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13. ABSTRACT (Maximum 200 words)
The Federal Railroad Administration (FRA) sponsored a project to demonstrate the effectiveness of an Acoustical Warning Device (AWD) to be used for generating a secondary Emergency Warning Signal (EWS). The focus of this Phase 2 work is to warn trespassers of an approaching train through the development of an EWS that produces a sense of urgency, is noticeable to wearers of headphones, and identifiable as a train. Several EWS sounds were developed and evaluated in surveys to assess the participant's response of the sense of urgency and detectability. Researchers identified sound characteristics that enhance detectability.

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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)
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1 cubic yard (cu yd, yd^3)	=	0.76 cubic meter (m^3)

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METRIC TO ENGLISH

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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)

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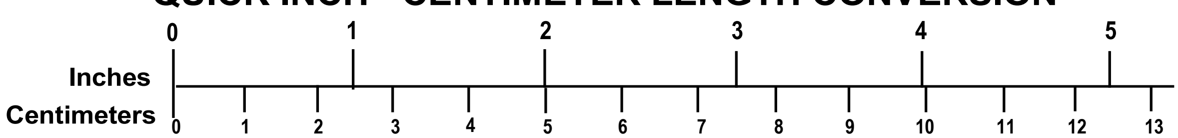
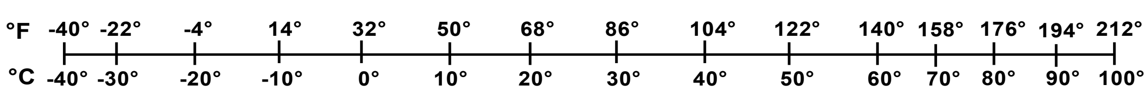


QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSIO



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Executive Summary

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 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 Federal Railroad Administration's (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 (QNA) carried out the research and development of alternative Emergency Warning Signal (EWS).

From September 2, 2014, to July 31, 2016, QNA and Harris Miller Miller & Hanson Inc. (HMMH) developed a secondary Emergency Warning Signal (EWS) generated by an Acoustical Warning Device (AWD) to supplement train horns. A secondary EWS has the potential to be more effective than a traditional train horn for warning trespassers on the right-of-way, especially when they are wearing earbuds or headphones. In a parallel study, researchers developed an AWD which used directive speakers to replace train horns. The AWD system offers the potential to generate an EWS with specially designed sounds to maximize detectability and provide greater warning for trespassers to vacate the tracks. This current study is Phase 2 of the EWS development effort. The earlier Phase 1 program developed candidate EWS sounds and identified the initial factors that affect detectability while wearing the latest listening devices. This Phase 2 program further optimized the customized EWS sounds based on a survey of people listening and judging the sense of urgency and detectability in a simulated trespassing audio environment. The work also determined the reasonable response time of trespassers reacting to train horns based on a review of the existing literature. Those results will guide the EWS sound levels that need to be generated by the AWD and the minimum train distance to initiate the warnings as a function of train speed. The local Institutional Review Board approved the survey testing of human subject tests that complies with the Department of Health and Human Services regulations.

1. Introduction

Although the number of accidents and fatalities of highway-rail grade crossings has decreased by almost 46 percent in the last decade, there are still approximately 460 railroad-related fatalities annually in the United States, with trespassers on the right-of-way representing the highest fatality group in railroad transportation. A recent study has analyzed injury data between 2004 and 2011 to understand the role that headphone use by pedestrians has played in train-pedestrian accidents (Lichenstein, R., Smith, D. C., Ambrose, J. L., & Moody, L., 2012). 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 was sounded before the crash. This has prompted the Federal Railroad Administration (FRA) to conduct research aiming at reducing railroad trespassing fatalities, especially among those wearing headphones or earbuds while walking on the ROW.

To reduce trespassing fatalities, a secondary Emergency Warning Signal (EWS) can supplement the standard train horn. This enhanced EWS must be capable of alerting trespassers with headphones, or ear buds, that a train is approaching. The development of electric Acoustical Warning Devices (AWD) with high amplitude output and a directive sound pattern offer the potential for customized EWS sounds that cannot be produced with standard train horns.

1.1 Background

Modern electronic acoustic sources are essentially loudspeakers that can reproduce directive sounds. With the use of such devices on locomotives, an effective EWS can be developed to better warn railroad trespassers and railroad workers of oncoming trains, and thus, save lives. EWS sounds must be identifiable as a train while still imparting a sense of urgency.

FRA funded the development of an EWS using electronic AWDs. These devices were shown to meet requirements for use as train horns. They were also shown to be able to produce a wide range of EWS sounds that are based on typical train horn sounds, such as the Nathan K-5-LA. The EWS sounds must be noticeable while wearing hearing protection, music headphones or earbuds.

The Phase I research developed the technical background and initial variations in EWS sounds (Campbell, T., Parida, B., Ross, J., & Zaouk, B., October 2019). Researchers conducted a detailed literature review to investigate the current practice of EWS development for all emergency responders, including fire, police and ambulance. The lessons learned were applied to the development of the particular EWS sounds for trains. The sounds must be identifiable as a train, develop a sense of urgency and be optimized to increase the likelihood of being detectable to people wearing headphones and listening to music. An iterative procedure evaluated sounds and used several design cycles for modification. Researchers developed and evaluated over 100 sounds. A subset of these EWS sounds forms the basis of the Phase 2 program evaluation.

The audiometric booth testing is critical to assessing the sound attenuation of headphones and earbuds in a larger population than used in Phase 1. Test results from the Phase 1 program showed that there is significant sound attenuation when wearing headphones. Figure 1 shows the noise attenuation with active noise cancellation features. Passive attenuation is greatest from 1 kHz and above. The active noise cancellation (ANC) feature adds additional attenuation in the 50 to 600 Hz range. There is a window from approximately 600 through 1,200 Hz where headphone attenuation is a minimum, even with active noise cancellation. The design of the EWS sounds are emphasized in this range.

