increases this stage, while practice decreases it.

The majority of reaction-time studies are performed in indoor, controlled, minimally complex environments, with visual cues and single-response schemas. This means that their estimate of (3) is unlikely to be a good indication of how long this process will take in a less controlled and more complex environment, with cues in a different modality and no simple response schemas.

Perhaps the best experimental analogue for the conditions at issue is Suied, Susini, and McAdams (2008), which found a mean reaction time of 0.4 second to auditory warning tones during a distraction task. Again, one major difference between that study and the conditions at issue, however, is that in Suied, Susini and McAdams, no response selection was necessary, while in the conditions at issue, the individual would need to assess the environment for response options as well as select the best option. It is also different from the conditions at issue in that it took place under controlled conditions with repeated, similar trials, so the participants could anticipate the cue at least in a general sense.

An analogous real-world situation might be hearing an unexpected fire alarm in a complex environment; like the EWS, it is unexpected, and has no clearly appropriate response. Benthorn and Frantzich (1996) found a reaction time of 35±22 seconds to a verbal warning of fire in a department store; however, as their research was focused on exit selection more than reaction time the methods behind those numbers were unclear. Proulx and Pineau (1996) found a minimum reaction time to begin an evacuation to a fire alarm of 36 seconds and a maximum of 9:46. It may still be argued that these numbers are not directly applicable since fire alarms, although they may require some route planning, do not incur the same degree of response selection as a train approach warning in a complex spatial environment. Additionally, fire alarms may be more subject to false alarms or fire drill than train approach warnings.

2.6.3 Movement Time

Movement time is the period it takes the responder's muscles to perform the programmed movement; the more complex the movement, the longer it takes to plan. Increased arousal and practice both decrease movement time.

Movement time is of course heavily dependent on distance. In this case, the minimum survivable distance from the center of the track is approximately 6 feet, and the ROW itself is 25 feet wide; however, and in cases with adjacent tracks, the minimum distance would be 20 feet to clear the tracks and a further 25 feet to clear the ROW.

No reliable data is available on plausible speeds over uneven ground; however, Tawrell (2008) estimates 4 mph for the general population on uneven but relatively flat ground. Using this estimate, it would take 7.68 seconds to traverse 45 feet. This is somewhat over the original estimate of 5 seconds movement time.

2.6.4 Reaction Time Conclusion

The assumed time of 7.5 seconds can only be supported by tangentially related research performed under circumstances that are not a close analogue to the issue at hand. There is no research establishing the amount of time required for a pedestrian to select and begin to enact a response to an unknown auditory signal in an unfamiliar, complex environment.

3. Train EWS Development and Preliminary Survey

This section describes the approach to developing candidate train EWS sounds and the results from a preliminary survey to evaluate the feasibility and effectiveness of different sounds.

Through an iterative process, researchers developed over 100 initial EWS signals covering a range of amplitude and time-varying features, frequency content, and other acoustic characteristics. From these signals a smaller number of candidate signals were selected and included in a listening survey to gauge their feasibility and effectiveness.

3.1 Train EWS Development Approach

The goals for designing a new EWS for use on board trains are to 1) improve detectability, 2) create a greater sense of urgency, and 3) increase the likelihood of causing the desired action – avoidance of an oncoming train. Additionally, the EWS should allow individuals to easily identify the source of the sound, the direction the sound is coming from, and other details of the event – such as whether the train is approaching or departing the individual and their distance from the train. To achieve these goals, the following acoustic characteristics were considered.

Sound Character

All candidate signals that have been developed were based fundamentally on a five-chime Nathan train horn with primary tones at 355, 415, 470, 555, and 710 Hz and their harmonics up to 14,000 Hz. This baseline horn sound was then modified in various ways for each EWS sound, using audio engineering software. Although the actual train horn signal is more of a saw-tooth or square waveform rather than sinusoidal, generating sine waves of specific harmonic frequencies more closely replicated the sound of the physical horn and were easier to manipulate. Some EWS signals also included a recording of the actual Nathan train horn as a baseline sound.

Amplitude

It is important for the EWS to be reproduced at optimal amplitude which strikes a balance among being detectable, limitations due to the pain threshold and potential hearing damage to trespassers, occupational noise exposure, and annoyance to abutters.

As discussed in Section 2.6, the ideal amplitude of an EWS should be 6 to 10 dB above the masked threshold/ambient noise level to ensure 100 percent detectability and 15 dB above the masked threshold to ensure rapid response from the listener. Based on typical headphone listening levels, as discussed in Section 2.4, trespassers may typically be exposed to music (masking noise) of 85 dBA or greater. Based on the active/passive sound attenuation results presented in Section 2.5, on-ear and over-ear headphones can reduce sound 10 dB or greater, depending on frequency. Therefore, it would be necessary to generate in-ear EWS sound levels up to 101 dBA (85 + 10 + 6) to achieve a level 6 dB above masking. Similarly, an EWS would need to be 110 dBA to achieve a level 15 dB above masking.

FRA-regulated train horns generate a maximum of 110 dBA at 100 feet forward of the locomotive, which equates to 101 dBA at approximately 280 feet. For a train traveling at 45 mph (66 feet per second), this equates to having less than 2 seconds of warning time for a trespasser to vacate the tracks when detectability is ensured and slightly more than 4 seconds of warning time to ensure a rapid response from the trespasser. Based on the research on the time needed to vacate the tracks which shows that 7.5 seconds may be needed, this analysis shows that the current maximum sound emissions from FRA-regulated horns may not provide sufficient warning to trespassers listening to music with headphones. Under a separate contract to the FRA, this research team is investigating how loud electronic acoustic sources such as speakers and acoustic hailing devices can reproduce warning signals.

In designing EWS sounds, increasing the amplitude in a periodic manner was evaluated as a potential means to increase the sense of urgency based on the phenomenon that approaching objects increase in amplitude. Researchers observed that the detectability of the EWS was lowered when the signal was not at full amplitude. This degradation in effectiveness was not outweighed by the subsequent increase in amplitude. Therefore, most EWS sounds that were included in the survey were based on maintaining the highest amplitude throughout the signal duration.

Cycle Time

Unlike air pressure horns which generate a static sound, the ability to generate dynamic sounds which change in frequency is a key to improving effectiveness. For one, an effective EWS should have frequency-content to optimize loudness. As discussed in Section 2.3, humans can perceive loudness well when signals increase in amplitude over a duration of 200 ms or greater. In another way, humans do not perceive sounds as loud when they increase in amplitude faster (more impulsive). Therefore, most candidate EWS have been designed to vary frequency and amplitude based on 200 ms cycles or longer.

It was observed that having the cycle time of the EWS not coincide with the typical tempo of music was another key factor in optimizing detectability. Music generally ranges in tempo between 60 and 200 beats per minute (bpm) which corresponds to a beat every 300 ms to 1 second. Therefore, cycle times longer than 1 second (i.e., between 2 and 8 seconds) which vary the frequency content were used for many of the candidate signals. Cycles that are too long will not provide sufficient warning to trespassers in many cases.

Researchers investigated the following options 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 (e.g., 0.05 to 0.2 second) to leave a gap in the signal and then restart the cycle from the beginning, and 3) repeat the cycle without a gap. The evaluation of these options showed that 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, leaving a gap between cycles, resulted in a discontinuous sound that sounded more like a malfunctioning acoustic device. The third option, repeating the cycle without a gap, was found to be effective at maximizing the sense of an object accelerating toward the listener.

Frequency Content and Other Acoustic Characteristics

As discussed in Section 2.6, tonal sounds have been found to be harder to localize than broadband sounds, but increase perceived urgency. It was also identified that the response accuracy and latency in identifying and localizing an AWS with complex tones was improved compared to a single tone and 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 is an important factor that was considered in the design of new EWS sounds because 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.

Some candidate EWS included discrete tones close in frequency to create a beating sensation caused by both frequencies exciting the same part of the basilar membrane.

Additionally, as the frequency difference of the tones increased (still within the critical bandwidth), the perceived roughness increased. Some candidate EWS have also been generated to increase perceived roughness.

The Doppler effect, by means of increasing the frequency of tones throughout each cycle, has been included in many of the candidate signals. Since this phenomenon relates to an object accelerating toward a stationary listener, it has been shown to create a greater sense of urgency. Some of the EWS simulated the Doppler effect of all of the fundamental tones and harmonics while some only simulated the Doppler effect for some of the tones and harmonics. This approach was found to allow a balance of an increased Doppler effect while maintaining the character and identification of a train horn.

To combat the noise-reducing properties of the headphones, the frequency content of some of the candidate EWS were shaped to increase amplitude in the 600- to 1200-Hz range where active noise cancellation was not as effective, and where the passive noise reduction of the headphones was also limited.

Some of the candidate signals also included tones below the lowest fundamental (355 Hz) of the baseline air pressure horn to extend low-frequency content. This was done either by mixing in a rumbler-like sound or by adding in "fractional harmonics" of the fundamental tones. For example, one EWS included tones at one-half and one-third of 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 were separated by approximately 20 Hz, a beating effect was also generated.

3.1.1 Preliminary Train EWSs

The following describes the 12 EWS tested and evaluated during the survey.

EWS 1: This signal was the digital baseline train horn sound with Doppler effect increasing all tones 20 percent over a cycle time of 0.2 second. The signal was repeated without any gaps. This EWS sounded fairly electronic and fast.

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

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

EWS 4: This signal was the digital baseline train horn sound with Doppler effect increasing all tones over a cycle time of 1 second. Each tone was increased in frequency 25 percent of the auditory filter critical bandwidth (see Section 2.3) of that tone. So, for example, the 355 Hz tone had an auditory critical bandwidth of 109 Hz, and 25 percent of that is 27 Hz. Therefore, the tone was increased from 355 to 280 Hz (or 8 percent). All tones were increased approximately 4 to 8 percent.

Additionally, the signal included 15 percent modulation at a modulation frequency of 4 Hz (beginning) and 20 Hz (end). Overall, this signal was very electronic and fast.

EWS 5: This signal was the digital baseline train horn sound with Doppler effect increasing all tones 5 percent over a cycle time of 0.25 second. This signal sounded like a "thumping" train horn, as it maintained more of the train horn character than other candidate EWS.

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

EWS 7: This signal included both a 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 was similar to EWS 2, which did not include a Doppler effect, but included frequency modulation or "shaking" of the tones. Additionally, the rumbler was added for additional low-frequency content. The overall signal sounded like it was being reproduced electronically and not from an analog mechanical source (actual horn).

EWS 8: This signal was the baseline train horn sound, including the primary and all harmonics. The rumbler was added for additional low-frequency content. The overall signal sounded more like the standard train horn warning signal than many other candidate EWS.

EWS 9: This signal was similar to EWS 7 – a mixture of the baseline and digital baseline sound; however, this signal did not include the rumbler. The overall signal sounded like a standard train horn signal with additional high-frequency content.

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

EWS 11: This signal was similar to EWS 9; however, instead of modifying the harmonics with just frequency modulation, the research team simulated Doppler effect which increases these harmonics 20 percent over a cycle time of 0.2 second. The overall signal sounded highly electronic and thumping.

EWS 12: This signal was the baseline train horn sounds including the primary and all harmonics. Lower frequency "fractional harmonics," including all one-half and one-third frequencies of the primary tones, were included. The overall signal sounded like a deep and rich train horn sound with a slight beating effect in the lower frequency.

3.1.2 Preliminary EWS Spectrograms

The following figures present spectrograms of representative EWS signals developed in Phase 1 of this research. The horizontal lines represent the tones of the standard train horn such as those shown on the top-right spectrogram. The frequency variation cycle time is shown by the changing pattern horizontally across the spectrogram. For example, the bottom left figure shows all frequencies increasing in frequency over a cycle time of 1 second.

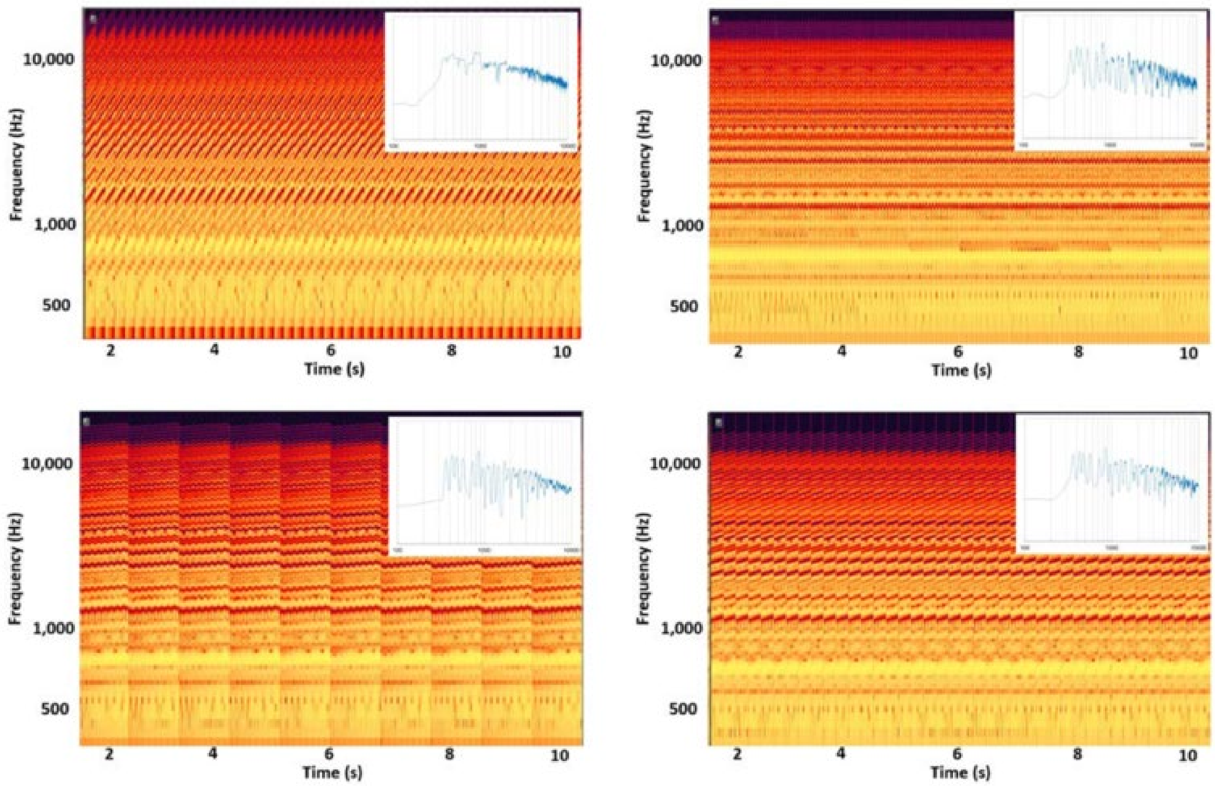

Figure 27. Representative Spectrograms of Preliminary Train EWS

3.2 Survey to Evaluate Preliminary Train EWS

A survey shown in the figures below was developed where participants wore over-ear headphones and listened to calibrated playbacks of different EWS sounds, including standard wail and yelp signals. The survey was administered in a typical office setting in a low-ambient environment to 25 participants. The goal was to identify specific features of the more effective EWS and reduce the group of candidate EWS for further refinement and evaluation. The survey included three parts:

- The first part measured listeners' responses to each EWS in regard to 1) causing a sense of urgency, 2) ability to identify the source of the sound, 3) certainty with which one could identify the source, 4) whether the sound startled the participant, and 5) whether the sound was annoying.
- The second part involved listening to a broadband (pink noise) masking sound or a music masking sound through headphones while each EWS was played with increasing

amplitude. The EWS began at a very low (inaudible) level and increased until it was clearly audible. The survey measured the time, amplitude, and detectability (d-prime) level at which the participant first heard the warning signal and then again when the warning signal was at a sufficient amplitude to cause the participant to feel a need to take action and move away from the source. The song played was a popular song with relatively equal (flat) frequency response and a tempo of 126 bpm. The same portion of the song was played for all tests to keep the masking sound an independent variable.

- The third part of the survey involved comparative listening of two different EWS. The listener was able to switch back-and-forth, listening to two different signals. The participants were then asked to rate which sound caused a greater sense of urgency, which sound the participant could identify the source of with more certainty, and which sound caused greater startle.
- Between playing each EWS, a 10-second clip of typical ambient sounds were reproduced to help minimize any "acoustic memory" of the prior EWS.

Twelve candidate EWS that represented a range of the different design features, along with the standard warning signals (wail, yelp, rumbler and baseline Nathan train horn), were tested and evaluated to quantify and compare their effectiveness. All EWS were reproduced with in-ear amplitude of 80 to 85 dBA. The formats of the three survey parts are shown in the figures below.

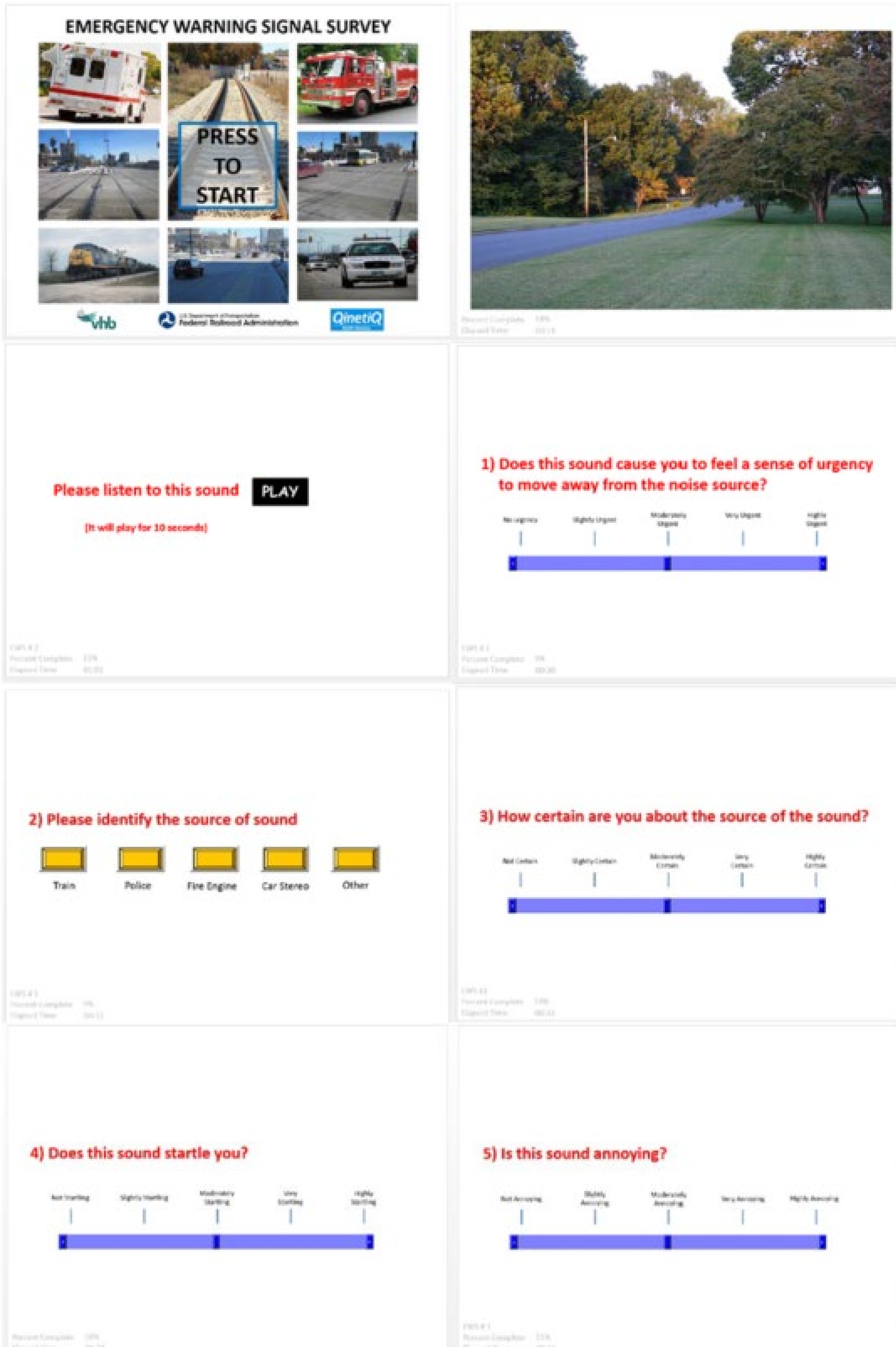

Figure 28. Listening Survey Format (Part 1, Ratings)