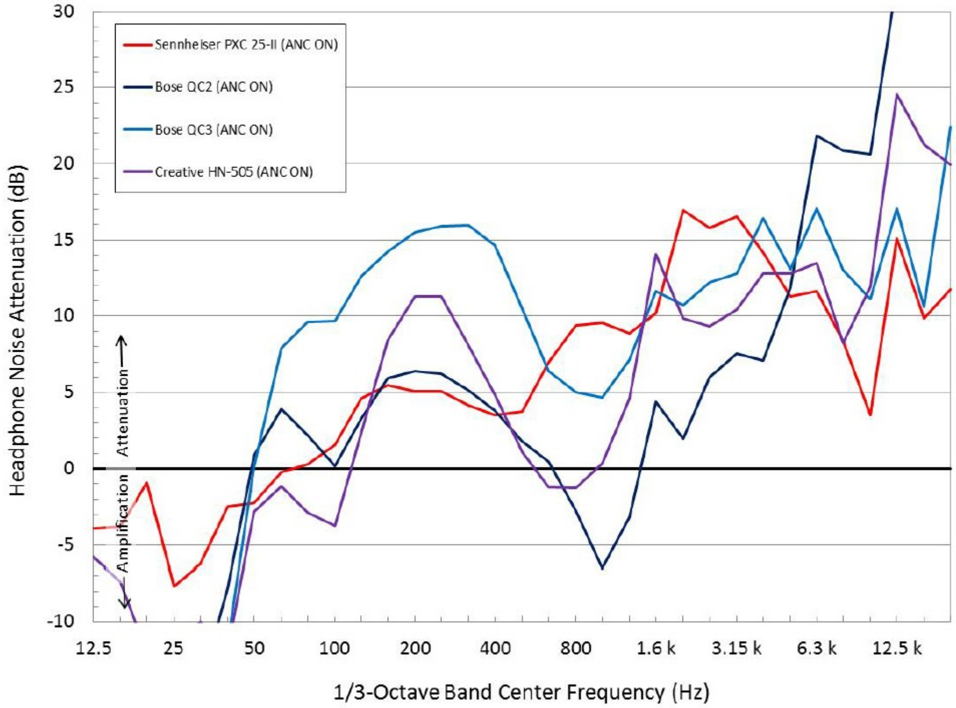

Figure 1. Sound Attenuation for Headphones with Noise Cancellation

Another significant finding from Phase 1 is that there is a masking effect from ambient noise or from music being played on headphones. Limited testing in the QinetiQ North America (QNA) audiometric booth in Phase 1 showed that external sounds are masked by the music being heard. This is an artifact of human hearing and the masking effect is within a critical band around any given frequency being heard. The critical band gets broader as the sound gets louder. Music generally covers a broad frequency range, so that the masking effect is over that broad range. Techniques to overcome the masking effect will be examined, as well as providing sufficient sound pressure levels to overcome the ambient or music levels being heard.

1.2 Objectives

The goal of this research is to demonstrate the effectiveness of an AWD as a secondary EWS. The focus is in warning trespassers of an approaching train through development of an EWS that produces a sense of urgency, is noticeable to trespassers wearing headphones or earbuds, and is identifiable as a train.

1.3 Overall Approach

This Phase 2 research builds on the EWS sounds developed during Phase 1. The research team evaluated the sounds and the sound selection narrowed to those that provide maximum noticeability and a sense of urgency to persuade trespassers to immediately vacate the right-of-way. The Phase 2 research assessed the sounds through a survey of 25 people. Background noise or music played through headphones while a simulated oncoming train and its EWS, or train horn, was superimposed. The train sound volume increased for the study and the subject's reaction time and detectability level was recorded. Follow-on work in a Phase 3 research will add external speakers to provide train and EWS sounds with subjects wearing headphones in an audiometric booth. This will better assess the effects of the headphones and earbuds. The optimized EWS sounds will be ultimately tested in dynamic tests with a moving train in Phase 3.

1.4 Scope

This Phase 2 research further optimized the customized EWS sounds based on a survey of people listening and judging the sense of urgency and detectability in a simulated trespassing audio environment. The work also determined the reasonable response time of trespassers reacting to train horns based on a review of the existing literature.

1.5 Organization of the Report

This report contains the following sections: Section 1 presents an introduction of the work conducted as well as what Phase 3 will need to address; Section 2 describes testing protocol and characteristics of the various tested EWS sounds, and the survey results ; Section 3 summarizes the reaction time literature review; Section 4 details the protocol submitted and approved by the Institutional Review Board; Section 5 concludes the study with indications that there is potential to create of a more effective EWS.

2. Optimize the Emergency Warning Signal

The EWS optimization is aided by a more extensive survey of people than in Phase 1. The survey greatly enhanced the knowledge of the effectiveness of EWS sounds and their characteristics. The following section describes the testing protocol, characteristics of the various tested EWS sounds, and the survey results.

2.1 Testing and Evaluation of Candidate Signals

Twelve of the candidate EWS sounds that represent a range of the different design features along with the standard warning signals (e.g., wail, yelp, rumbler and baseline Nathan 5-chime train horn [Figure 2]) were tested and evaluated to quantify their effectiveness. Emergency response vehicle AWDs for police, fire and ambulances are controlled by the Society of Automotive Engineers (SAE) standard J1849:201210. The AWDs must generate wails or yelps with specific characteristics. Both a wail (Figure 3) and yelp (Figure 4) must be in sound bursts with frequency content in the range from 650 to 2,000 Hz with at least a spread of 850 Hz. A wail has a slower variation at a 2 to 6 second cycle and a yelp is more rapid, at 0.24 to 0.4 second cycles. A rumbler (Figure 5) is a low frequency pulsating signal that includes a series of signals between 150 and 450 Hz, spaced by at least 20 Hz. It is a very fast sound burst with cycle times of 0.08 seconds.