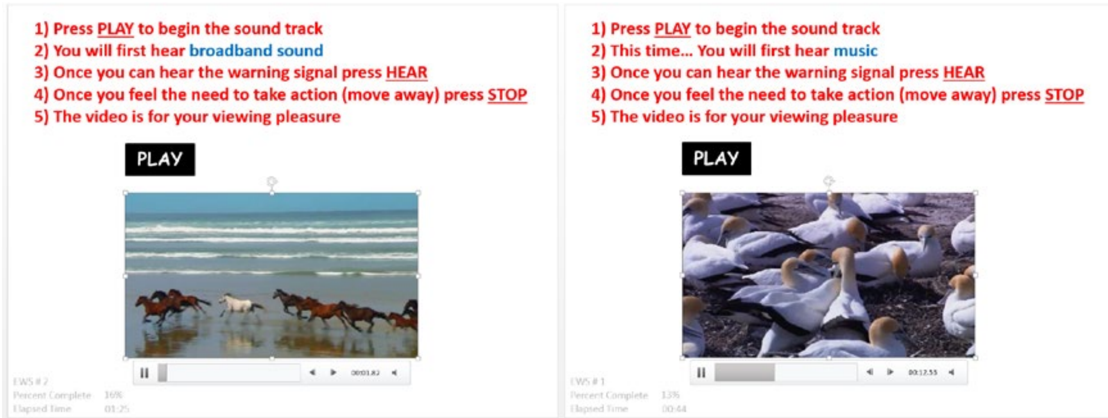

Figure 29. Listening Survey Format (Part 2, Detectability)

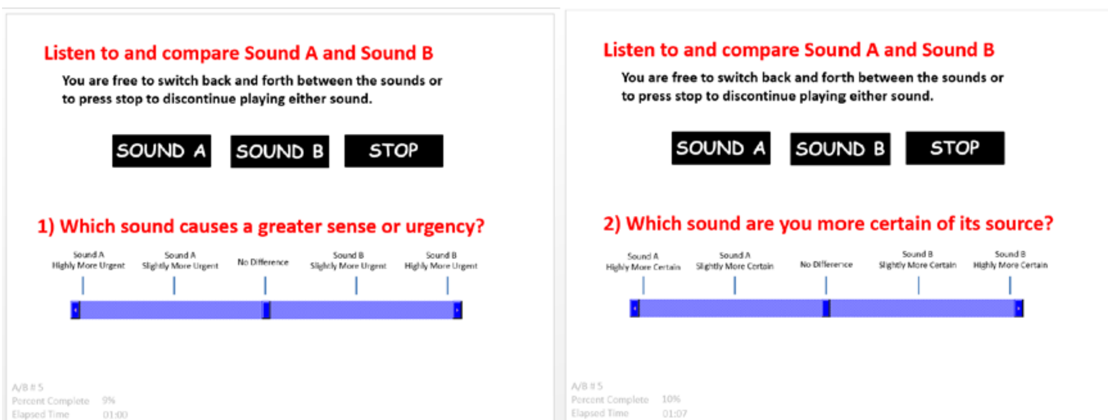

Figure 30. Listening Survey Format (Part 3, Comparative A/B Ratings)

3.3 Survey Results

The source identification results, shown in the figure below, indicate that the actual baseline train horn was identified correctly by all participants. Interestingly, the rumbler was only correctly identified as a police warning signal by 4 of 25 participants. Of the candidate EWS, there was a broad range of results – some signals were almost always identified as a train and some were not readily identified as a train. This showed that varying the different acoustic parameters could easily affect the association of the sources with a train and that care must be taken to maintain proper source identification.

The average sense of urgency rating (plus and minus one standard deviation) that each signal caused is shown in Figure 32. The sense of urgency is considered to be one of the most important metric to assess the effectiveness of the EWS as the primary purpose is to cause the listener to take action and move away from the tracks. The results show that there was not a substantial difference among the EWS, including the standard wail and yelp warning signals, but some EWS (1, 4, 5, 6, and 9) did perform better than the standard train horn.

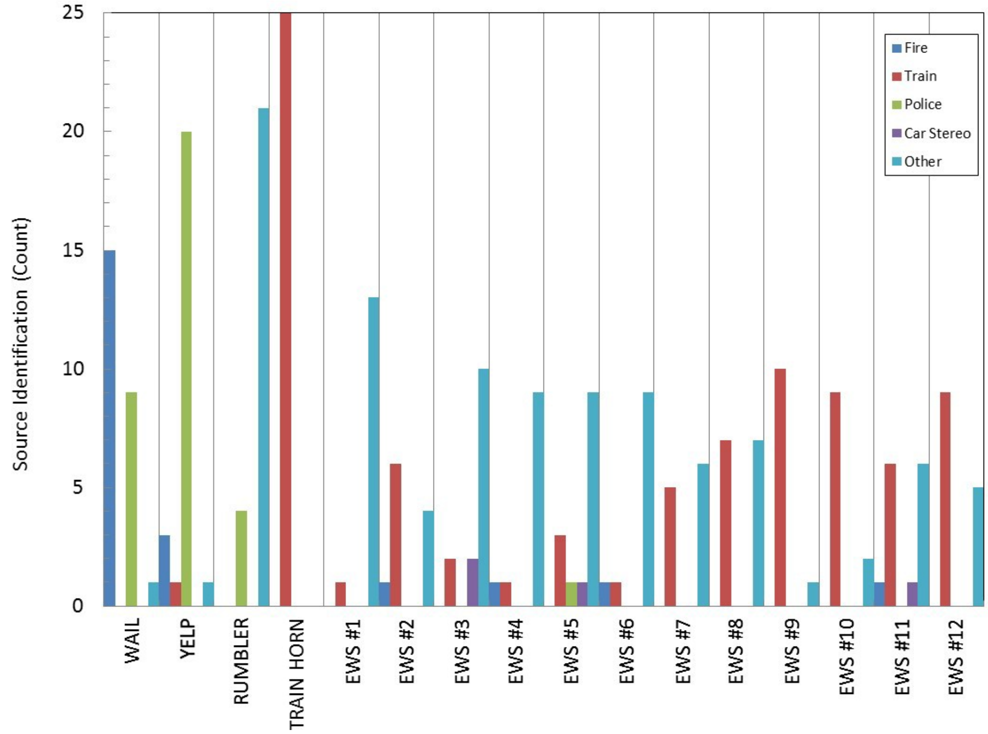

Figure 31. Source Identification Results

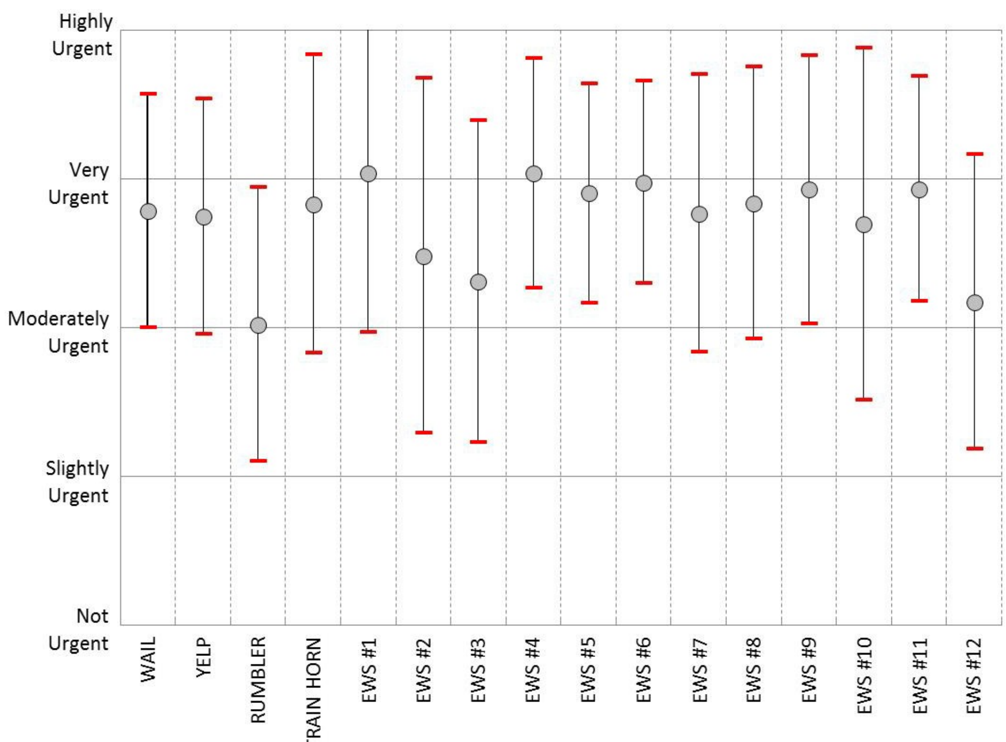

Figure 32. EWS Urgency Rating (Average +/- Standard Deviation)

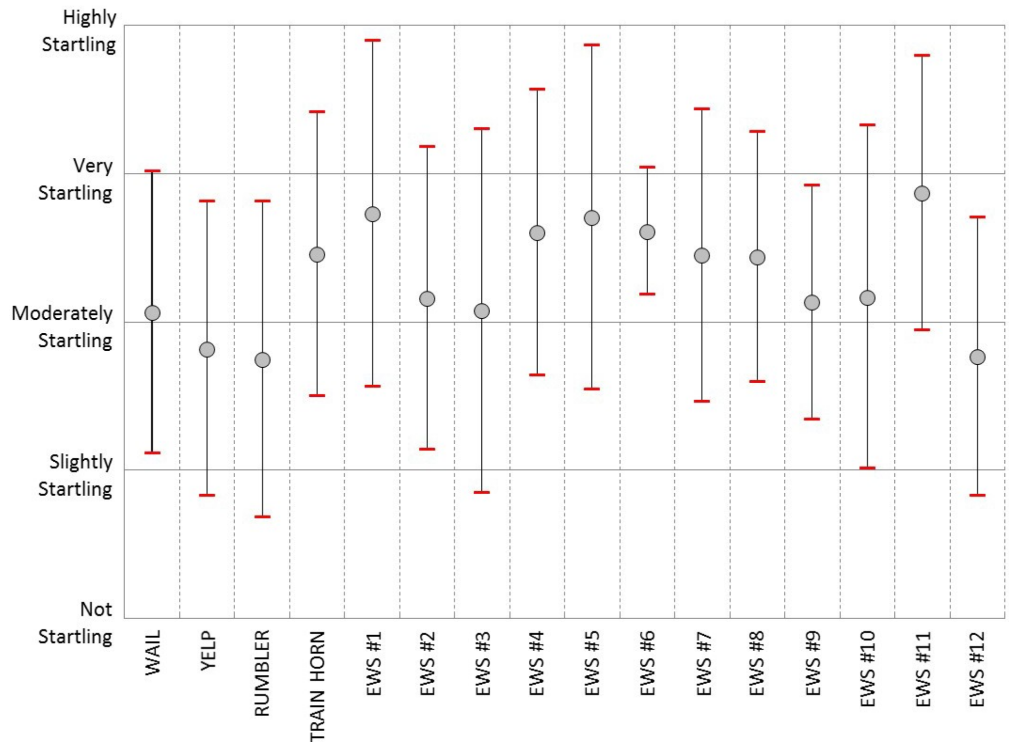

Figure 33. EWS Startle Rating (Average +/- Standard Deviation)

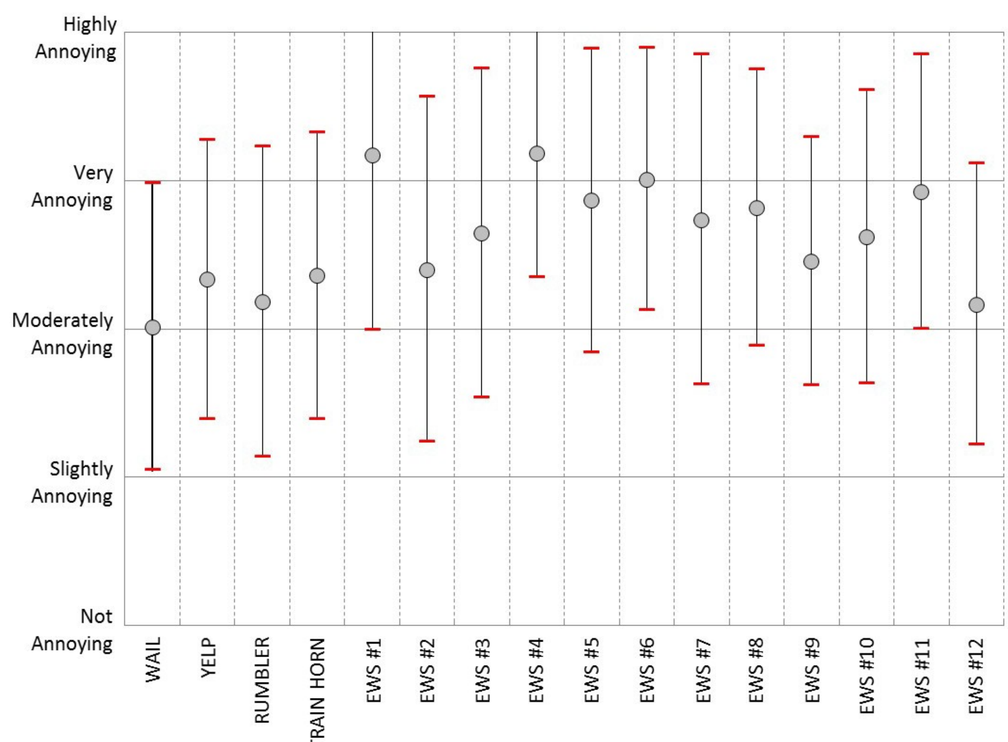

Figure 34. EWS Annoyance Rating (Average +/- Standard Deviation)

Figure 33 shows the startle ratings for each EWS, and Figure 34 shows the annoyance ratings for each EWS including the average rating plus or minus one standard deviation. These figures show that the standard wail, yelp, and rumbler warning signals were the least startling and annoying.

Generally, startling the listener is not desirable, as this could cause a trespasser to not follow the correct course of action – to vacate the track safely. Most candidate EWS had a similar startle effect as the standard train horn sound. Most EWS had a greater level of annoyance than the traditional train horn sound.

The relative differences in detectability with pink noise and music masking compared to the baseline train horn are shown in Figure 35 and Figure 36, respectively. 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 up to 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 track.

The wail and yelp standard warning signals were shown to have the best detectability among all of the signals. This is an important finding which showed that incorporating wail or yelp-like features into a new train EWS could improve performance. With music masking, 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. Researchers believe this was due to acoustic characteristics of these warning signals as well as the prevalence of these signals in U.S. communities. Many of the candidate EWS improved audibility by 5 dB or more compared to the standard train horn. This shows that a new EWS could perform better than a standard train horn sound. However, this also showed that maintaining characteristics of the wail and yelp could further improve train EWS effectiveness.

Figure 37 shows the A/B comparative results of the EWS versus the standard train horn sound or other EWS. EWS 1, 5, and 8 created a greater sense of urgency compared to the train horn. Figure 38 presents the source identification results versus the sense of urgency. The figures show that EWS 9 and 10 performed well in regard to sounding like a train horn and providing a sense of urgency.

Figure 39 plots the sense of urgency rating of the warning signals versus the difference in detectability relative to the standard train horn. Signals near the lower-right corner were more effective because they were more easily heard and created a greater sense of urgency. EWS 1, 2, 6, 9, and11, as well as the standard wail and yelp signals, were shown to perform best.

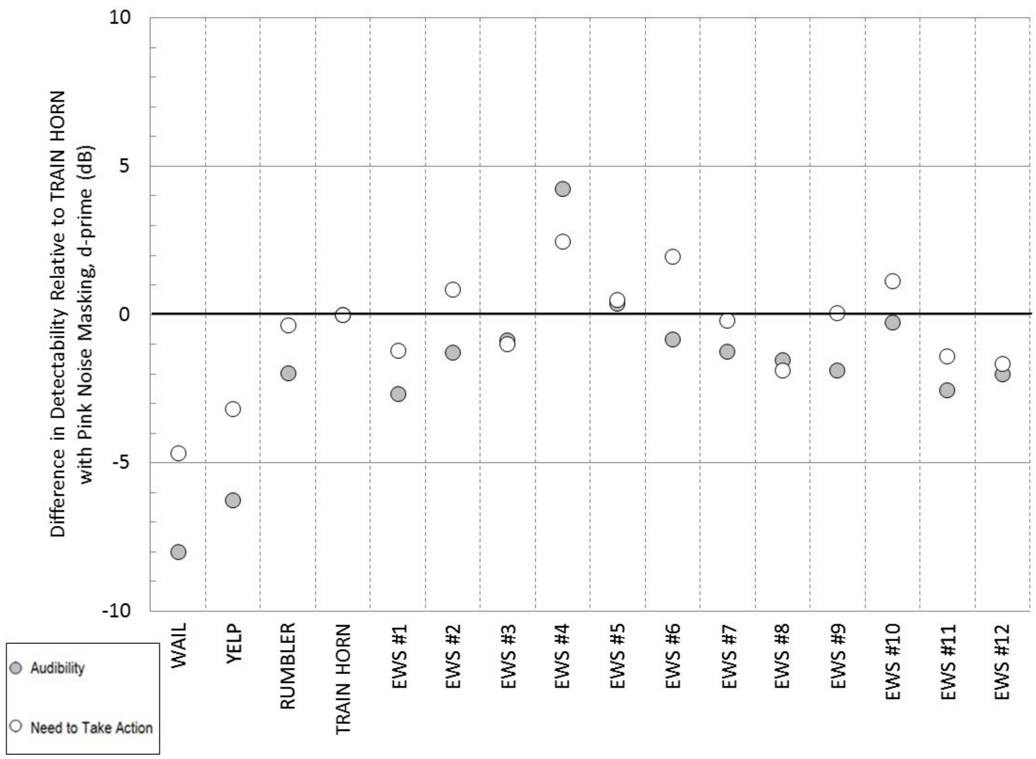

Figure 35. Difference in Detectability Relative to Train Horn with Pink Noise Masking

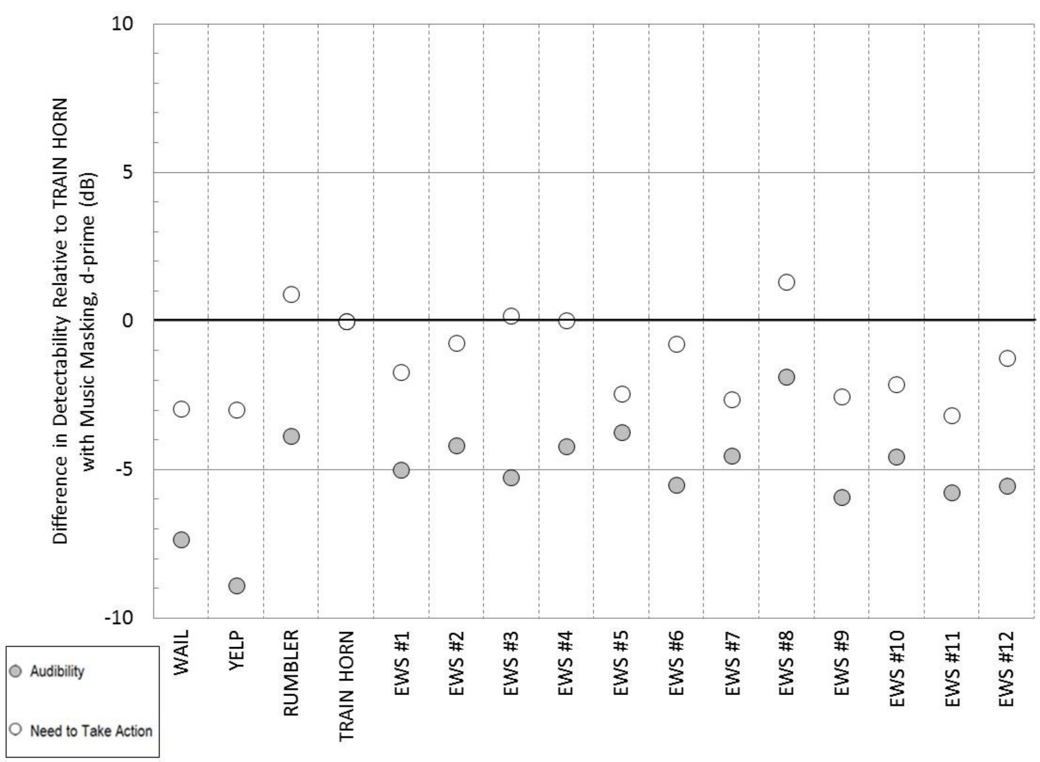

Figure 36. Difference in Detectability Relative to Train Horn with Music Masking

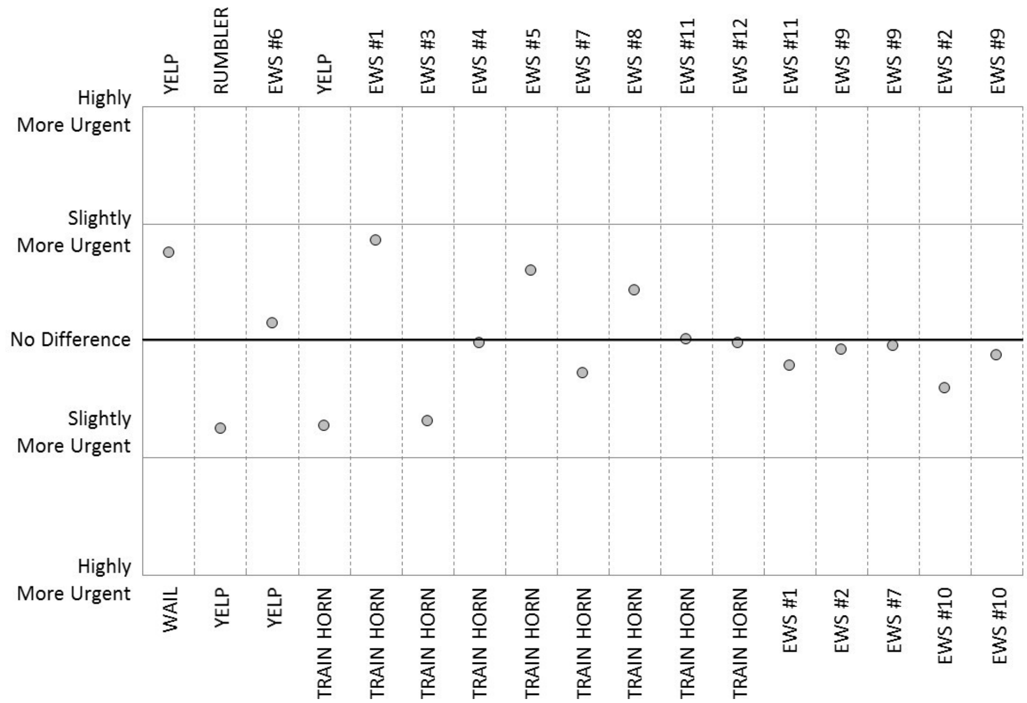

Figure 37. A/B Comparison of Urgency

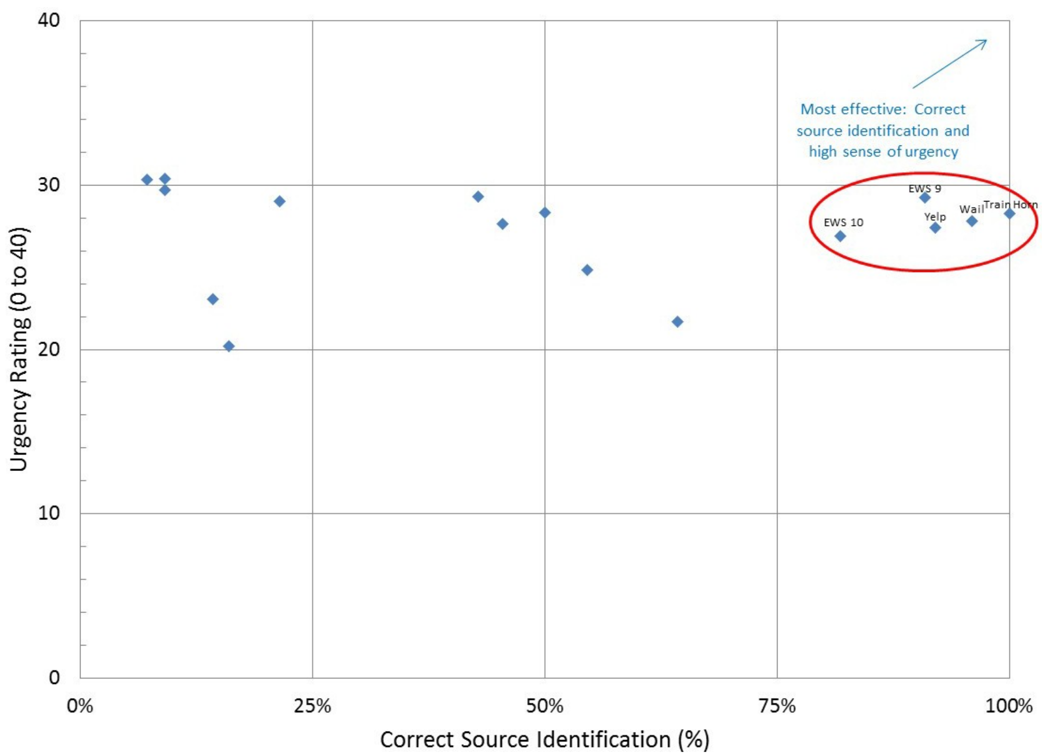

Figure 38. Source Identification vs. Urgency Rating

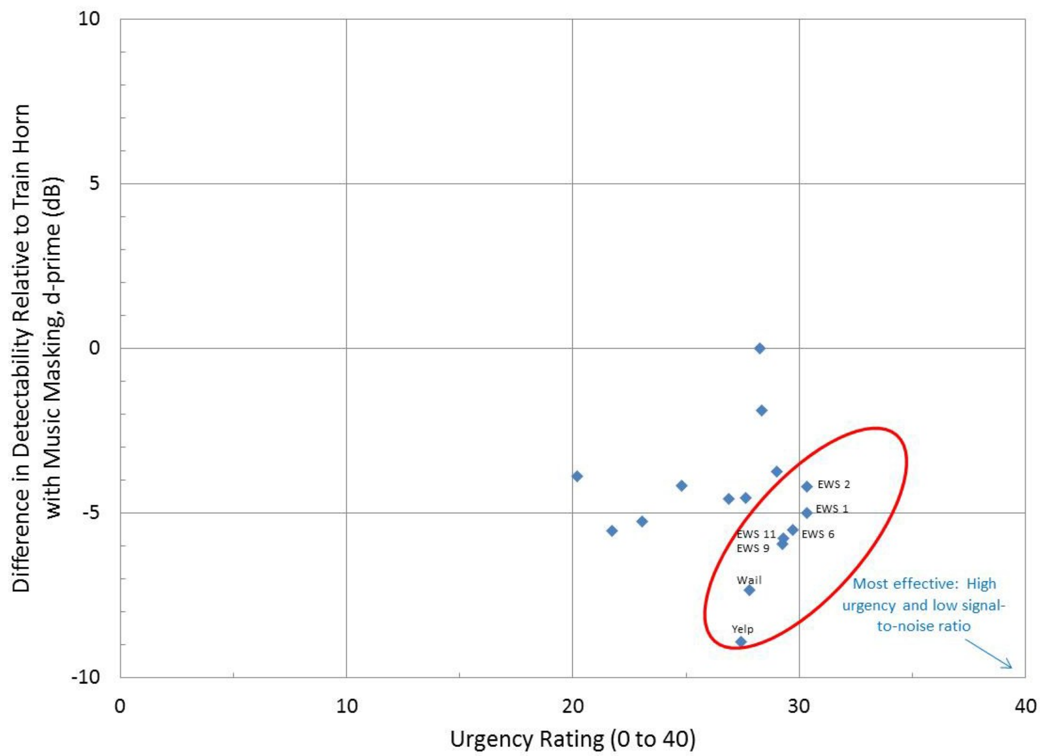

Figure 39. Urgency Rating vs. Difference in Detectability with Music Masking

The survey indicated that it was possible to create a more effective EWS which met the goals of increasing a sense of urgency, improving detectability, and maintaining the identification of the noise source. The standard wail and yelp signals used on emergency response vehicles performed better than a standard train horn in certain areas. The rumbler performed poorly in regard to both source identification and creating a sense of urgency.

Similarly, adding a rumbler-like sound or extending low-frequency content of candidate EWS sounds did not improve performance.

Overall, this preliminary investigation showed that candidate EWS should be investigated which include attributes from the standard wail and yelp signals such as the cyclical variation in frequency and the cycle time used. The investigation should also evaluate which of the specific tones of the EWS should be varied.

4. Optimized Train EWS Development (Audio Booth Testing)

The preliminary train EWS development provided insight into how to design candidate EWS sounds which maintain the association of a train event and increases the sense of urgency. EWS designs were then optimized based on these findings. The optimized set of candidate EWS were tested for effectiveness in increasing detectability and sense of urgency in an audio booth.

4.1 Audio Booth Test Setup

The audio booth provided a quiet environment where participants could listen to masking music with headphones and where the EWS were reproduced using an electronic source (a speaker) within the booth. The EWS were played back to simulate an approaching train at 45 mph with a sound emission level relative to 110 dBA at 100 feet forward of the locomotive.

The amplitude of each EWS as a function of frequency and time was modified using digital signal processing software to simulate the spherical spreading and atmospheric attenuation that would occur from an acoustic source on an approaching train. This processing did not include the ground effect – a sound propagation phenomenon that occurs when a source and receiver are relatively close to the ground. The ground effect generally increases sound reduction in mid-range frequencies due to the interaction between reflected and direct sound paths. The ground effect depends on the type of ground cover. Recent studies have shown that railroad ballast can be a highly absorptive surface and can provide significant noise reduction.

There were two phases to the audio booth testing:

- The first phase allowed the participant to select their music playback volume (80 or 85 dBA in-ear) and select different songs to play as masking throughout the tests. Throughout the test, the participant was forced to select from a range of songs with slow, medium, and high tempo, but were generally given the opportunity to select a specific song within a given music tempo. This approach minimized the risk that they would be listening to a song they did not like which could potentially affect their response. In this phase, the participant was asked to press a button at the moment the EWS could be heard and then second button when the participant "felt that danger was imminent and that they should vacate the tracks." During these tests a video of the perspective one would have walking down a railroad track was played. The tests included 10 candidate EWS, a standard train horn sound, a train horn sound played in 0.5-second pulses (similar to the short sequencing that some railroads define as the sounding pattern to use when there are people on the tracks), and a police wail. This phase resulted in only a limited number of participants who selected the higher music playback volume.
- Since it was anticipated that the music listening level would be an important factor in determining the effectiveness of warning signals, the second phase of testing forced the participant to listen to music at in-ear levels of 80, 85, and 90 dBA. This phase included three candidate EWS sounds, the standard train horn sound, and the standard train horn sound played as repeating pulses. For these tests, the participant was only asked to press one button when the sound created a sense of urgency to vacate the tracks. The video displayed in the first phase of tests was found to potentially have visual clues that may have indicated when the EWS was being sounded. Therefore, a stationary photo from the

perspective one would have walking down a railroad track was displayed during this phase of testing instead.

The same pair of on-ear headphones used in the listening survey was also used during the audio booth testing. The first phase of testing utilized a set of two-way amplified speakers, balanced to provide a relatively flat frequency response inside the booth. The second phase of testing used a Community RMG-200 speaker which has more mid-range frequency output and is a component in the AWD prototype being developed under a separate project for FRA. Figure 40 shows a survey participant in the audio booth with in-ear microphones used to calibrate the warning signal playback. Figure 41 shows the simplified survey formats used for the audio booth tests.

Figure 40. Audio Booth Test Participant

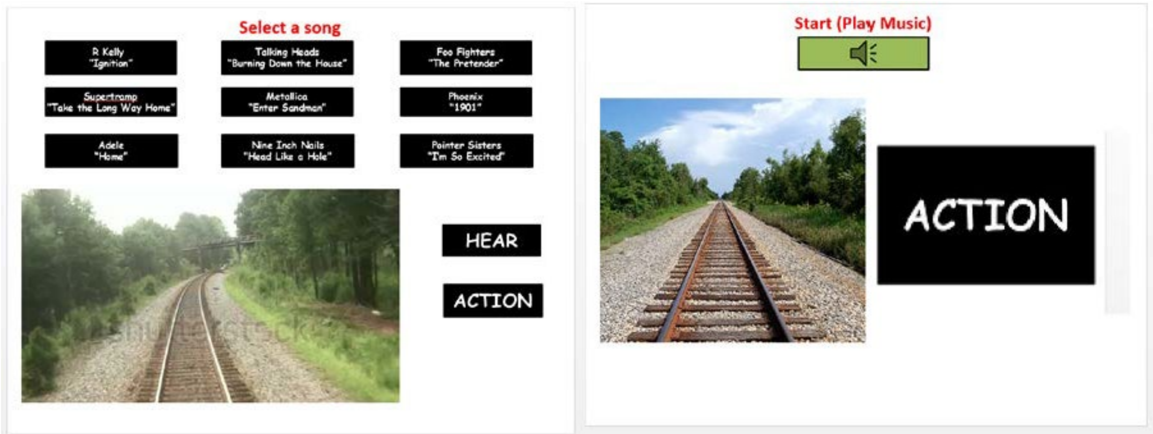

Figure 41. Audio Booth Test Format (Phase 1 left, Phase 2 right)

4.2 Expanded Selection of Listening Music

The music selections used during the booth testing as well as their tempo, corresponding time per beat, and tempo category are shown in Table 3. Researchers observed that if the music tempo and EWS cycle time were similar, the detectability was reduced as compared to when the tempo and cycle time were different. Therefore, a wide range of music tempos were selected.

Table 3. Masking Music Selections

Song, Artist	Tempo (bpm)	Time per Beat (ms)	Tempo Category
Song 1	56	1070	Largo
Take the Long Way Home, Supertramp	76	790	Adagio
Hello, Adele	79	760	Adagio
Burning Down the House, Talking Heads	104	577	Moderato
Enter Sandman, Metallica	112	536	Moderato
Head Like a Hole, Nine Inch Nails	115	522	Moderato
1901, Phoenix	144	417	Allegro
The Pretender, Foo Fighters	175	343	Presto
I'm So Excited, Pointer Sisters	180	333	Presto

4.3 Optimized EWS Sounds

A total of 10 EWS sounds, the standard train horn, wail, and yelp were used during the first phase of audio booth testing. These EWS were built off the findings from the preliminary EWS development and survey results. Specifically, some of these optimized EWS sounds incorporated the standard wail and yelp acoustic signatures signals such as the cyclical variation in frequency and the cycle time used. Additionally, many of these EWS sounds varied the frequency of train horn tones in the 800- to 1,200-Hz region where headphones have been found to be less effective at attenuating sound and there is a greater opportunity for detection.

Ten EWS were tested and evaluated during the booth testing:

EWS 1: This signal included a 500-ms cycle of frequencies between 700 and 1,200 Hz, doubling in frequency. Each cycle was repeated with no gap in between. This EWS sounded fairly electronic with a pulsing sound at each 500-ms cycle.

EWS 2: This signal included a 2,000-ms cycle of all frequencies doubling as well as modulating at a constant 16-Hz frequency. The EWS sounded highly electronic and did resemble a train horn sound.

EWS 3: This signal merged a standard train horn sound with a yelp signature. It included a 250-ms sinusoidal cycle of frequencies between 800 and 1,200 Hz, which doubled in frequency and then returned to their initial frequency. Amplitude of the frequency-varying tones between 800 and 1,200 Hz were increased by 6 dB relative to other tones.

EWS 4: This was the same signal used in the preliminary survey. The signal was the digital baseline train horn sound, with Doppler effect increasing all tones over a cycle time of 1 second. Each tone was increased in frequency 25 percent of the auditory filter critical bandwidth (see Section 2.3) of that tone. So, for example, the 355-Hz tone had an auditory critical bandwidth of 109 Hz and 25 percent of that is 27 Hz. Therefore, the tone was increased from 355 to 280 Hz (or 8 percent). All tones were increased approximately 4 to 8 percent. Additionally, the signal included 15 percent modulation at a modulation frequency of 4 Hz (beginning) and 20 Hz (end). Overall, this signal was very electronic and fast.

EWS 5: This signal merged a standard train horn sound with a wail signature. It included a 2-second sinusoidal cycle of frequencies between 800 and 1,200 Hz, which doubled in frequency and then returned to their initial frequency. Amplitude of the frequency-varying tones between 800 and 1,200 Hz were increased by 6 dB relative to other tones.

EWS 6: This signal merged a standard train horn sound with a yelp signature, including two different cycle times depending on frequency. The lower tones near 800 Hz were cycled in a sinusoidal manner over a 500-ms period, while the tones near 1,200 Hz were cycled over a 250-ms period. The resulting sound carried more of a yelp signature than a train horn signature and created somewhat of a pulsing effect based on the different cycle times.

EWS 7: This signal merged a standard train horn sound with both yelp and wail signatures. Tones between 800 and 1,200 Hz were cycled in a sinusoidal manner over both a 250-ms and 2-second period which both doubled in frequency. The resulting sound was a relatively complex sound, as it encompassed standard warning signals from both fire and police vehicles.

EWS 8: This signal increased all frequencies over a cycle time of 200 ms and repeated. The resulting sound had very little association with a train horn sound and was very electronic and fast.

EWS 9: This signal merged a standard train horn sound with a yelp signature that had a varying cycle time. Tones between 800 and 1,200 Hz were cycled in a sinusoidal manner over a period that started at 1 second and then ramped up to a period of 250 ms.

EWS 10: This signal was the same as EWS 1; however, during playback that simulated a train approaching, the warning signal jumped 6 dB in amplitude approximately 20 seconds prior to the train reaching the listener.

4.3.1 Optimized EWS Spectrograms

Figure 42 through Figure 44 presents spectrograms of optimized EWS signals included in the audio booth testing. Figure 45 presents spectrograms of the standard train horn, wail, and yelp signals.