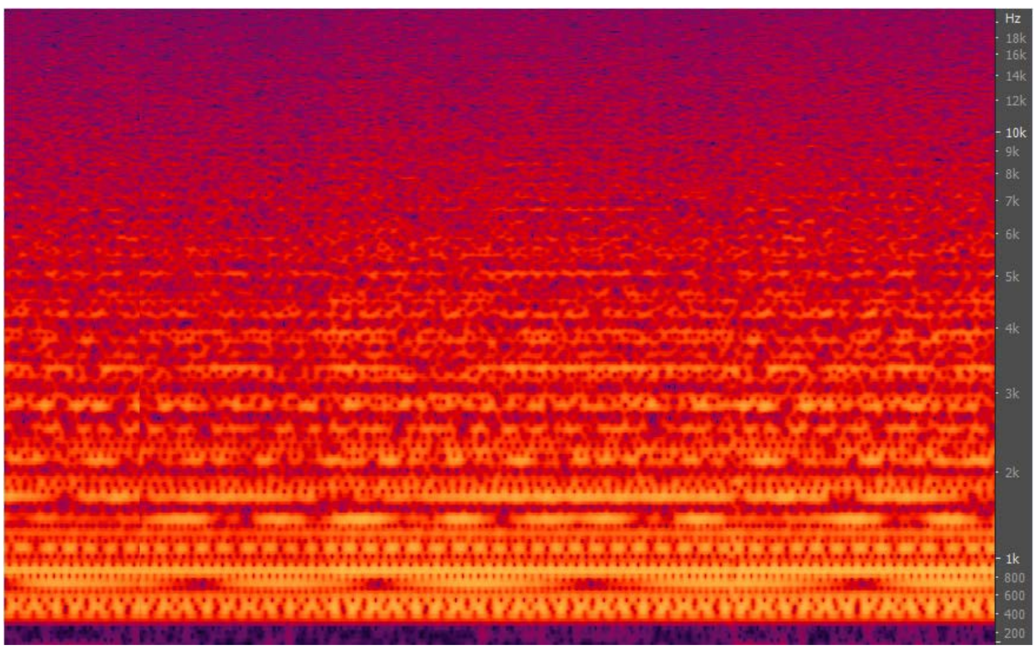

Figure 2. 1-Second Sample of an Analog Recorded Nathan Horn Spectrogram

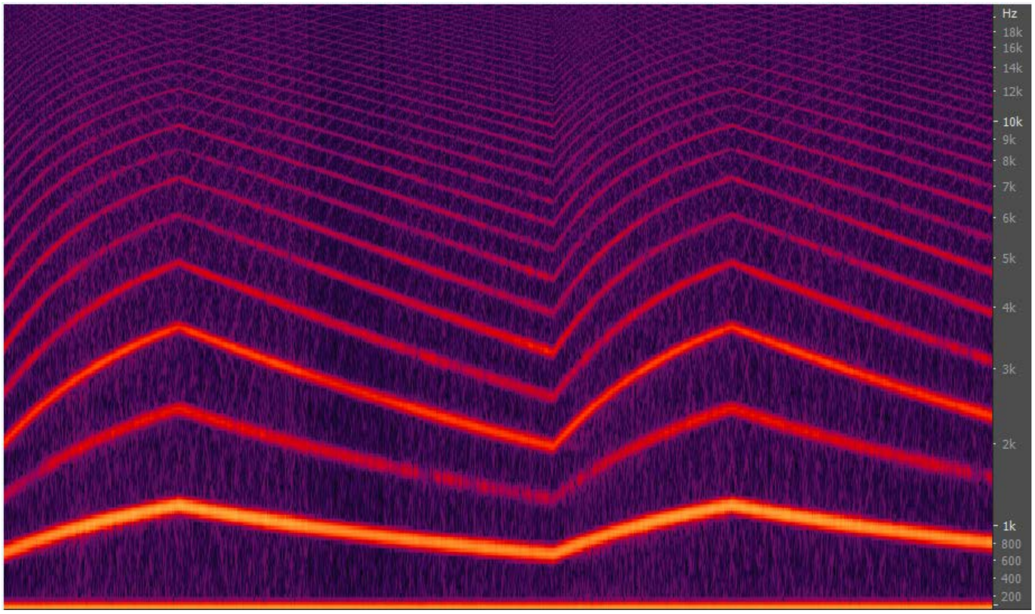

Figure 3. 10-Second Sample of a Wail Spectrogram

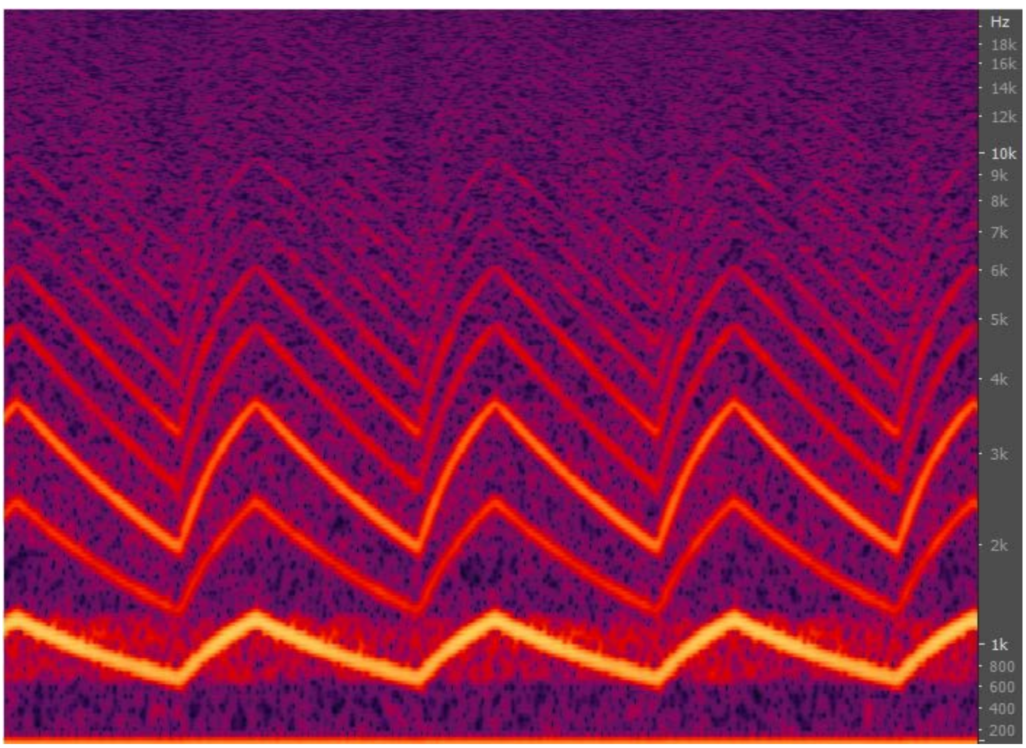

Figure 4. 1-Second Sample of a Yelp Spectrogram

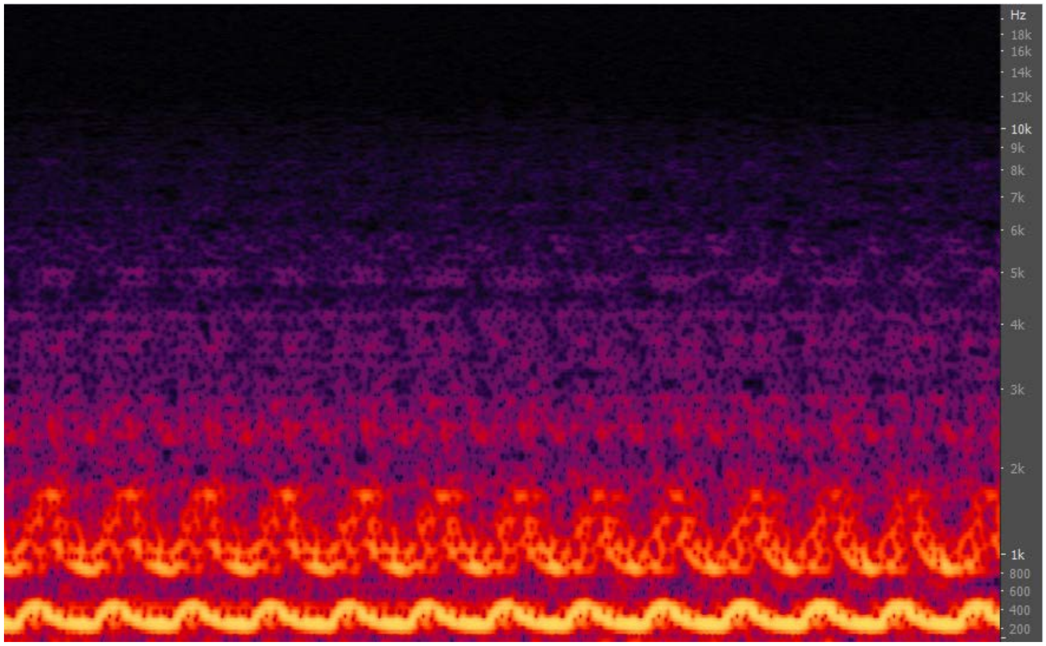

Figure 5. 1-Second Sample of a Rumbler Spectrogram

Participants completed two surveys by listening to calibrated playbacks of the different EWS sounds with headphones. Each survey included six candidate EWS sounds and the four standard warning signals. The goal of this testing and evaluation was to identify specific features of the more effective EWS sounds and reduce the group of effective EWS sounds for further refinement and evaluation.