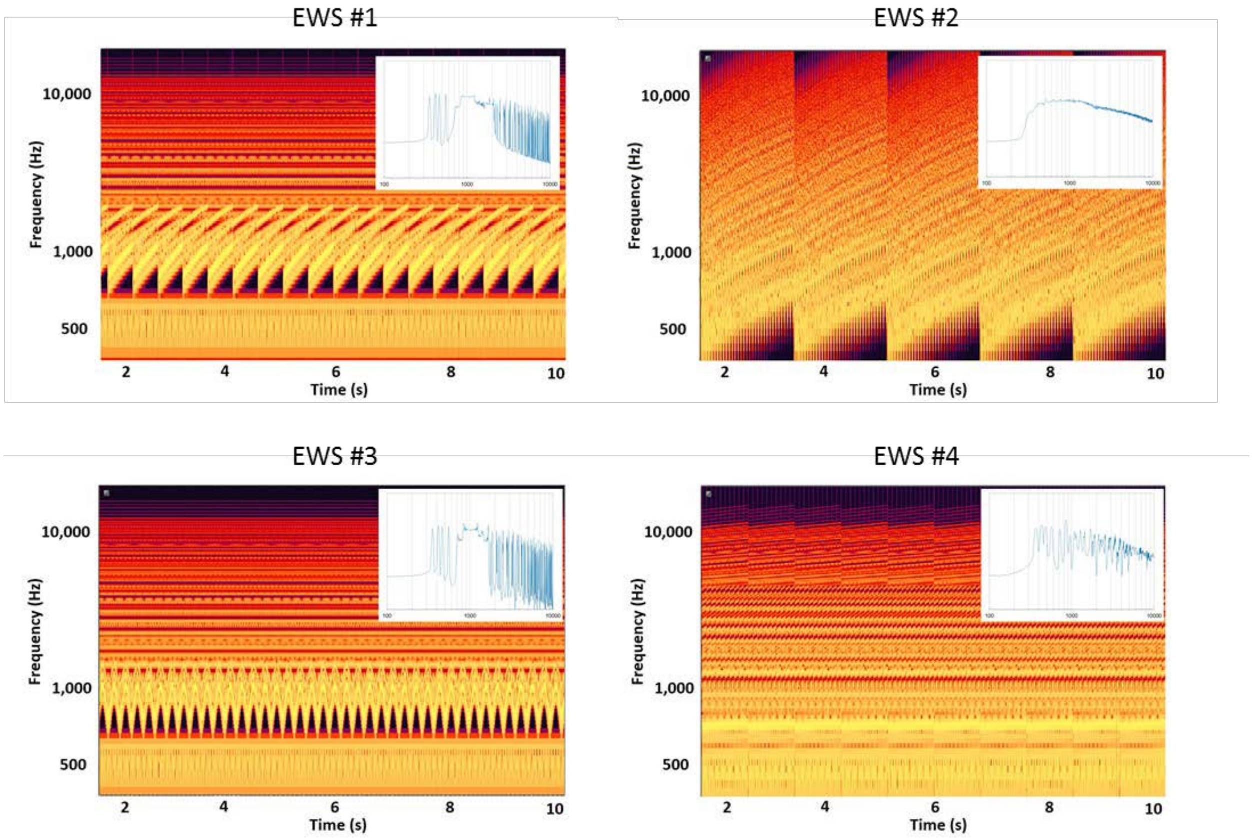

Figure 42. Optimized EWS Spectrograms for EWS 1 through EWS 4

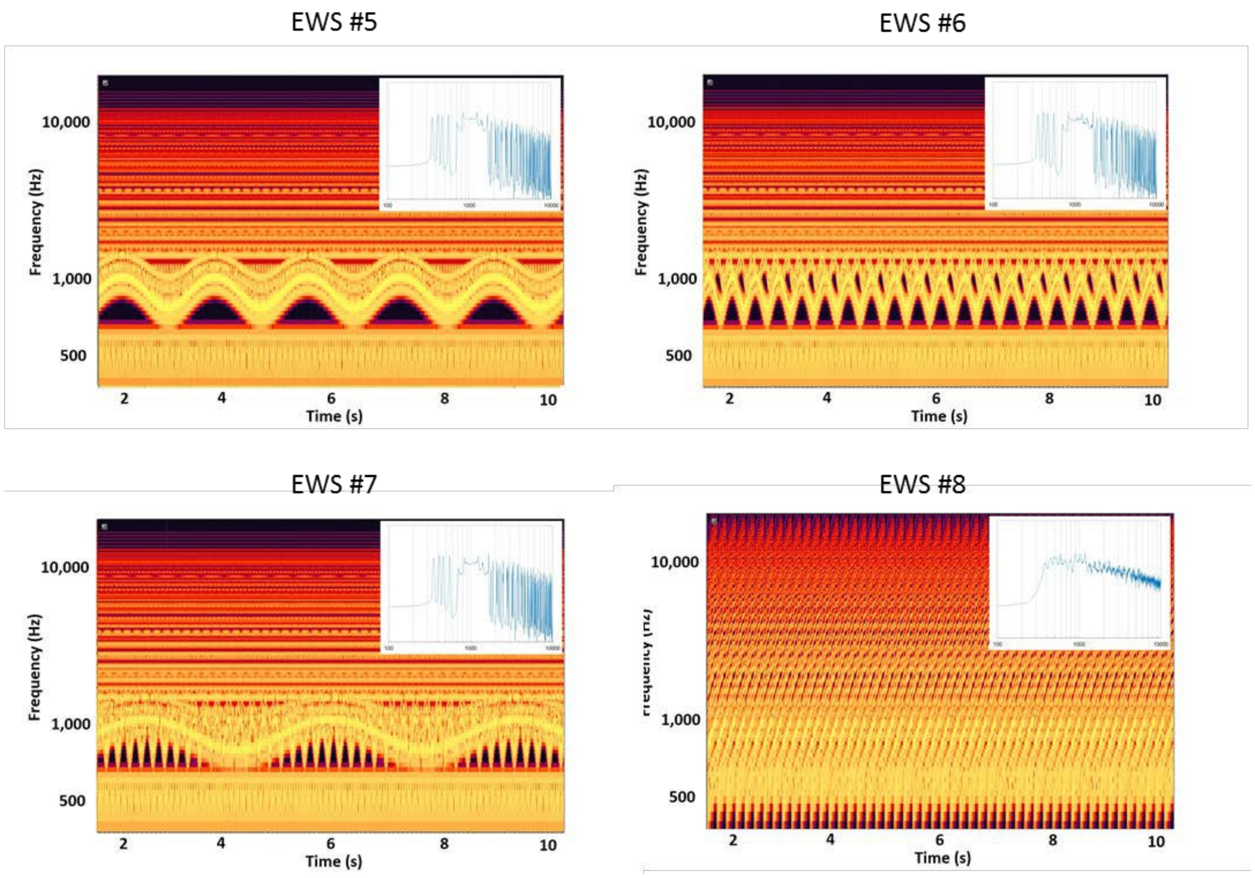

Figure 43. Optimized EWS Spectrograms for EWS 5 through EWS 8

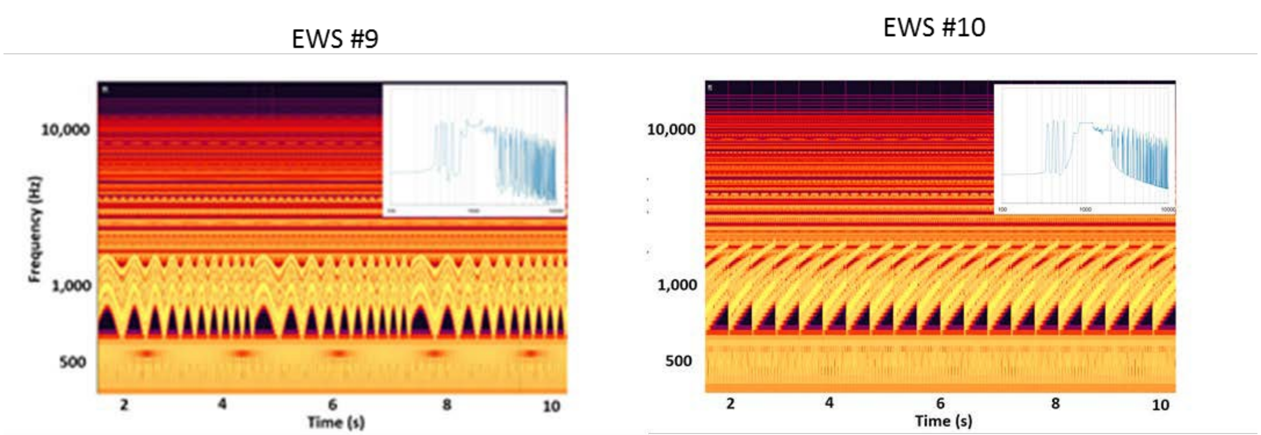

Figure 44. Optimized EWS Spectrograms for EWS 9 and EWS 10

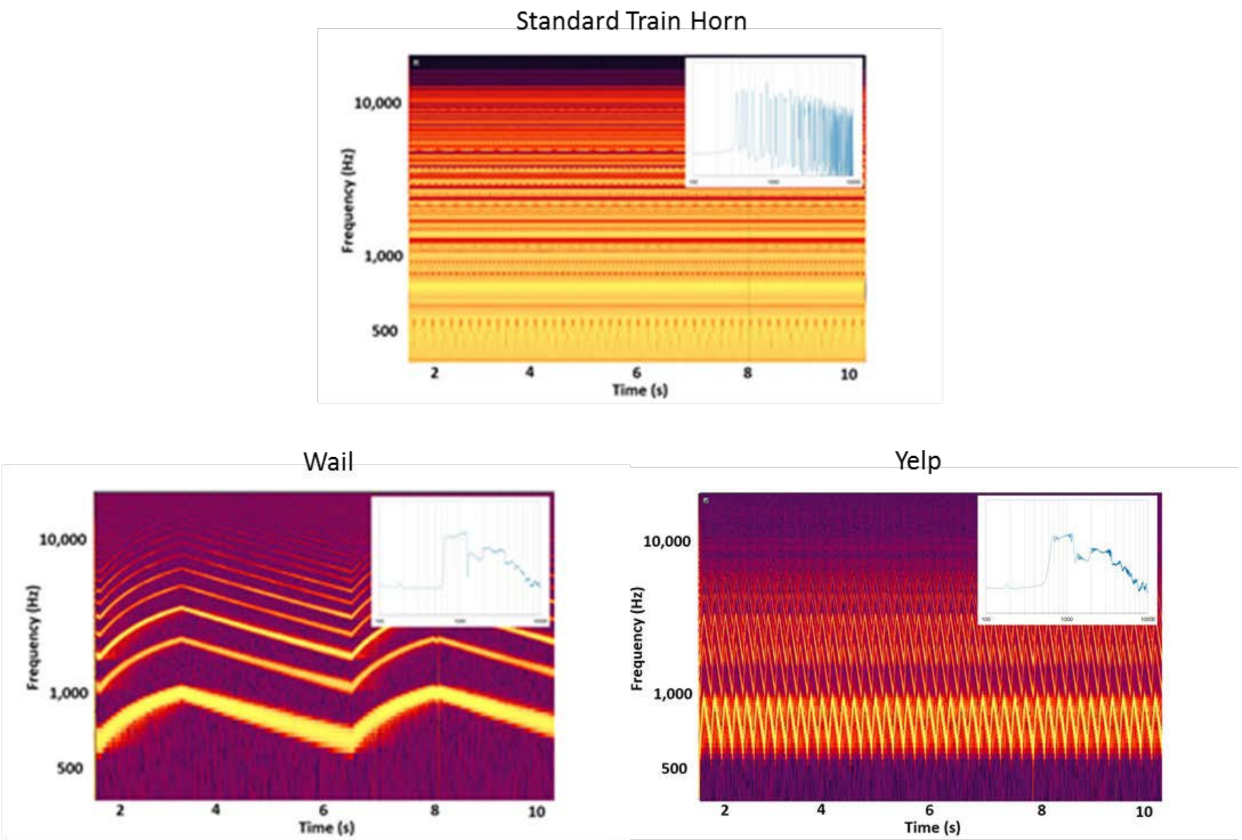

Figure 45. Spectrograms for a Standard Train Horn, Wail, and Yelp

4.4 Audio Booth Test Results

Phase 1 Results

Figure 46 presents all of the phase 1 audio booth test results for the time available to vacate tracks with a music listening level of 80 dBA. This figure shows a considerable amount of variation among the responses and that ample warning time (30 to 60 seconds) was available on average. The average responses (shown in orange bars) were relatively similar across all of the EWS, standard train sound, wail, and yelp. There were a few responses, such as those for EWS 2 and 4, where individuals had less than 7.5 seconds of warning to vacate the track. These results show that when a warning signal was sounded for an extended period of time (i.e. up to two minutes prior to reaching a trespasser), normally the signal could be detected with sufficient time available to vacate the tracks when listening to music at 80 dBA.

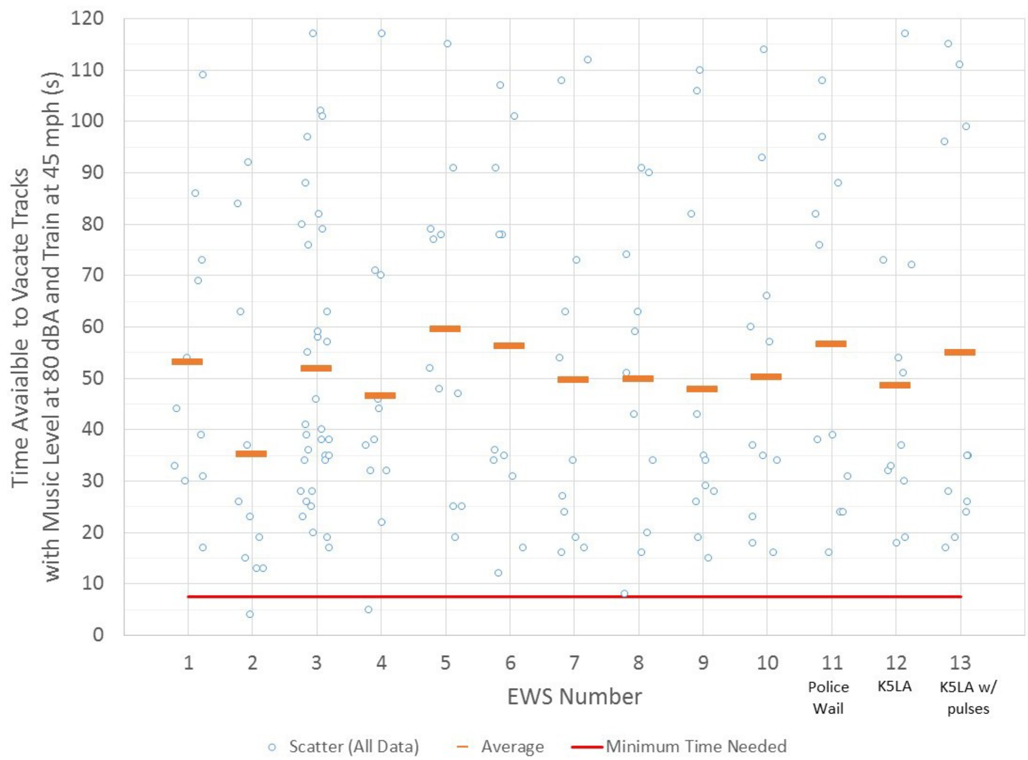

Figure 46. Time Available to Vacate Tracks with Music Level at 80 dBA

Phase 2 Results

Unlike the first phase where two responses (audibility and sense of urgency) were measured, the second phase of audio booth tests required the participants to only respond when they had a sufficient sense of urgency. This phase only sounded the warnings 20 seconds prior to reaching the trespasser, which is more typical of actual incidents. The second phase also forced tests under higher music listening levels, including 80, 85, and 90 dBA, to gain a better understanding of the effect of music listening level.

The time history of sound levels at the listener's ear location (not including the passive or active noise reduction of headphones) are presented in the following figures along with the responses. As shown in Figure 47 for a standard train horn, most participants detected the warning signal with 15 to 20 seconds of warning. A few responses provided less than 7.5 seconds of warning, despite having EWS amplitudes at the outside of headphones (not including active or passive reduction) over 100 dBA. Figure 48 presents similar results for the standard train horn signal played as a series of pulses. The pulses were 0.5 second on, 0.5 second off, and repeated. This was to represent Norfolk Southern's policy of sounding a series of repeated bursts when people or animals are detected on the track. This figure shows 20 percent of responses (5 out of 24) provided less than 7.5 seconds of warning. These results were mostly with in-ear music levels of 85 or 90 dBA. Figure 49 through Figure 51 present the reaction time results for EWS 3, 5, and 7, respectively, which include fewer responses with less than 7.5 seconds. Overall, this phase of testing indicates there was a greater probability that a trespasser listening to music may not have sufficient time to vacate the tracks compared to the phase 1 tests.

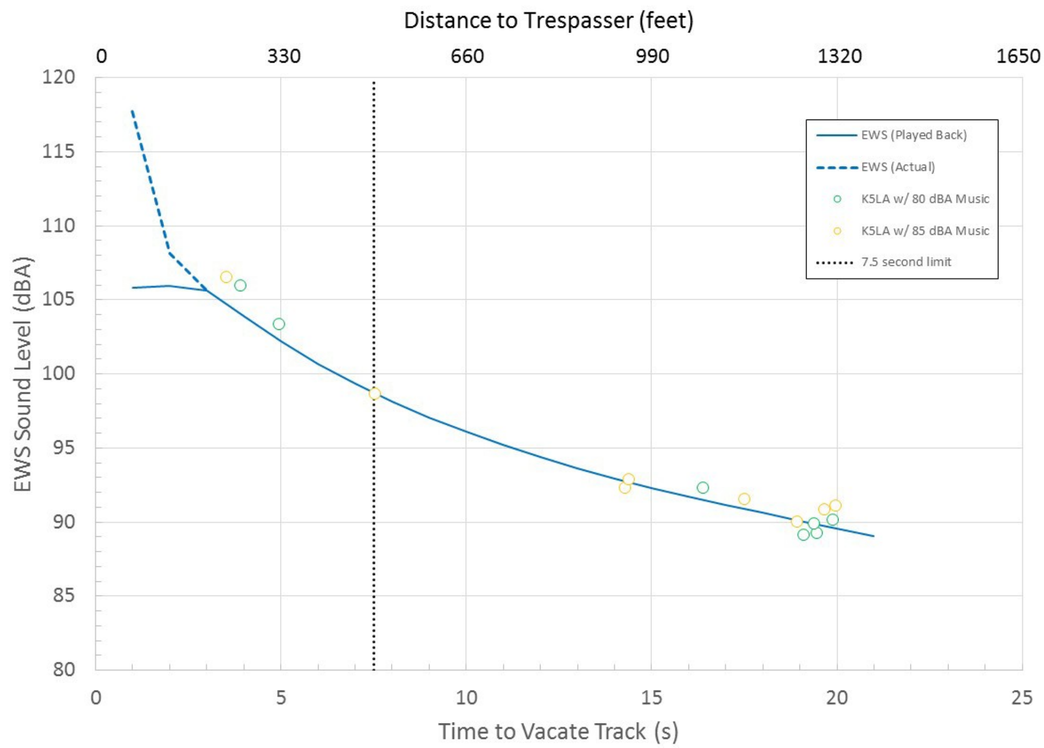

Figure 47. Simulated Approaching 45 mph <u>Standard Train Horn</u> Sound Level and Time Available to Vacate the Track with On-Ear, Noise-Cancelling Headphones

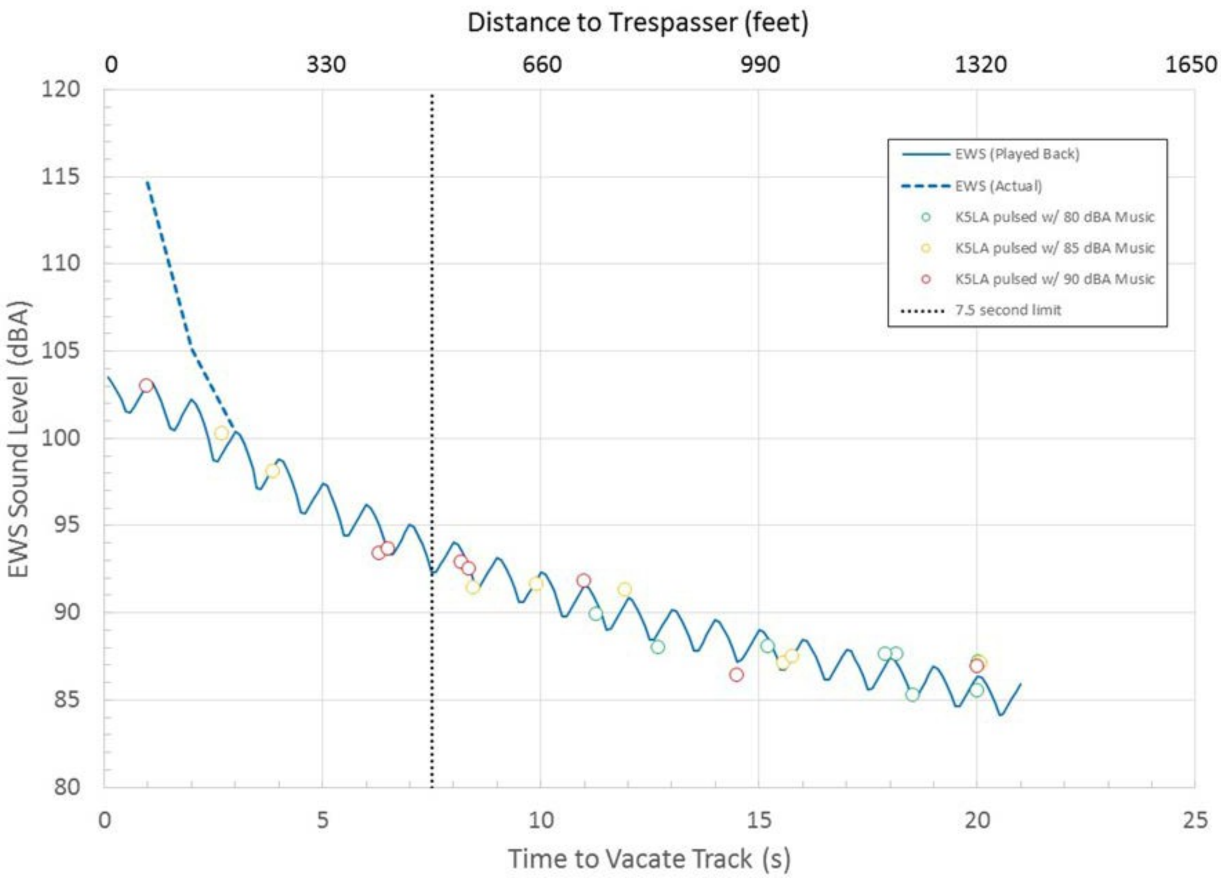

Figure 48. Simulated Approaching 45 mph Standard Train Horn <u>with Pulses</u> Sound Level and Time Available to Vacate the Track with On-Ear, Noise-Cancelling Headphones