All EWS sounds were reproduced with in-ear amplitudes of 80 to 85 dBA. Participants had an opportunity to adjust the amplitude so that it would be at a reasonably comfortable listening level. A background pink noise signal was reproduced at constant amplitudes of 80 to 85 dBA and the EWS slowly ramps up to a maximum level of 90 dBA.

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

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

- "Is this sound annoying?" (i.e., 5-point rating scale: not annoying, slightly annoying, moderately annoying, very annoying, and highly annoying)

The survey quantified how efficiently the listeners can detect each signal by playing a calibrated recording where each signal slowly increased in amplitude while either 1) broadband pink noise, or 2) music played as masking background noise. To simulate the attenuation from headphones and earbuds, the sounds were filtered according to Figure 6 to simulate the passive attenuation of headphones. No active noise cancellation was simulated.

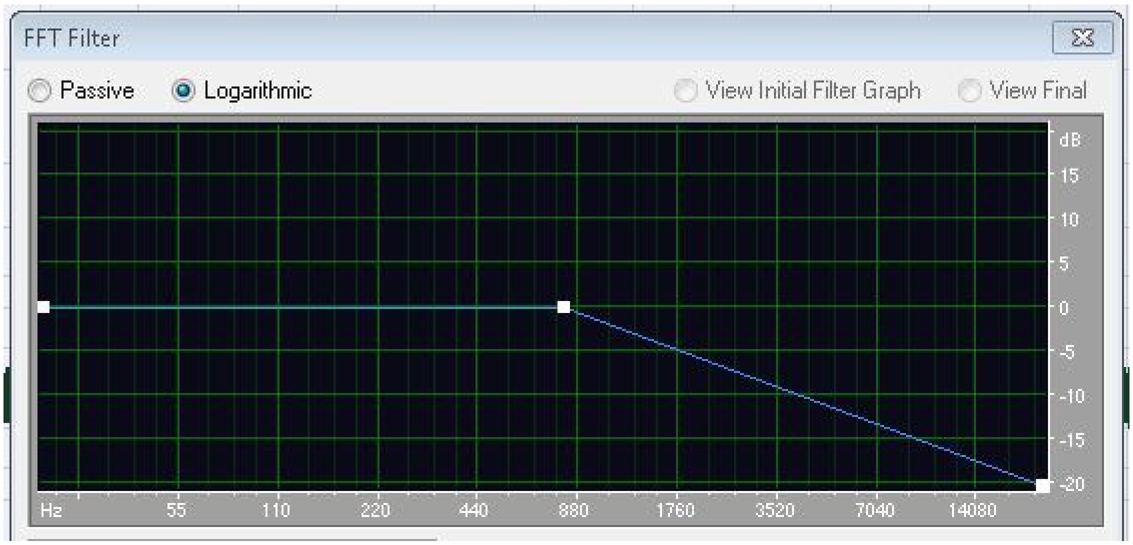

Figure 6. EWS Filter Simulating Passive Sound Attenuation of Headphones

The listeners pressed a button when they first heard the sound to assess audibility of the EWS and to press a second button when the EWS was loud enough to "cause a need to take action (move away from the source)." Based on the time they pressed each button, a "d-prime" detectability level, which is a comparison of the EWS signal to the masking background noise, was measured. This study focused on the results obtained when music was played as masking background noise.

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

- Sense of urgency
- Certainty in identifying the source of sound
- Startle effect

2.2 Candidate Signals

This survey tested and evaluated the following 12 EWS sounds.

EWS #1: Figure 7 shows this signal is the digital baseline train horn sound with Doppler-effect increasing all tones frequency by 20 percent over a cycle time of 0.2 seconds. The signal is repeated without any gaps. This EWS sounds fairly electronic and fast.

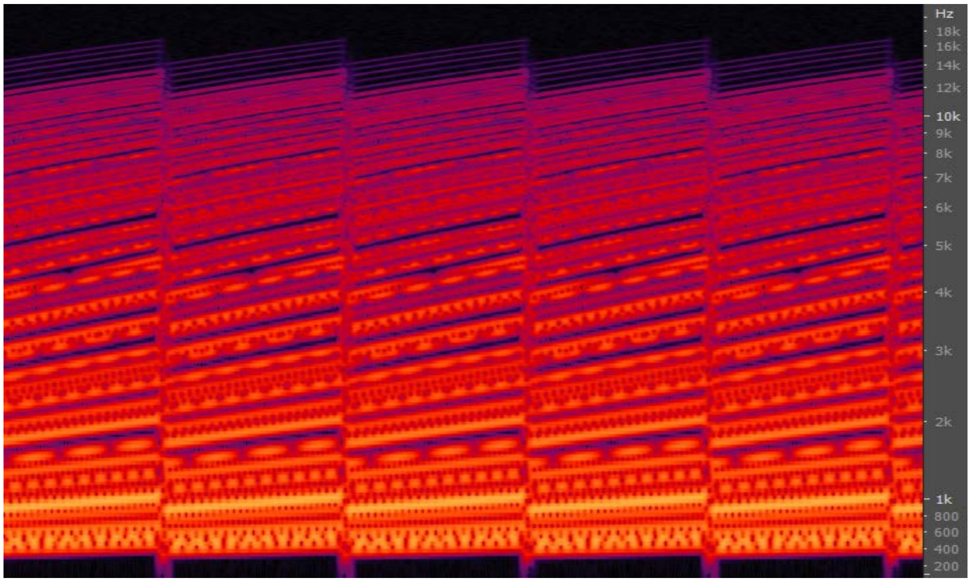

Figure 7. 1-Second Sample of EWS #1 Spectrogram

EWS #2: Figure 8 shows this signal is the digital baseline train horn sound without any Doppler effect. Instead, over a cycle time of 1 second, all the tones are modulated by 2 percent at a modulation frequency of 15 Hz (both beginning and end of the cycle). Additionally, the entire signal is amplitude modulated +/- 6 dB 10 times a second. The EWS sounds like an electronic train horn with a significant amount of warble.