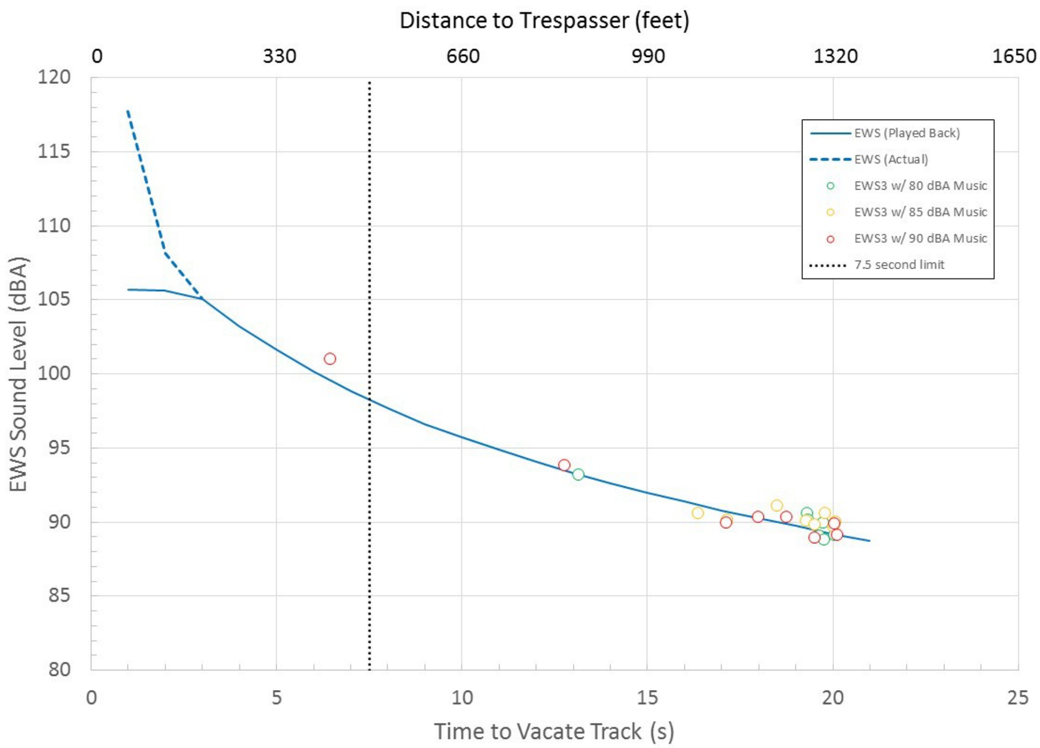

Figure 49. Simulated Approaching 45 mph EWS 3 Sound Level and Time Available to Vacate the Track with On-Ear, Noise-Cancelling Headphones

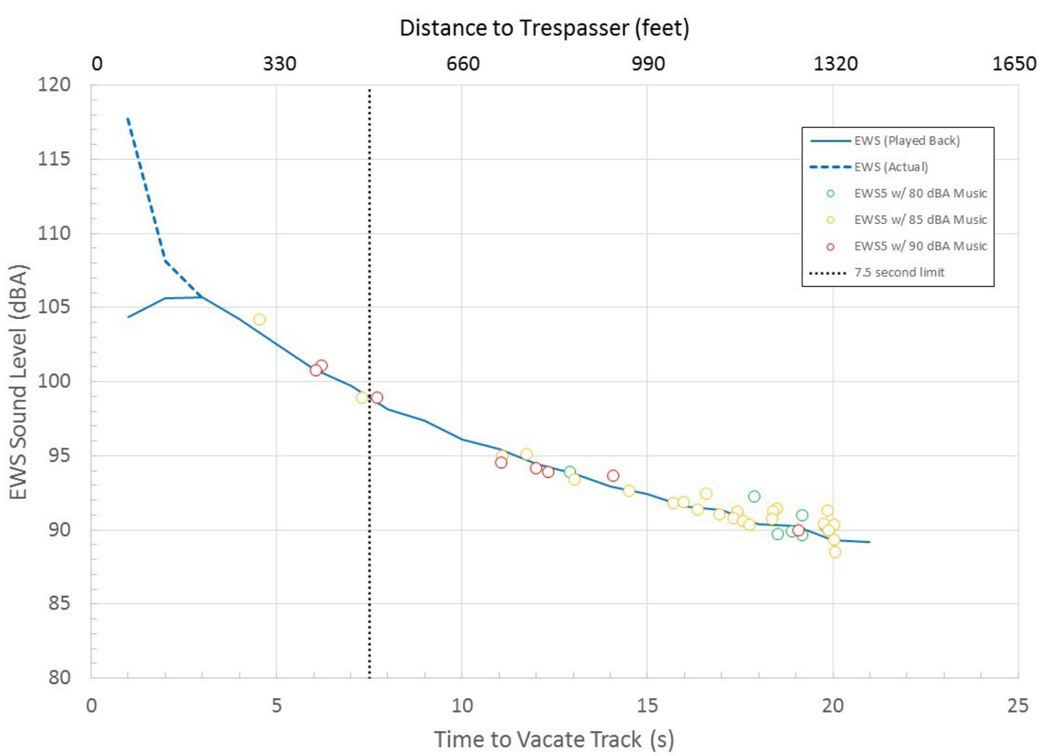

Figure 50. Simulated Approaching 45 mph EWS 5 Sound Level and Time Available to Vacate the Track with On-Ear, Noise-Cancelling Headphones

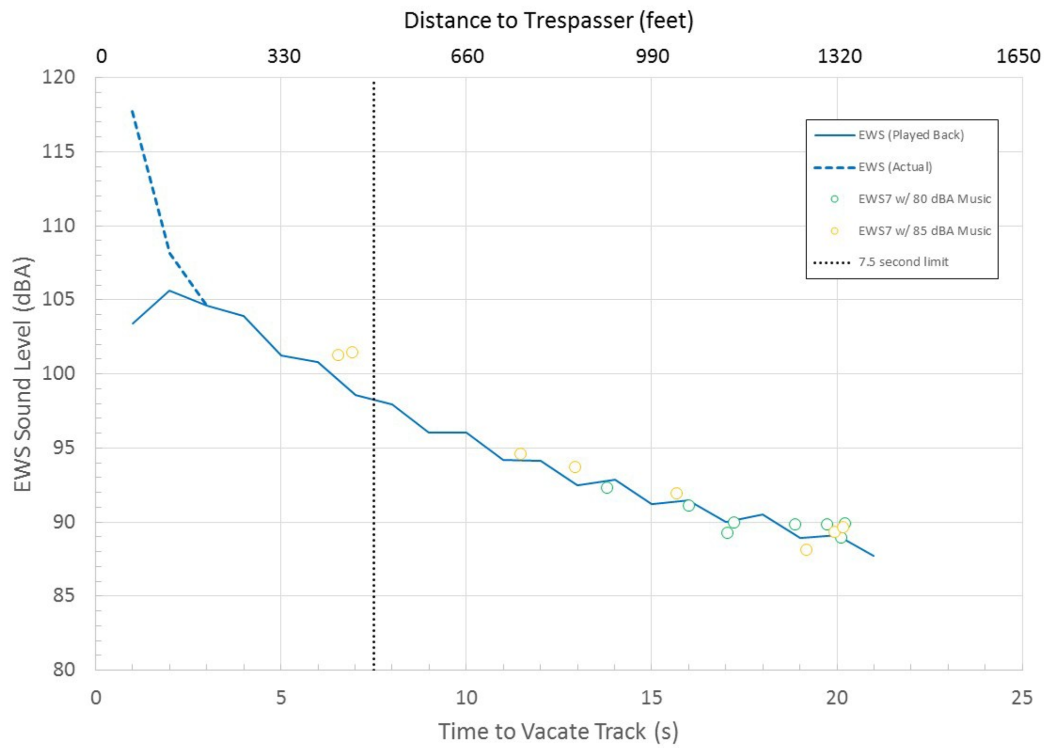

Figure 51. Simulated Approaching 45 mph EWS 7 Sound Level and Time Available to Vacate the Track with On-Ear, Noise-Cancelling Headphones

Figure 52 summarizes all of the phase 2 response times categorized by EWS and music listening level. This figure shows that EWS 3 and 5 provided longer times to vacate the tracks on average. The pulsed train horn sound and all three candidate new EWS provided a minimum of 11 seconds to vacate the track when music levels were 80 dBA; however, the standard horn had two responses less than 7.5 seconds. When music levels increased to 85 or 90 dBA, there were substantially more responses that provided less than 7.5 seconds of warning time. All of the candidate train EWS provided more time to vacate the tracks on average and with fewer specific responses with less than 7.5 seconds of warning time compared to the standard train horn sound.

Figure 53 shows the average EWS sound level above music listening level to produce an urgent response in the phase 2 booth testing. Note that higher music listening levels required a lower EWS sound level above the music to produce an urgent response. So those listening to music at 90 dBA, on average, required an EWS at 2 to 6 dB above listening, and those listening at 80 dBA required an EWS at 8 to14 dBA above. This produced a nearly constant absolute EWS sound level to create an urgent response. On average, EWS 3 needed 90.7 dBA for an urgent response, EWS 5 needed 91.5 dBA, K5LA with pulses needed 93 dBA, and the K5LA only required 94 dBA. So the two EWS required about 3 dBA less for an urgent response than a K5LA train horn.

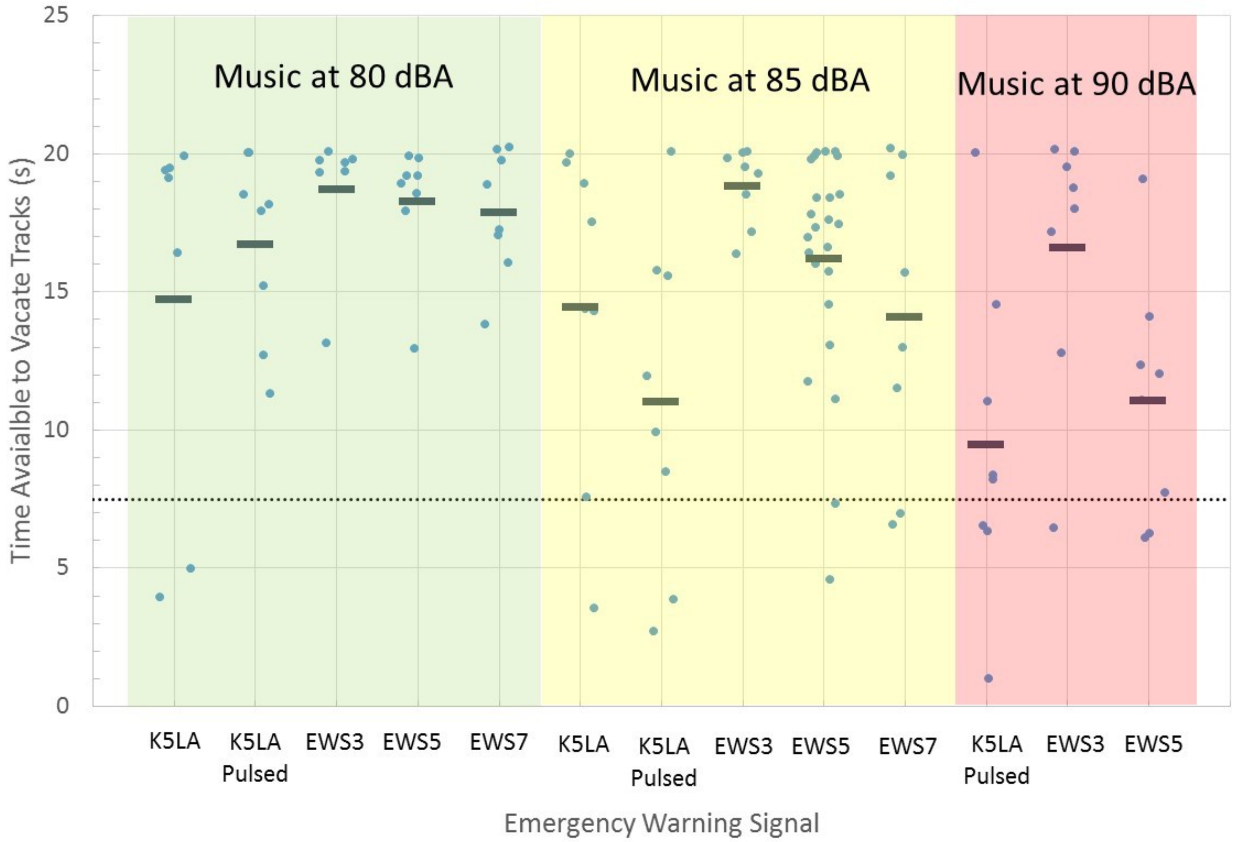

Figure 52. Phase 2 Audio Booth Test Results – Time Available to Vacate Tracks for Various Music Levels

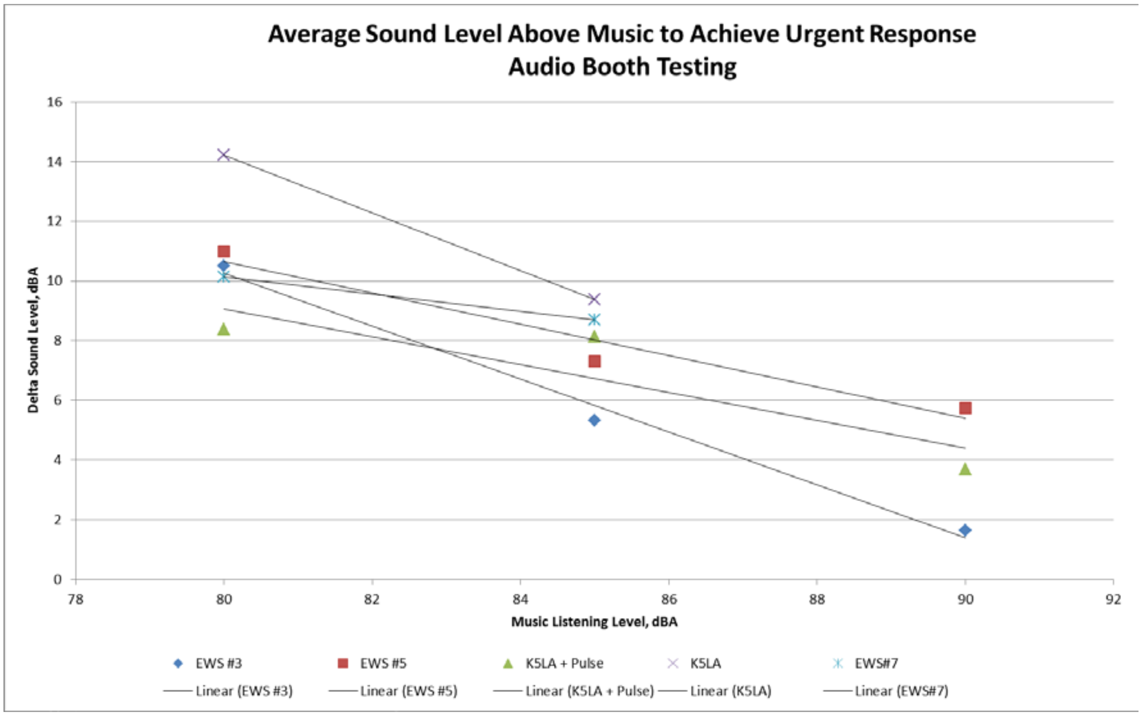

Figure 53. Average Sound Level Above Music Listening for Urgent Response in Phase 2 Audio Booth Tests

5. Onboard Locomotive EWS Field Tests

Through a listening survey and two phases of audio booth testing, candidate train EWS sounds potentially improved detectability and increased the amount of time available to vacate the tracks for trespassers listening to music with headphones. To further assess the effectiveness of candidate EWS, tests were conducted on board a moving locomotive using an AWD system. The goal of these tests was to further understand the potential benefits of a new train EWS compared to a standard train horn in a realistic environment. The tests were conducted at the Transportation Technology Center (TTC) Railroad Test Track (RTT) in Pueblo, Colorado, on June 7, 2016.

A section of the RTT was selected to be away from most of the ongoing activity at TTC to provide the quietest environment for EWS testing. A tangent section of track was selected that provided sufficient room for achieving constant train speeds passing through the test site.

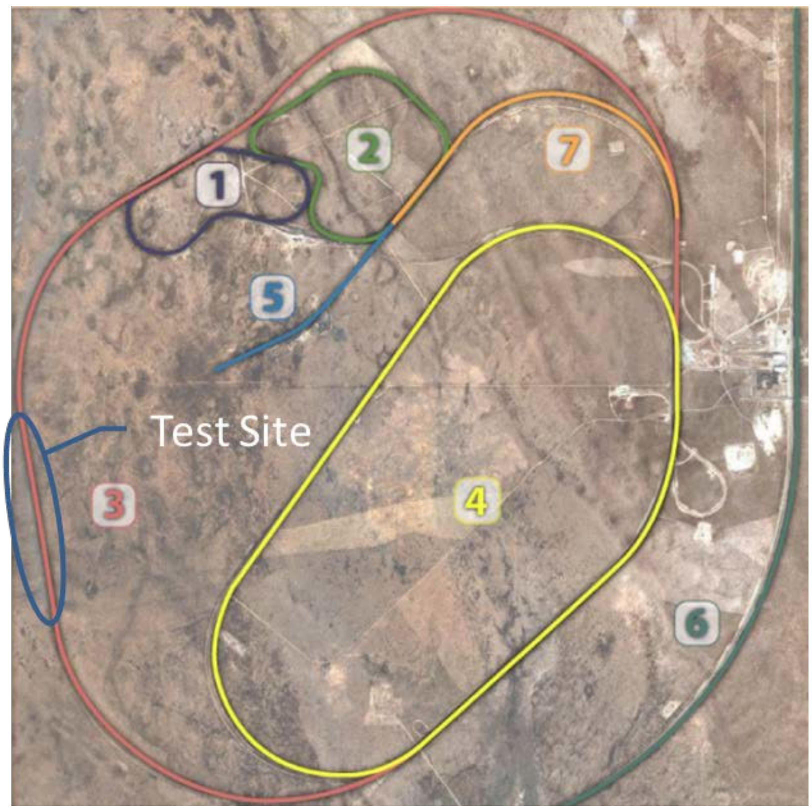

Figure 54. Test Location on the RTT at TTC

5.1 Onboard Test Setup

The test setup included a test zone marked along the track where four participants, as seen in Figure 55, stood facing away from the oncoming train as though they were trespassing – without visual clues of potential train activity. The participants were set back approximately 25 feet from the tracks for safety. Three participants were listening to music at in-ear levels of 80 to 85 dBA using ear-bud headphones, on-ear and over-ear headphones. The music levels were calibrated using an in-ear microphone. The fourth participant wore over-ear hearing protection.