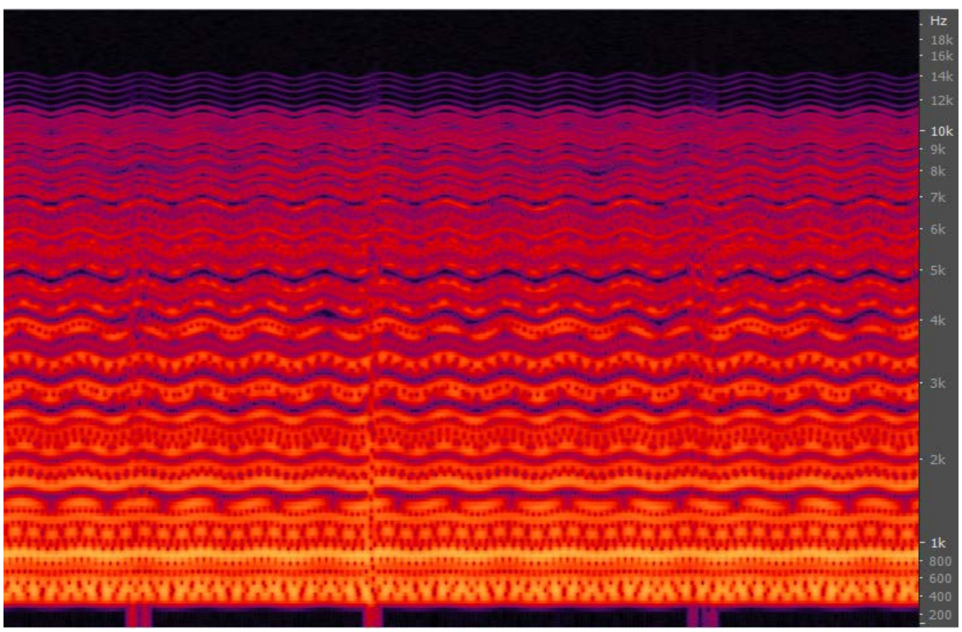

Figure 8. 1-Second Sample of EWS #2 Spectrogram

EWS #3: Figure 9 this signal is the digital baseline train horn sound with Doppler effect increasing all tones frequency 5 percent over a cycle time of 1 second. The tones are modulated 1 percent at a modulation frequency of 8 Hz at both the beginning and end of the cycle.

Additionally, the entire signal amplitude is ramped up 3 dB over the 1-second cycle. The signal is repeated without any gaps.

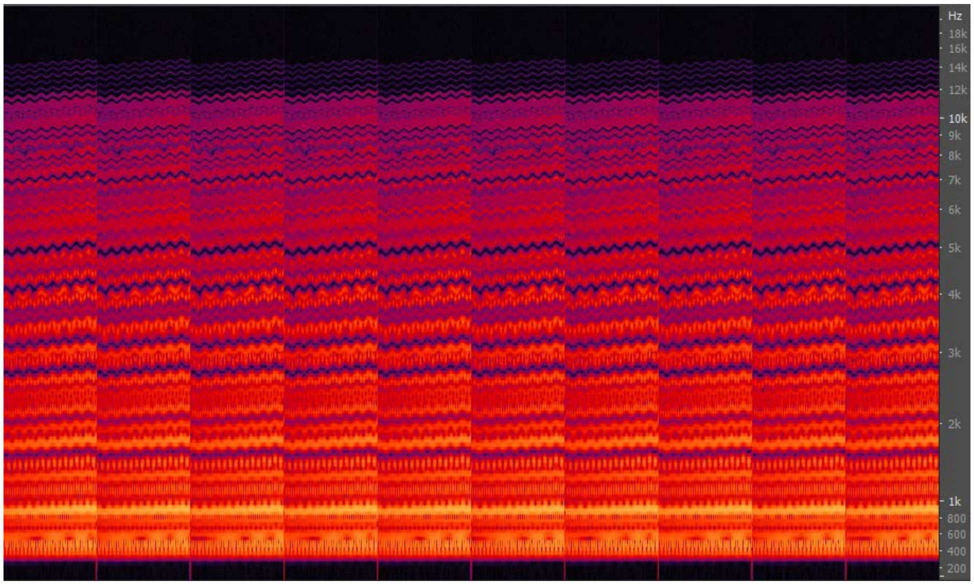

Figure 9. 10-Second Sample of the EWS #3 Spectrogram

EWS #4: Figure 10 shows this signal is the digital baseline train horn sound with Doppler effect increasing all tones frequency over a cycle time of 1 second. Each tone is increased in frequency 25 percent of the auditory filter critical bandwidth of that tone. So, for example, the 355 Hz tone has an auditory critical bandwidth of 109 Hz and 25 percent of that is 27 Hz. Therefore, the tone is increased from 355 to 380 Hz (or 8%). All tones were increased approximately 4 to 8 percent. Additionally, the signal included 15 percent modulation at a modulation frequency of 4 Hz (beginning) and 20 Hz (end). Overall, this signal is very electronic and fast.

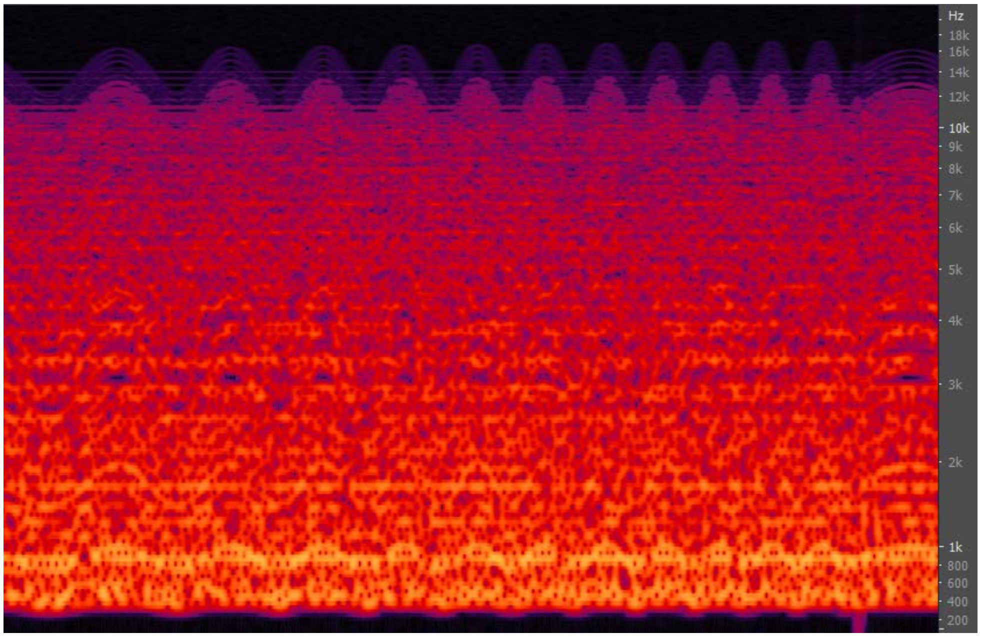

Figure 10. 1-Second Sample of the EWS #4 Spectrogram

EWS #5: Figure 11 shows this signal is the digital baseline train horn sound with Doppler effect increasing all tones frequency 5 percent over a cycle time of 1/4 second. This signal sounds like a "thumping" train horn as it maintains more of the train horn character than other candidate EWSs.