Figure 55. Test Participants Recording Reactions to EWS Sounds

Two EWS sounds and the standard Nathan K5LA train horn sound were tested through a six-speaker AWD system mounted atop an EMD F40 locomotive as shown in Figure 56. The AWD system generated a maximum amplitude of 96 to 98 dBA at 100 feet forward of the locomotive. Note that this sound level output is within FRA-regulated limits (96 to 110 dBA), but is substantially lower than the output used during audio booth tests which were calibrated to output levels relative to 110 dBA at 100 feet. Sizes RMG-200A speakers from Community Loudspeakers were used in the testing. Directional speakers with greater sound output are available commercially, but are more expensive.

The AWD system consisted of six loudspeakers arranged at 15/35/70 degrees from the locomotive axis. The arrangement was designed for research on variable train horn sound directivity under a separate program. In this program, the six speakers were all active and sounding at the same output levels.

Figure 56. AWD Speakers Mounted on an F40 Locomotive (DOTX 4113)

A total of 18 different tests were conducted at TTC where the train traveled at speeds of 40, 50, 60, or 70 mph, and the warning signal began sounding at distances of 660, 800, 1,000, or 1,320 feet away from the test zone. The starting distance was controlled by GPS position relative to the test zone. The train speeds and the start of EWS sounding were randomized such that the participants could not predict the EWS sounding. The participants used a stopwatch to measure the time between when the train was at a particular location away from the test zone (as defined by communication from the locomotive to the test director) and when they detected the EWS and had a sense of urgency to vacate the tracks.

5.2 Field Test EWS Sounds

The EWS sounds were similar to EWS 3 and EWS 5 developed and tested in the audio booth, except a recording of the actual Nathan 5-chime air pressure horn (see Figure 58) on the DOTX 4113 locomotive was used as the baseline with similar wail and yelp signatures applied. These EWS sounds included a 250-ms cycle period (yelp) or a 2,000-ms cycle period (wail) sinusoidal variation to the 800- to 1,200-Hz tones with 6 dB increased amplitude, as shown in Figure 57.

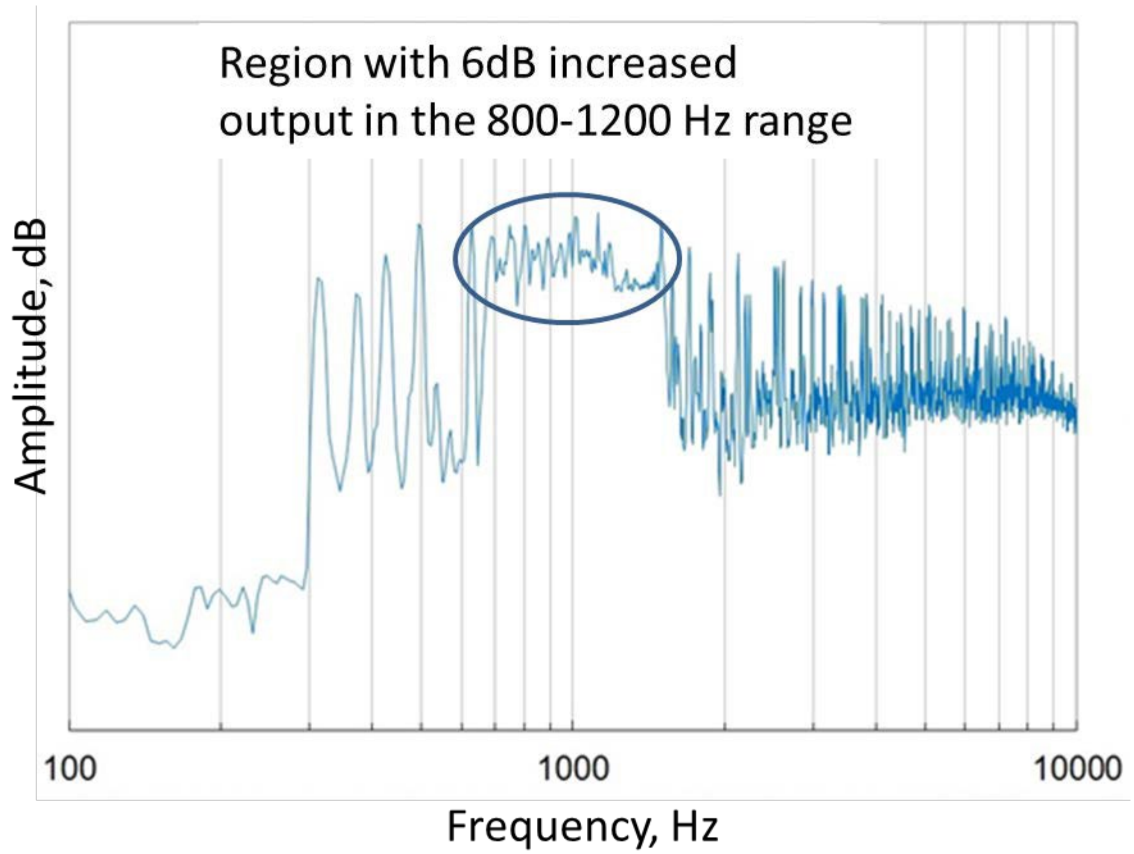

Figure 57. Increased sound level in the 800-1200 Hz range for enhanced detectability

Figure 58. Measuring the DOTX 4113 5-Chime Air Horn Sound

5.2.1 Spectrograms

Spectrograms of the EWS and standard train horn sounds used in the testing are shown in the figures below.

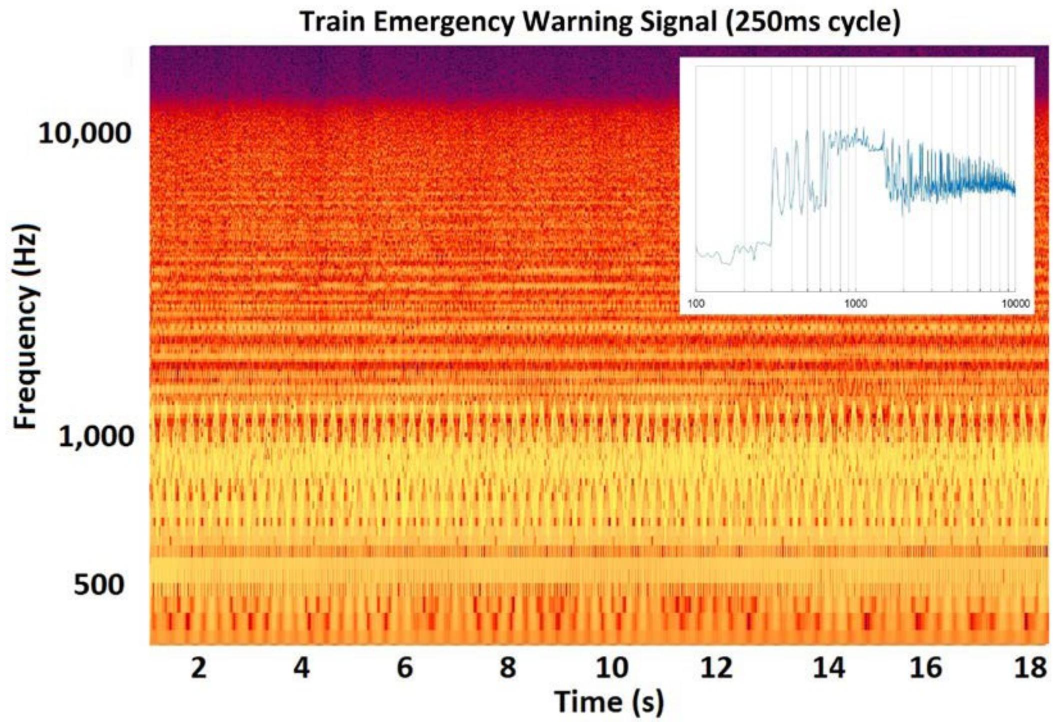

Figure 59. Spectrogram of Train EWS with Yelp (250 ms) Signature

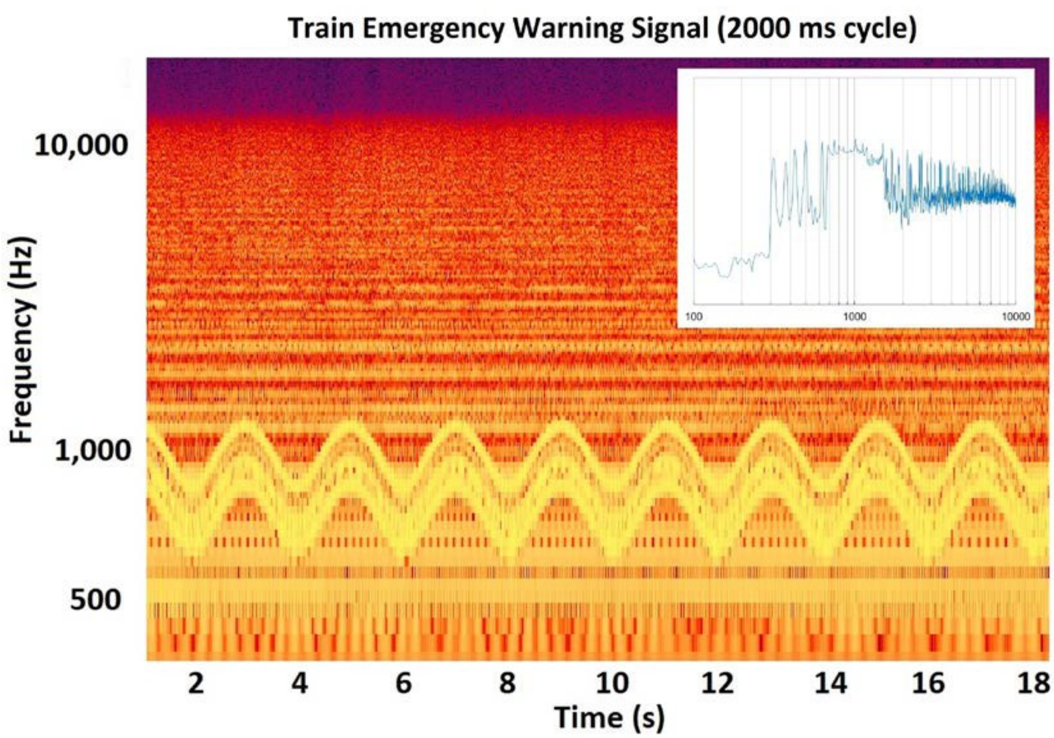

Figure 60. Spectrogram of Train EWS with Wail (2,000 ms) Signature

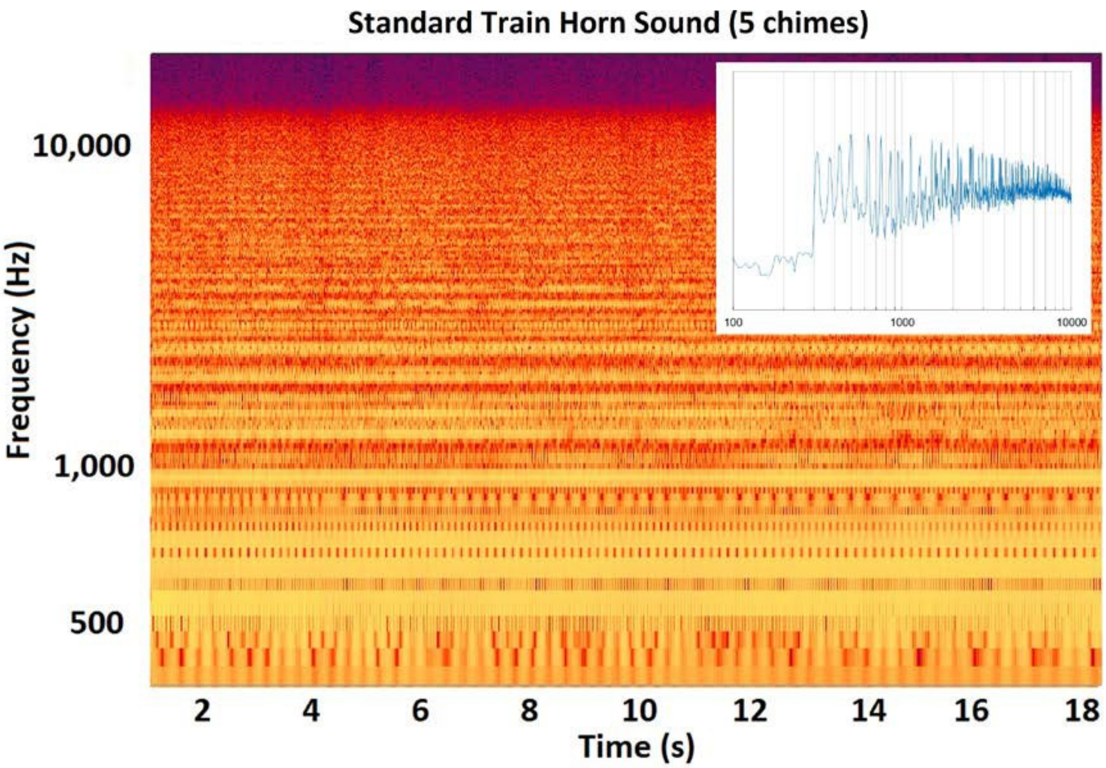

Figure 61. Spectrogram of Standard Train Horn Sound

5.2.2 Measured Sound Levels of Approaching Train

Sound level measurements at the participant location were conducted for each EWS sounding during the train approach. Figure 62 presents time histories of three train passes at 40 mph and sounding its horn beginning 660 feet from the test zone. This figure shows relatively similar amplitudes among all signals.

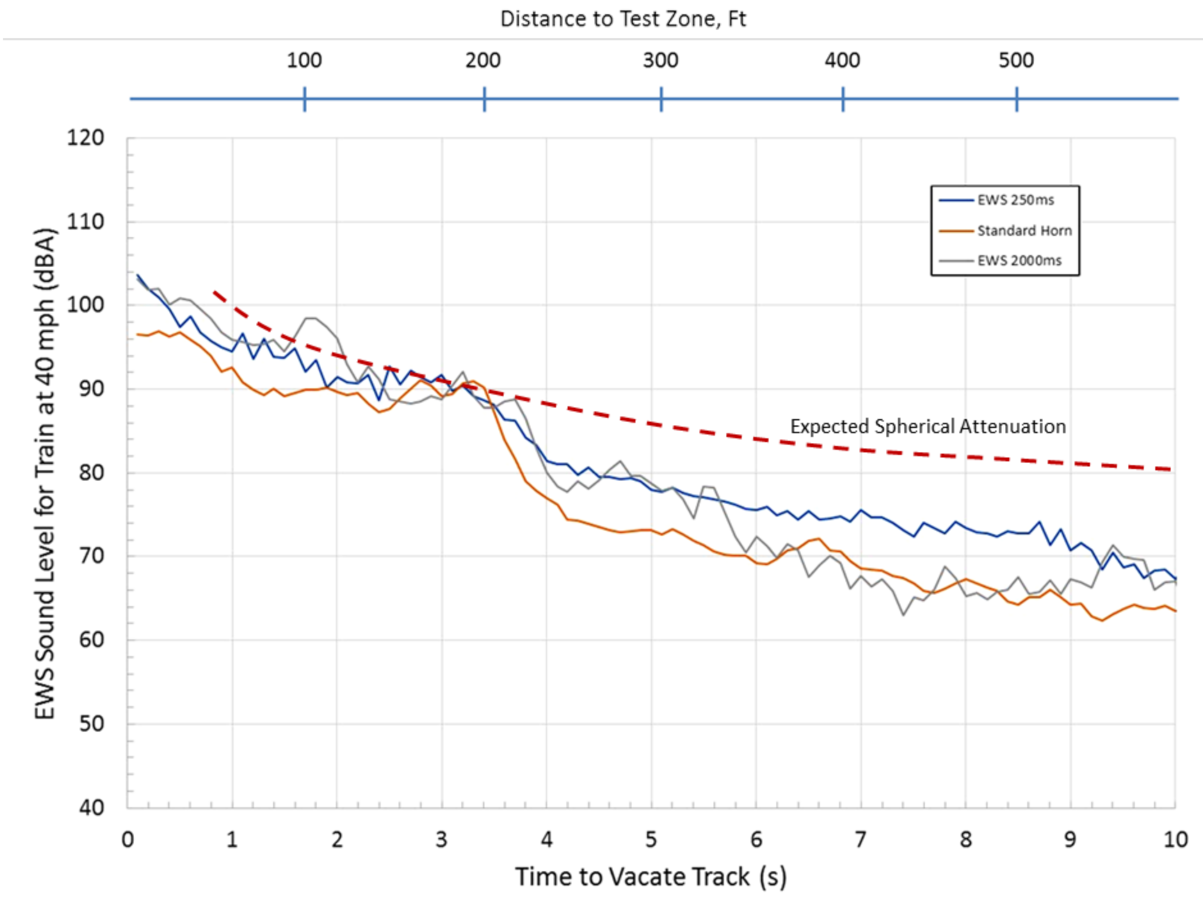

Figure 62. Time History of Sound Levels for Onboard Locomotive Tests at 40 mph

5.3 Selection of Listening Music

The participants selected their own music to increase their attention and to more closely simulate the actions of a trespasser. The songs were calibrated to 85 dBA average listening levels. The particular songs selected are found in Table 4.

Table 4. Field Test Listening Music

Listening Device	Songs	Volume Level on iPhone
Over-the-Ear Headphone (Beats Studio)	Afterlife by Ingrid Michelson	10 bars
Ear Buds (J-Lab J2)	Water Under the Bridge by Adele	10 bars
On-Ear Headphone (Sennheiser PXC-250-II)	Volcano & Every Breaking Wave by U2	13 bars
Hearing Protection(3M Ear Muff Peltor X2A)	NA	NA

The Sennheiser PXC-250-II headphones were measured for noise attenuation, as shown in Figure 15. Research team measurements showed 15-dB attenuation at greater than 1,600 Hz and from 10-dB to 0-dB attenuation from 1,600 Hz to 100 Hz with active noise cancellation on (ANC). When tested at TTC, the on-ear Sennheiser headphones inadvertently had the ANC turned off. This changed the noise cancellation from 20 dB at 1,600 Hz to 0 dB at 600 Hz.

The 3M X2A hearing protection is advertised with a 24 dB noise-reduction rating. 3M data shows 40 dB attenuation from 1,000 Hz through 8,000 Hz and down to 15 dB at 125 Hz.

The Beats Studio headphones do not have specific information on attenuation. A www.innerfidelity.com headphone measurement of Beats Studio 2 headphones showed similar values to the hearing protection shown for the 3M X2A. They measured 40 dB attenuation from 2,000 Hz to 45 dB at 8,000 Hz, and attenuation of 12 dB at 1,000 Hz and 20 dB at 500 Hz. So the Beats Studio 2 had only 12 dB attenuation in the EWS target frequencies from 800 Hz to 1,200 Hz.

There were no available attenuation data for the Jlab J2 earbuds.

5.4 Field Test Results

Table 5 summarizes the time available to vacate the tracks for all 18 tests and all 4 types of headphones/hearing protection. This table shows the train speed, distance away from the trespassers where the soundings began, duration of the sounding, which warning signal was used, and the timed responses of the trespassers. The hearing protection (HP) results coincided very closely with the beginning of the warning signal sounding. This shows that hearing protection alone (without music masking) may not have significantly compromised the ability to detect warning signals.

Figure 63 through Figure 65 present the sound level time histories at the test zone, not including any passive or active noise reduction provided by headphones or hearing protection. These figures present the standard train horn, EWS with yelp signature (250 ms), and EWS with wail signature (2,000 ms), respectively. The figures also show the moment in time when each of the trespassers listening to music detected the warning signal. Most responses occurred with warning signal amplitude of 70 dBA – 10 dB or more below the music listening level.

This was an interesting finding since audio booth results showed that significantly higher sound levels relative to music listening were needed for detection. This may have been due to a heightened sense of a train approaching in the realistic setting, due to non-acoustical cues, or corresponds to lulls in the songs being played, as the EWS warning was a continuous sound.