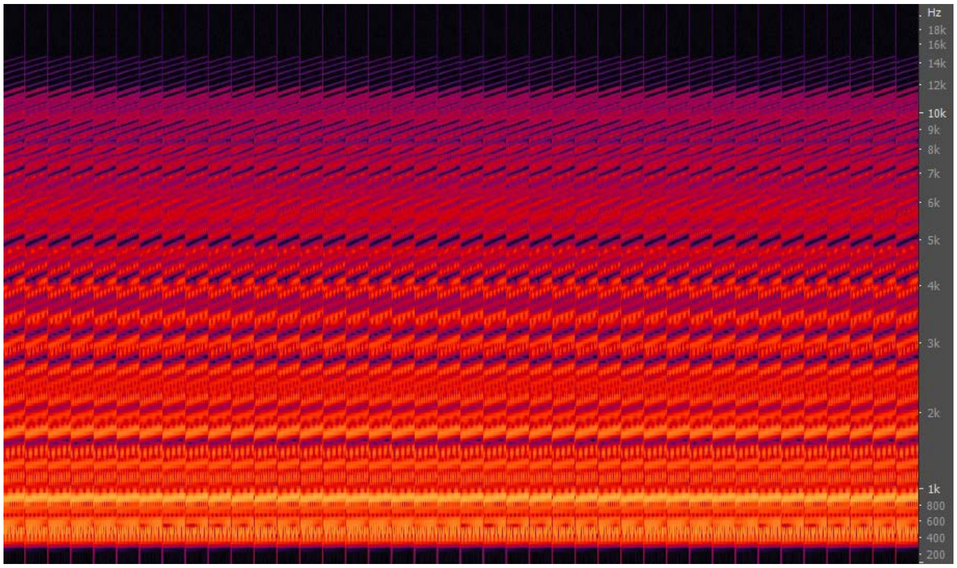

Figure 11. 10-Second Sample of the EWS #5 Spectrogram

EWS #6: Figure 12 shows this signal is the digital baseline train horn sound with Doppler effect increasing all tones frequency 5 percent over a cycle time of 1 second. This signal is similar to EWS #5 with a slower "thumping" characteristic.

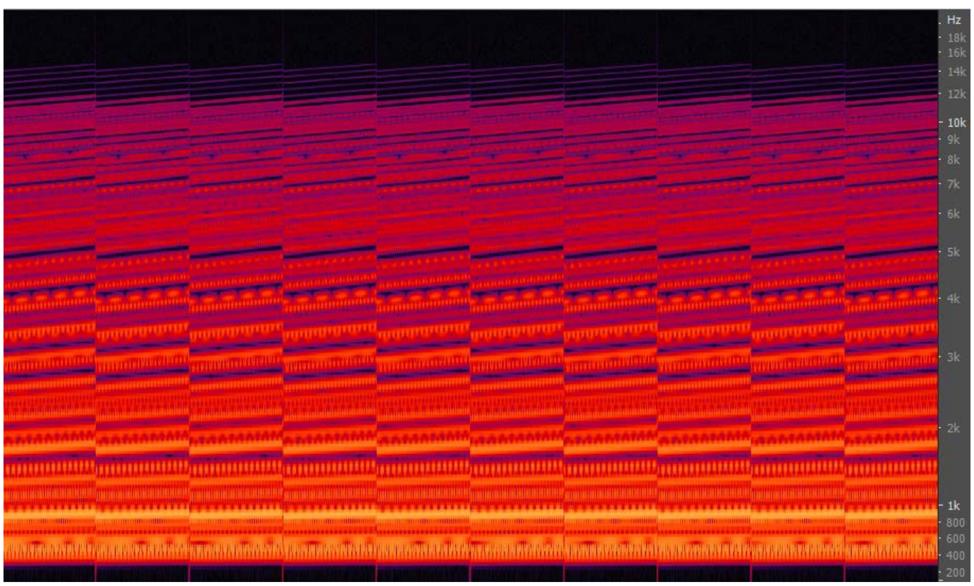

Figure 12. 1-Second Sample of the EWS #6 Spectrogram

EWS #7: Figure 13 shows this signal includes both an analog baseline train horn sound (for the primary tones) and the digital baseline train horn sound for all harmonics. For the harmonic tones (700 Hz and above), the signal is similar to EWS #2 which does not include a Doppler-effect, but frequency modulation or "shaking" of the tones. Additionally, the rumbler was added in for additional low-frequency content. The overall signal sounds like a fairly electronic train horn.

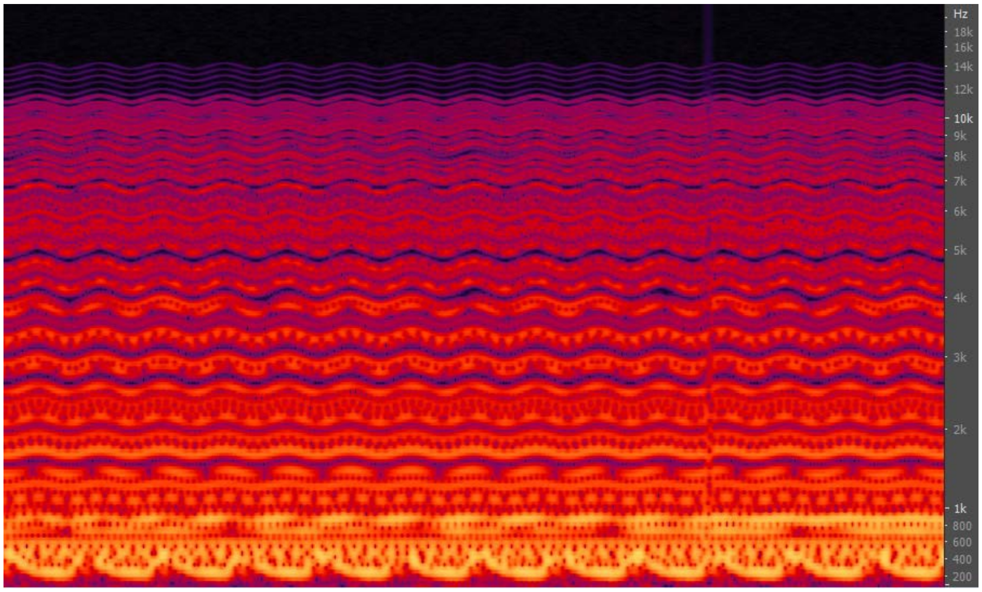

Figure 13. 1-Second Sample of the EWS #7 Spectrogram

EWS #8: Figure 14 shows this signal is the analog baseline train horn sound including the primary and all harmonics. The rumbler has been added in for additional low-frequency content. The overall signal sounds more like the standard train horn warning signal than many other candidate EWSs.