Table 5. Summary of Times Available to Vacate the Tracks

Test No.	Train Speed (mph)	Distance Sounding Began (feet)	Total Time of Sound (sec)	Warning Signal	Time Available to Vacate Tracks (s)			
					Ear Buds	On-Ear	Over-Ear	HP
1	50	1,320	18	Standard Horn Signal	1.82	12.96	1.25	14.38
2	40	800	13.6	EWS (250 ms yelp)	10.44	18.38	4.84	12.44
3	40	660	11.2	EWS (2000 ms Wail)	10.00	8.45	7.74	11.29
4	50	1,000	13.6	Standard Horn Signal	9.85	10.1	2.1	12.38
5	70	1,320	12.9	EWS (250 ms yelp)	4.72	8.69	5.19	11.28
6	50	1,320	18	EWS (2000 ms wail)	6.22	11.98	4.5	16
7	40	800	13.6	Standard Horn Signal	13.76	10.41	3.19	14.19
8	40	660	11.2	EWS (250 ms yelp)	8.66	12.76	7.44	12.44
9	50	1,000	13.6	EWS (2000 ms wail)	5.57	10.18	6.82	14.1
10	70	1,320	12.9	Standard Horn Signal	2.8	8.53	0.78	11.37
11	50	1,320	18	EWS (250 ms yelp)	6.72	8.03	6.51	16.78
12	50	1,000	13.6	EWS (250 ms yelp)	4.74	4.88	4.63	13.06
13	60	1,000	11.4	EWS (2000 ms Wail)	5.07	5.44	3.13	10.6
14	60	1,000	11.4	Standard Horn Signal	2.19	5.95	1.93	10.38
15	60	1,000	11.4	EWS (250 ms yelp)	5.75	9.29	5.6	10.35
16	70	1,320	12.9	EWS (2000 ms wail)	3.31	6.68	5.35	11.16
17	40	660	11.2	Standard Horn Signal	5.08	7.16	1.25	12.56
18	40	800	13.6	EWS (2000 ms wail)	11.54	10	4.59	13.16

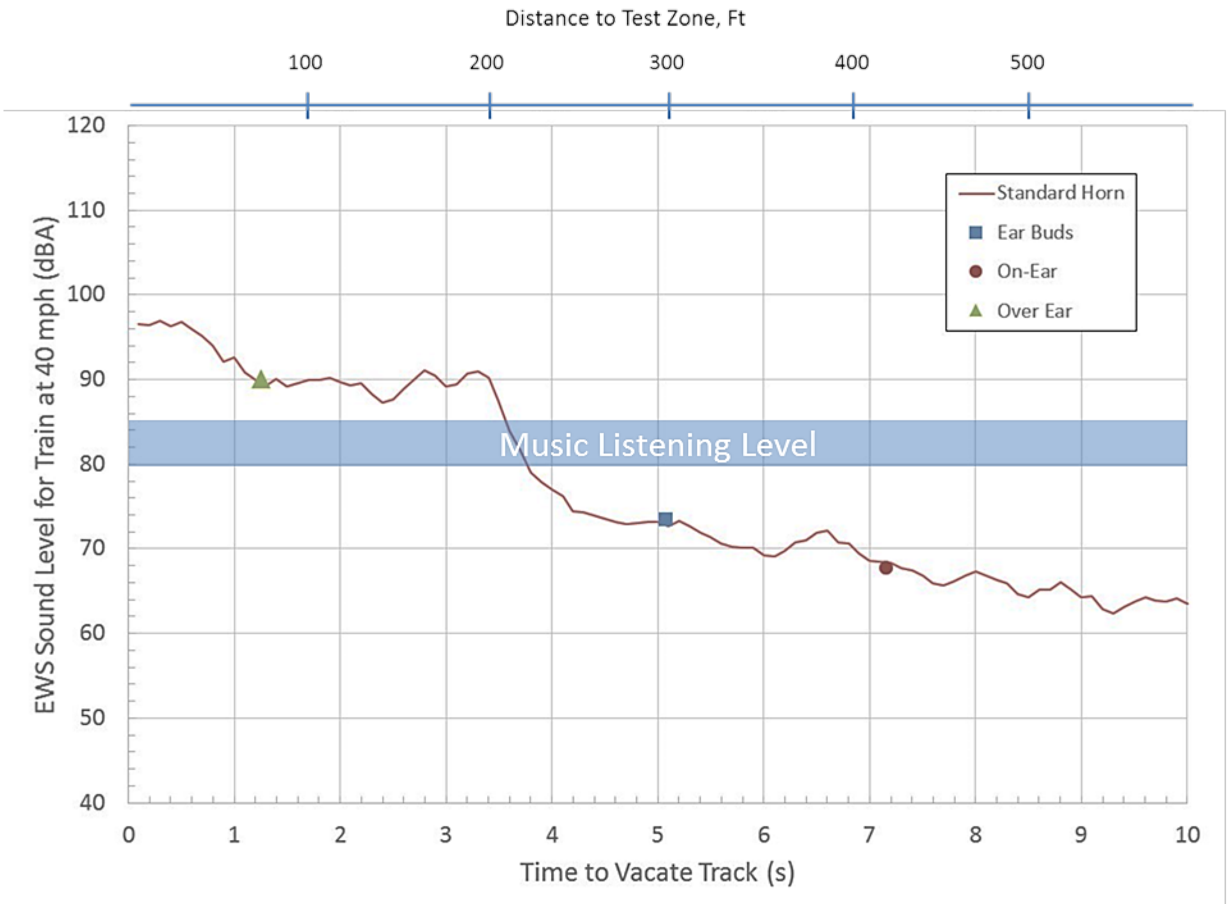

Figure 63. Standard Train Horn Sound Level and Time Available to Vacate

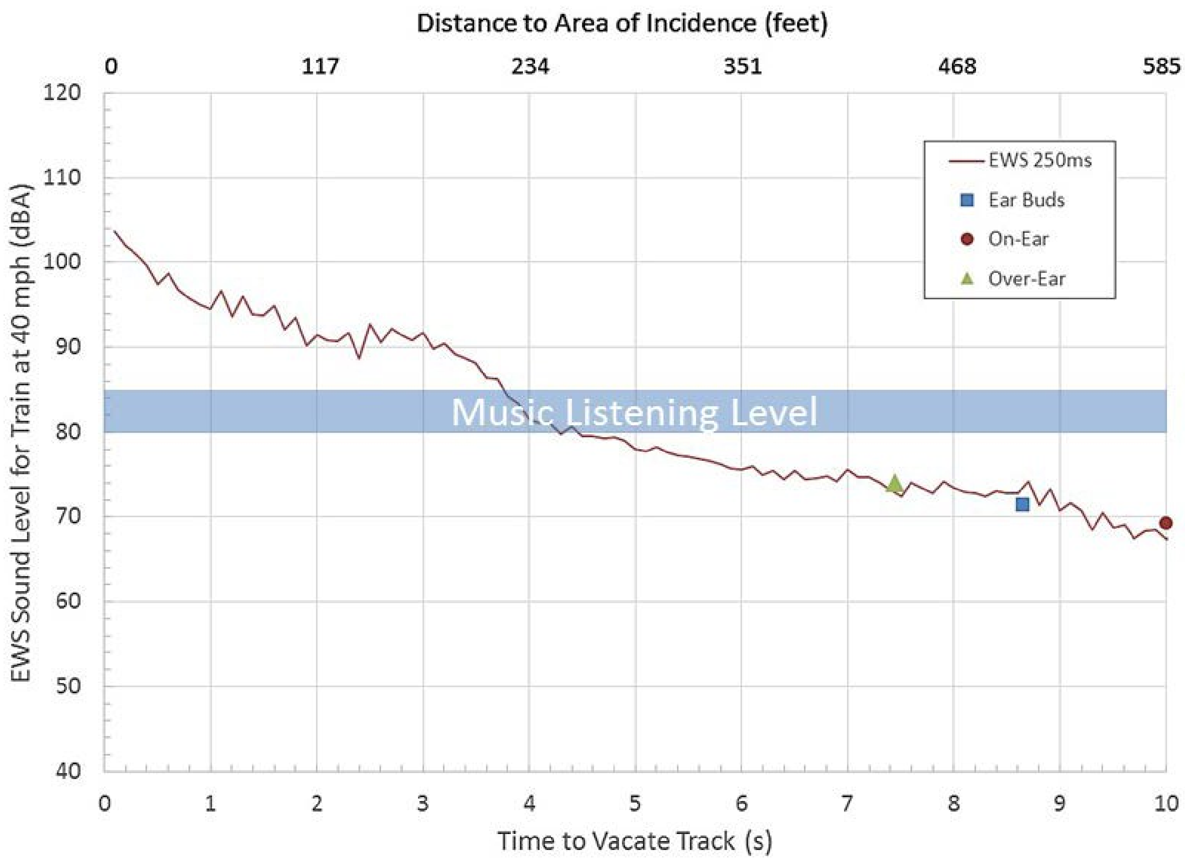

Figure 64. EWS (with Yelp) Sound Level and Time Available to Vacate

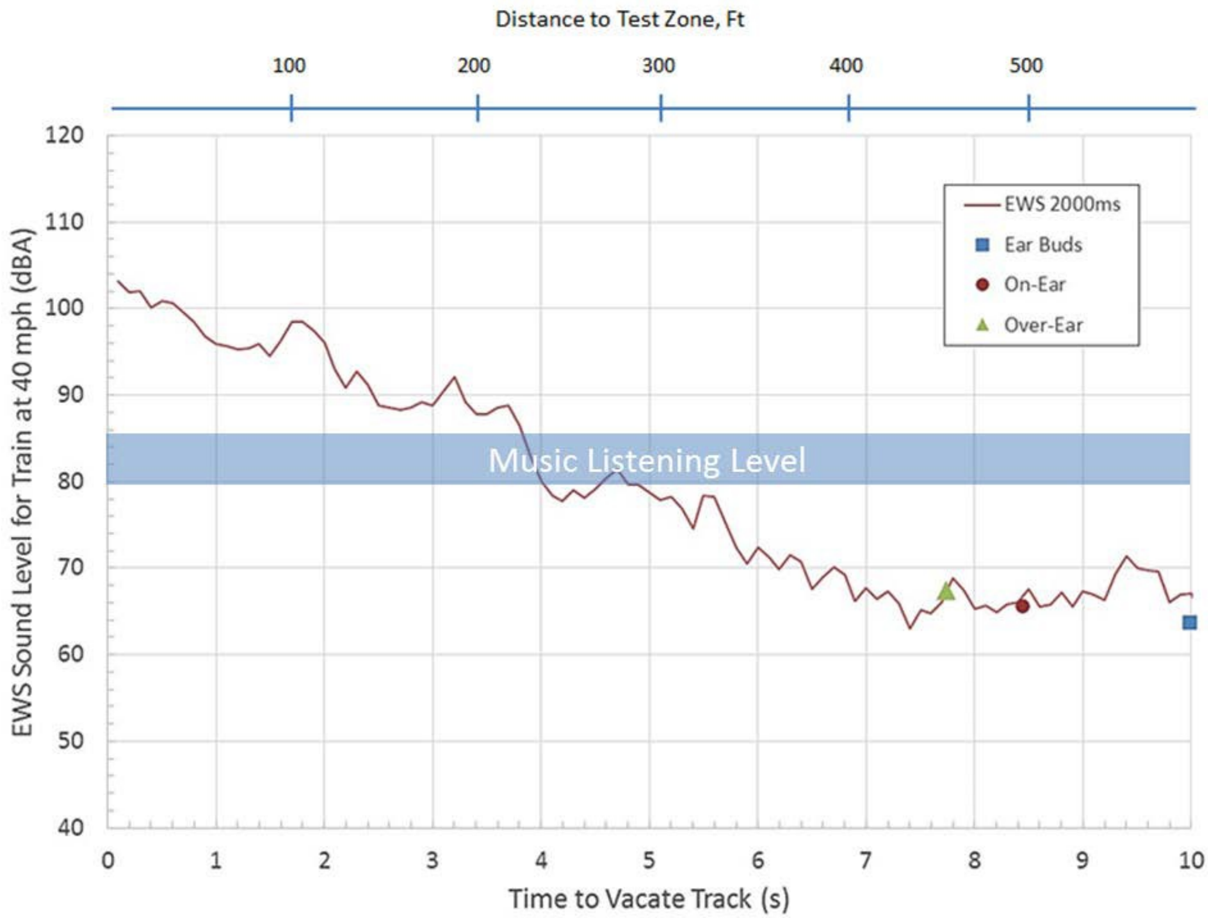

Figure 65. EWS (with Wail) Sound Level and Time Available to Vacate

Figure 66 presents the time available to vacate tracks for all train passes and all headphones/hearing protection separated by the type of warning signal. This figure shows that several responses provided less than 7.5 seconds of warning, particularly for the standard train horn signal and over-ear headphones and ear buds. Figure 67 shows a comparison between the two candidate warning signals and the standard train horn. This figure shows that EWS with a yelp signature provided 1.7 seconds more time than the standard train horn, on average, and the EWS with wail signature provided 1.2 seconds more time.

Figure 68 through Figure 71 show the time available to vacate the tracks versus the amount of time of the warning sound for each type of hearing protection. This isolates the effectiveness of the EWS for a given listener with the listening music and headphone device being consistent in the figure. The dashed line in the figures indicates the boundary of an immediate response after the warning sound.

The response time with standard worker hearing protection was almost immediate, and all warning sounds had equivalent response. Both over-the-ear and earbuds had similar results, with the standard train horn providing the least warning and the EWS sounds providing a greater amount of time to vacate the tracks. EWS sounds provided from 2 to 4 more seconds to vacate the track than the standard train horn. However, wearing earbuds and over-the-ear headphones still did not provide sufficient time to vacate the tracks for almost all horn sounds and all train operating conditions. Also, they showed a flat trend over sound duration, indicating that absolute warning sound volume was critical to penetrating the listening devices. Over-the-ear headphones had less of a trend. However, they generally provided just enough time to vacate the tracks, as did the hearing protection.