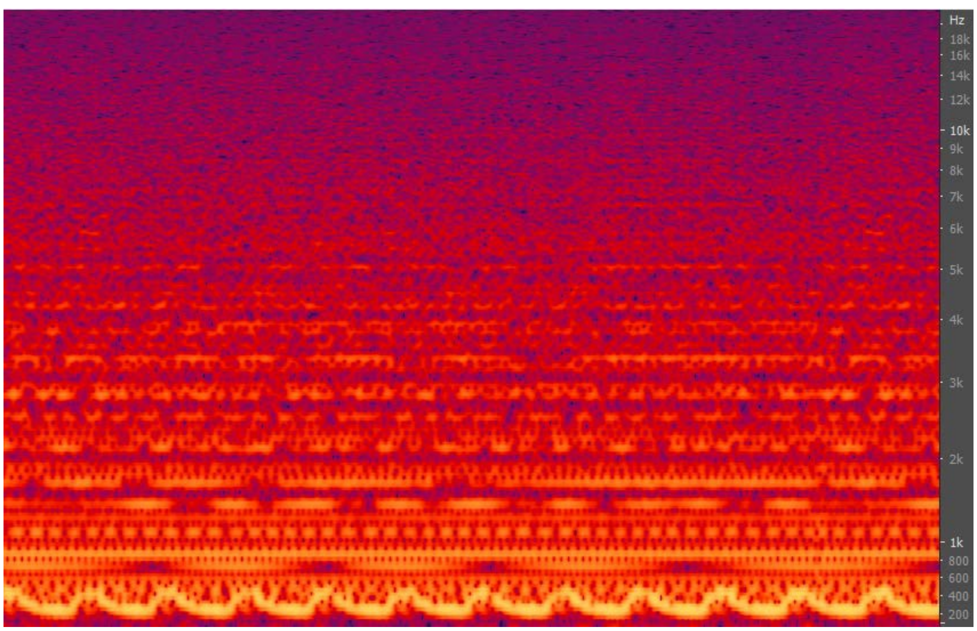

Figure 14. 1-Second Sample of the EWS #8 Spectrogram

EWS #9: Figure 15 shows this signal is similar to EWS #7 which is a mixture of the analog baseline and digital baseline train horn sound; however, this signal does not include the rumbler.

The overall signal sounds like a standard train horn signal with additional high-frequency content.

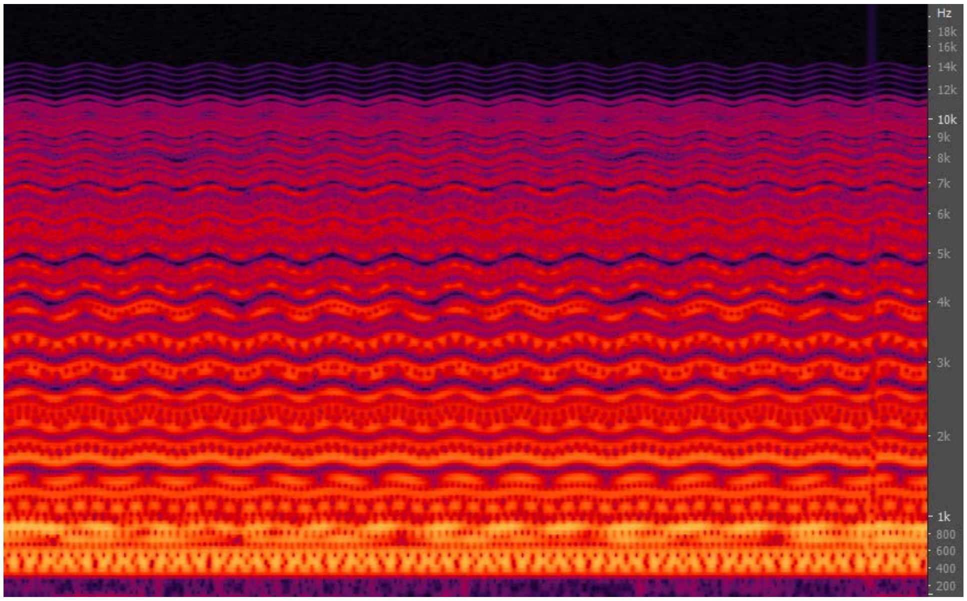

Figure 15. 1-Second Sample of the EWS #9 Spectrogram

EWS #10: This signal is similar to EWS #9; however, instead of keeping just the primary tones in the analog baseline stationary, the primary tones and their first two harmonics are kept stationary (see Figure 16). Upper harmonics (i.e., 3rd harmonics and above) are based on the digital signal that includes frequency modulation or "shaking" of the tones. The overall signal sounds more like the standard train horn warning signal than many other candidate EWSs.

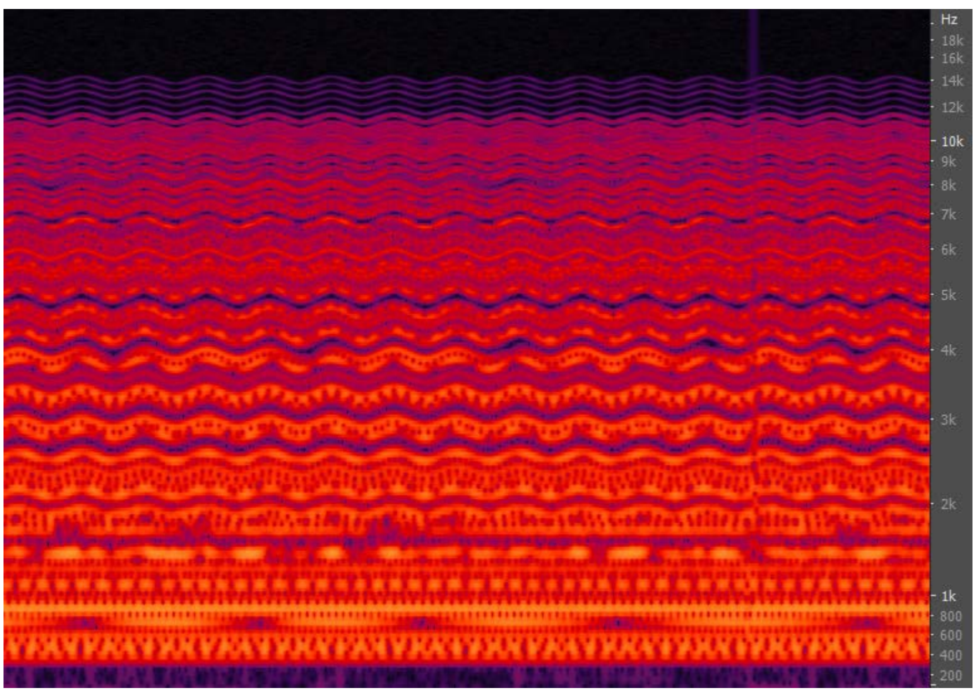

Figure 16. 1-Second Sample of the EWS #10 Spectrogram

EWS #11: This signal is similar to EWS #9; however, instead of modifying the harmonics with just frequency modulation, they have simulated Doppler-effect which increases these harmonics 20 percent over a cycle time of 0.2 seconds (see Figure 17). The overall signal sounds highly-electronic and thumping.