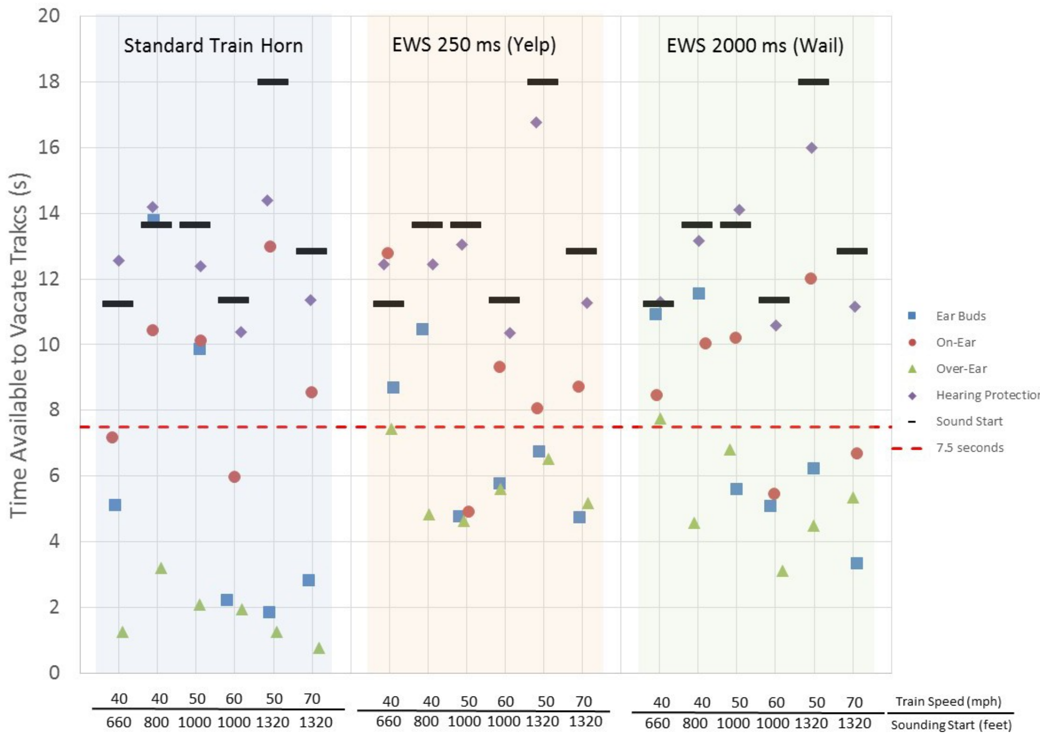

Figure 66. Time Available to Vacate Tracks for Standard Horn and EWS

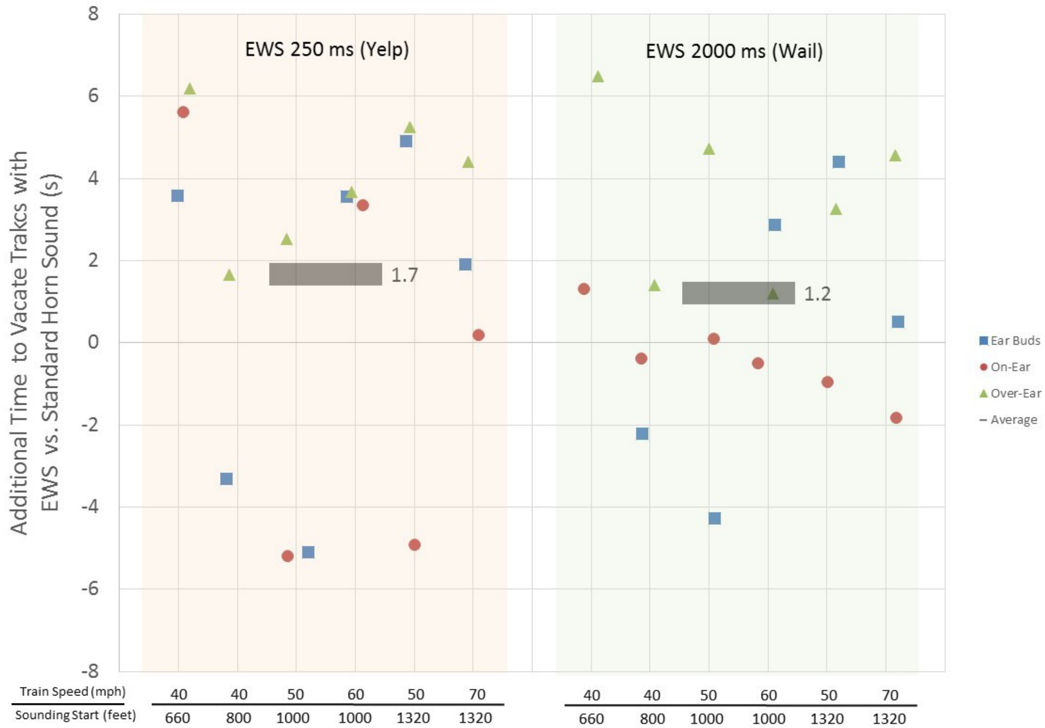

Figure 67. Increase in Time Available to Vacate Tracks for Train EWS

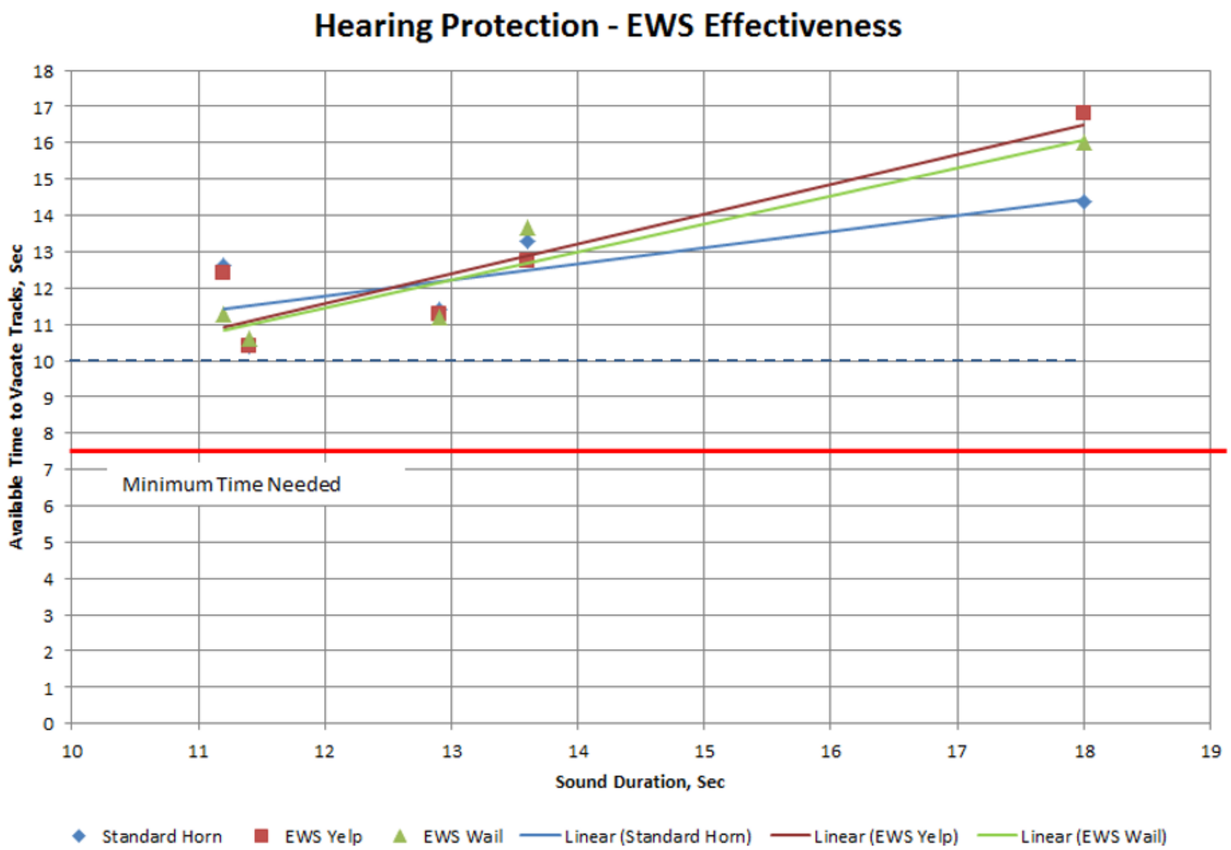

Figure 68. Summary of EWS Effectiveness with Hearing Protection

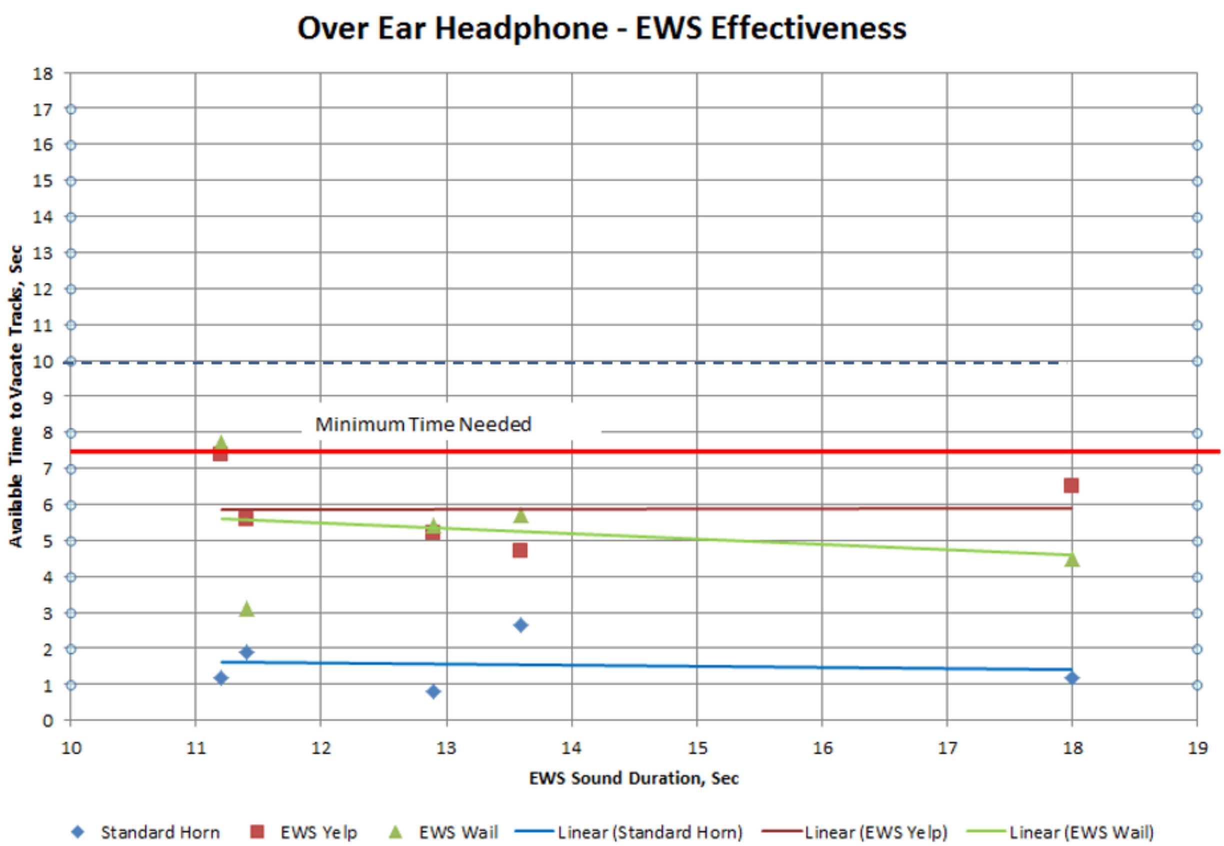

Figure 69. EWS Effectiveness with Over-the-Ear Headphones

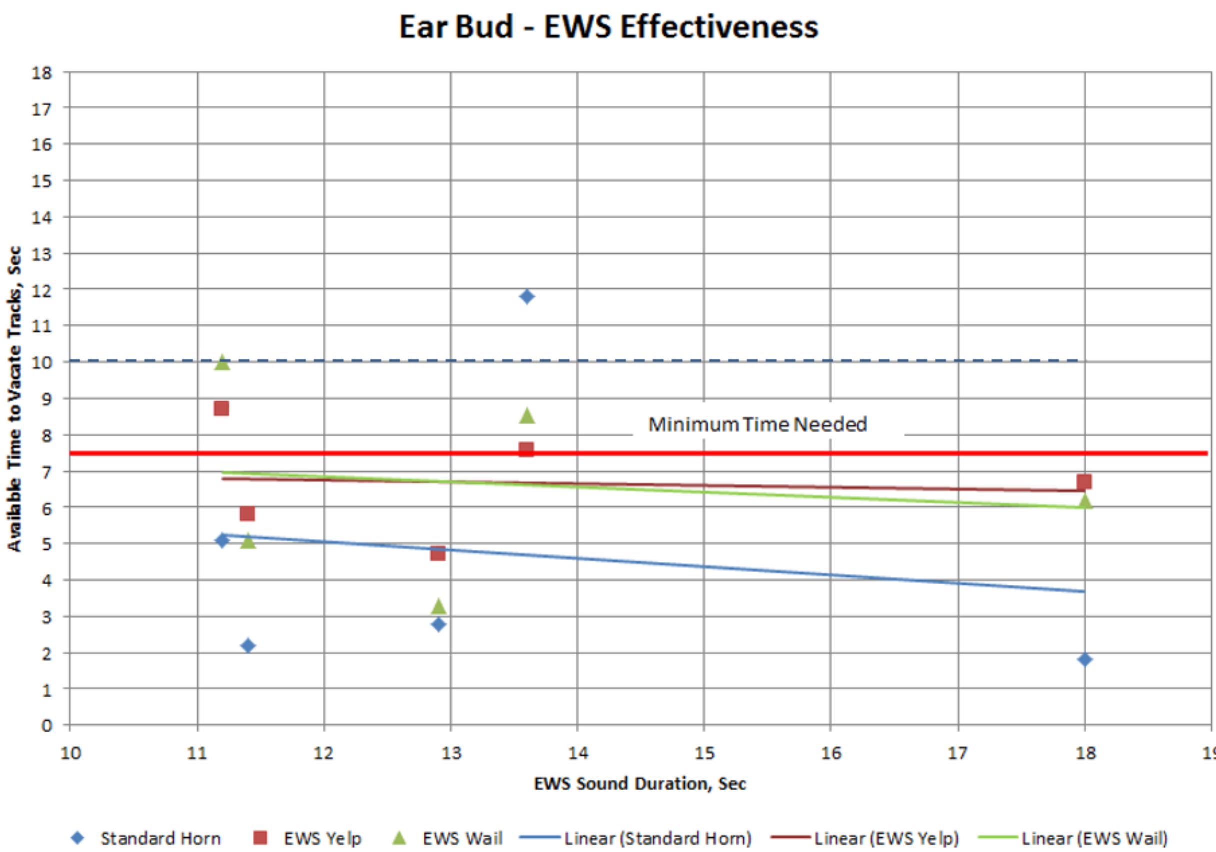

Figure 70. EWS Effectiveness with Ear Buds

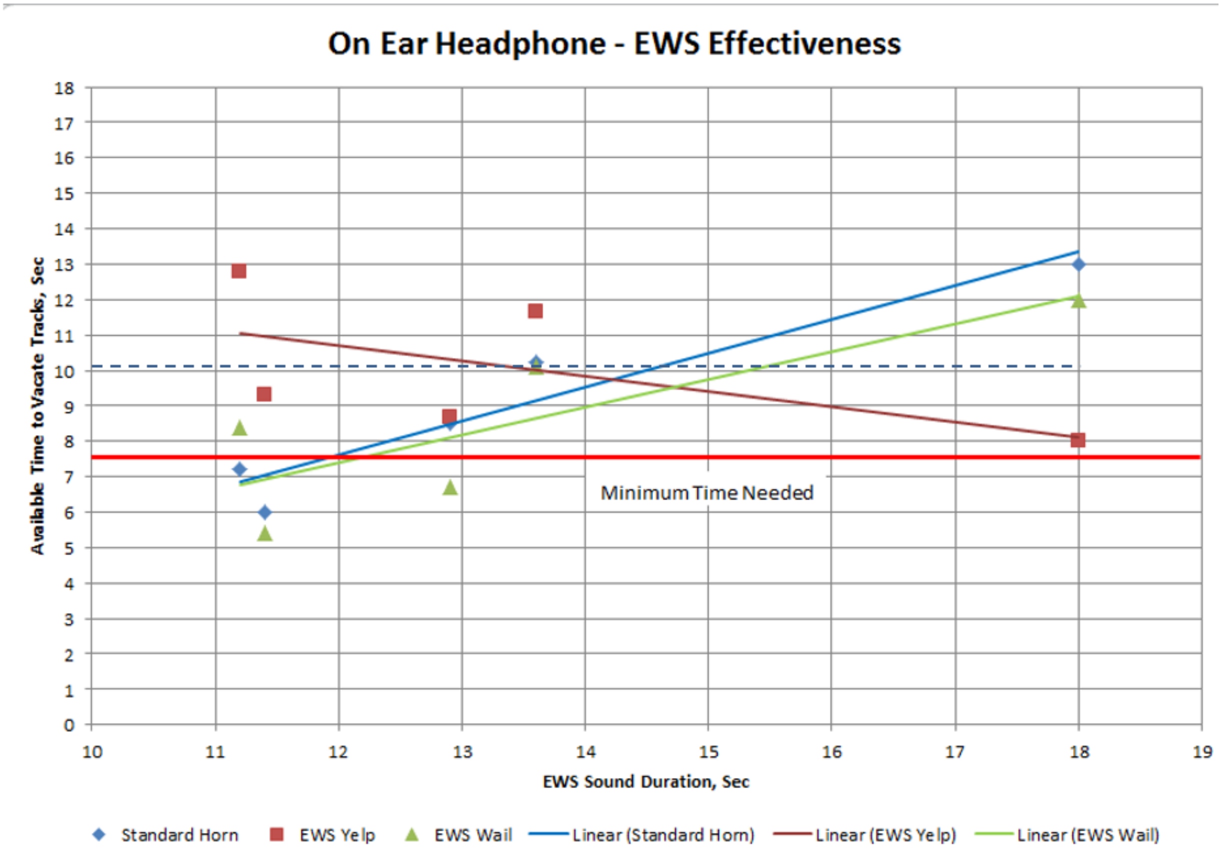

Figure 71. EWS Effectiveness with On-Ear Headphones – Noise Cancellation Off

6. Conclusion

The primary results of this study show that listening to music while trespassing on the railroad tracks dramatically increased the probability of being struck by a train even when warning sounds are given with sufficient time to respond. The music and listening device combination provided much less response time relative to standard worker hearing protection.

An EWS which includes acoustic characteristics of police/fire wail and yelp signatures can maintain its association/identification of a train approaching, improve detectability, and reduce recognition and response time for persons wearing headphones.

The standard worker hearing protection provided the least attenuation in EWS sound and the fastest response to vacate the tracks when EWS sounded. There was no discernable difference between types of EWS in the response time.

Both over-the-ear (circum-aural) ANC headphones and tight-fitting earbuds provided the most masking effect to reacting towards EWS. Circum-aural headphones provided a 3.5-second reaction benefit with EWS over standard train horns. The wail component was somewhat more effective than the yelp. However, none of the reactions provided sufficient time to vacate a track safely.

The earbuds provided a 2-second reaction benefit with EWS over a train horn. The wail and yelp had equivalent reactions. Only one-third of the tests provided sufficient time to vacate the tracks.

The on-ear (supra-aural) headphones without ANC had no discernible trend regarding EWS versus a train horn. However, nearly 75 percent of the tests did provide sufficient time to vacate the tracks. The difference between the supra-aural and the circum-aural or earbuds may be the relatively loose fit to the ear.

A surprising result of the testing was that many selections of an urgent response occurred at EWS sound levels lower than the music listening level. This amount varied from 5 dB to 15dB below listening levels in some cases. The EWS sounds were recorded at the same time as the test runs, and the microphone was placed adjacent to the test participants. This was likely because the EWS did not work by overwhelming the listening music, but by creating a sound that got the listeners' attention in frequencies and beats different than the music.

The general times for vacating the track at TTCI were significantly less than the 7.5 seconds thought to be the minimum needed. It is likely that higher sound levels for EWS are needed to increase the response time. Estimates earlier in the program indicated that an EWS that generates 120 dB at 100 feet forward of the locomotive may be required to ensure urgent attention, assuming a +15 dB over ambient is needed.

6.1 Recommendations

The EWS developed in this program have the potential to save lives and dramatically decrease the number of railroad trespasser casualties, especially for those wearing headphones and earbuds. The FRA Office of Safety Analysis has summarized statistics of trespasser deaths for all causes excluding those from highway-rail incidents. These trespasser deaths have remained fairly constant over the past decade and average 445 deaths per year, as seen in Figure 72.

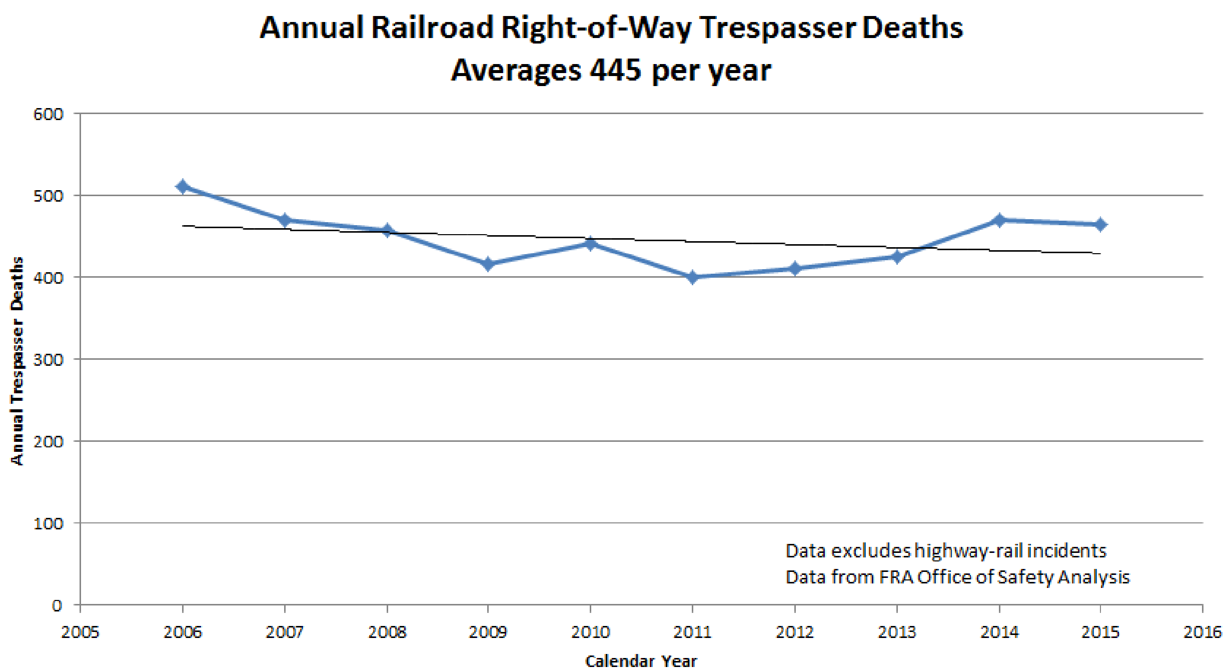

Figure 72. FRA Office of Railroad Safety Analysis Trespasser Casualties over the Last 10 Years

The U.S. Department of Transportation Under Secretary for Policy has published Guidance on Treatment of the Economic Value of a Statistical Life (VSL). This is intended as guidance in valuing investments and regulations aimed at reducing fatalities and injuries. The data available at the time of writing this final report shows that the VSL (https://www.transportation.gov/office-policy/transportation-policy/guidance-treatment- economic-value-statistical-life) has increased from $9.1M in 2013 to $9.2M in 2014 to $9.4M in 2015.

The value of EWS is in enabling a loudspeaker system on each locomotive capable of producing these sounds at appropriate dB levels. Systems producing 110 dB at 100 feet forward of a locomotive currently cost in the range of $15,000. Although this may seem high, one must consider the statistical value of lives saved. If one assumes that only 15 percent of the non-highway-rail incident deaths caused annually could be saved with an effective EWS (60 lives), the statistical value of those lives is $634M.

Considering a simple cost-benefit analysis, it is estimated that there are currently an estimated 17,500 interstate line haul locomotives used by the Class I Railroads and 1,000 locomotives used in passenger railroads. If the new locomotives inducted into railroad service, while phasing out the old ones, and also the remaining in-service locomotives are fitted with EWS systems at $15,000 each over certain period, the overall investment required would be around $278M. Against such an investment of $278M, it is expected to accrue a benefit of $634M annually in terms of saved lives (VSL).

The technical results of the program showed that certain key characteristics of an EWS that keep the train horn characteristics, and which were modified by higher amplitude wails and yelps between 800 and 1,200 Hz, were effective in increasing the time available to vacate tracks by 2 to 4 seconds.

Although this is a valuable finding, the benefit was not found for all types of headphones or earbuds consistently. The program goal is to increase the probability of providing sufficient reaction time to vacate the tracks for trespassers listening to music and wearing listening devices. More research is recommended in the following areas.

Higher sound level EWS systems are likely needed to ensure the 7.5-second response time to safely vacate the track ROW for all types of listening devices and likely music levels. These electronic loudspeaker-based systems are available commercially. Selection of the best types of loudspeaker designs and drivers are needed to find cost effective EWS. The six-loudspeaker EWS system used in this program would not be practical for widespread use as an EWS. It was not specifically designed for this application but was a reasonable demonstration system. Project researchers assumed that a single loudspeaker system may be most accepted by the industry.

Testing the effectiveness of EWS sound levels meeting the limit and even exceeding FRA regulations is worth pursuing. Indications from the program results are that sound levels up to 120 dB at 100 feet forward of the locomotive may be needed for the highest probability of saving lives. This level of sound would not be needed in normal operation, but only in the case of attempting to save a life. Testing at these sound levels would be valuable in determining if this level of sound is truly required with the EWS sound designs. Tests at TTC indicated that lower dB levels could be effective with the proper frequency content in the EWS at the appropriate amplitudes.

Test results were produced with a relatively small sample size. The variability in the results may be a function of this sample size. Repeats of the tests with the same EWS would be valuable with a larger participant sample size. An increased sample size would also increase the availability of listening devices and music types to assess their effect on response times.

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