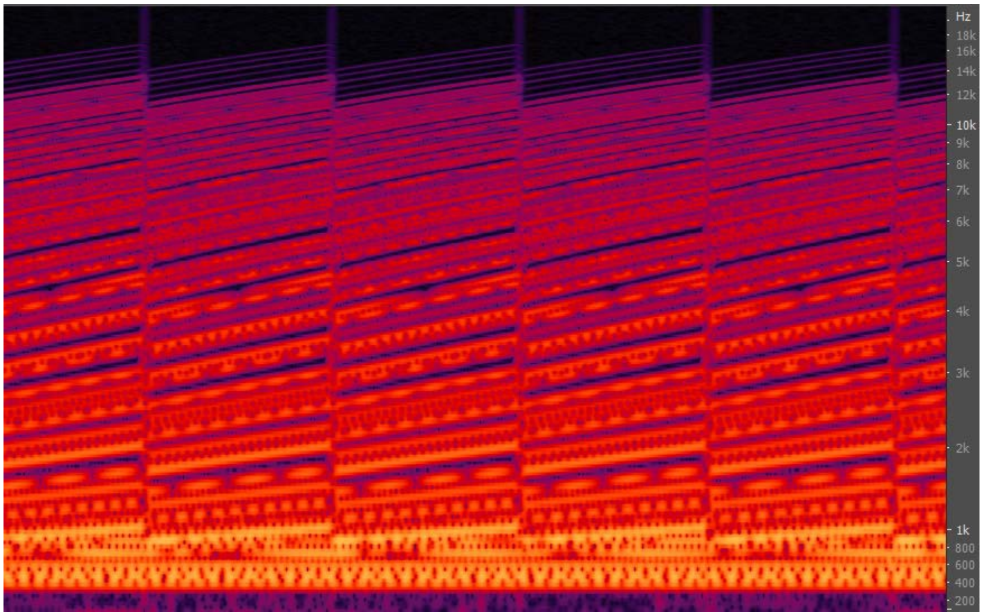

Figure 17. 1-Second Sample of the EWS #11 Spectrogram

EWS #12: Figure 18 shows this signal is the analog baseline train horn sounds including the primary and all harmonics. Lower-frequency "fractional harmonics" including all 1/2 and 1/3 frequencies of the primary tones have been included. The overall signal sounds like a deep and rich train horn sound with a slight beating effect in the lower frequency.

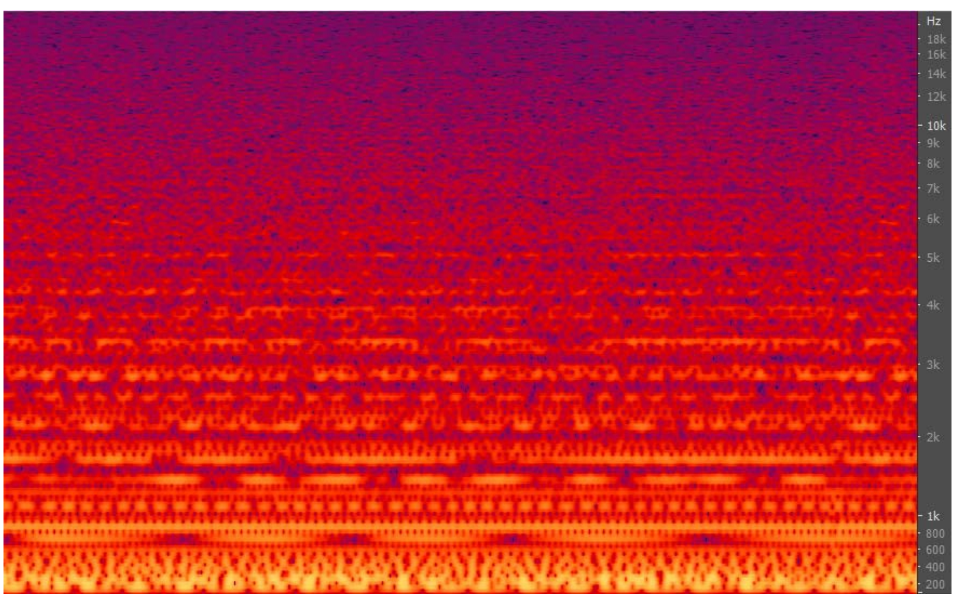

Figure 18. 1-Second Sample of the EWS #12 Spectrogram

2.3 Survey Results

2.3.1 Source Identification

A total of 25 participants completed the surveys. As shown in Figure 19, the source identification results indicated 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 the 25 participants. Of the candidate EWS sounds, #9 and #10 had the highest number of participants identify the source as a train. Ten of the 11 participants identified #9 as a train and 9 of 11 identified #10 as a train. As shown in Figure 20, participants responded that they had the highest level of certainty in the source of the sound for EWS #9.

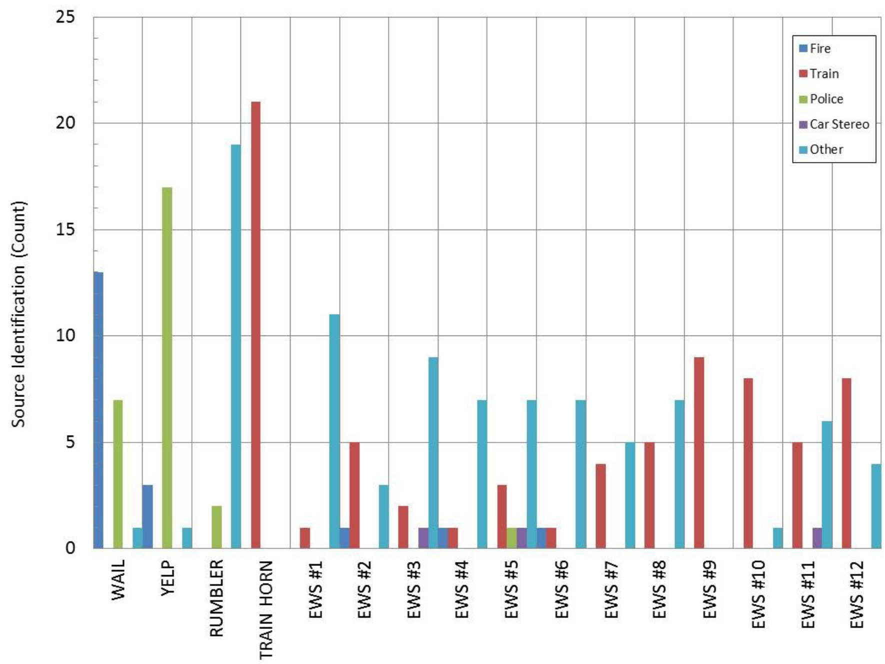

Figure 19. EWS Source Identification

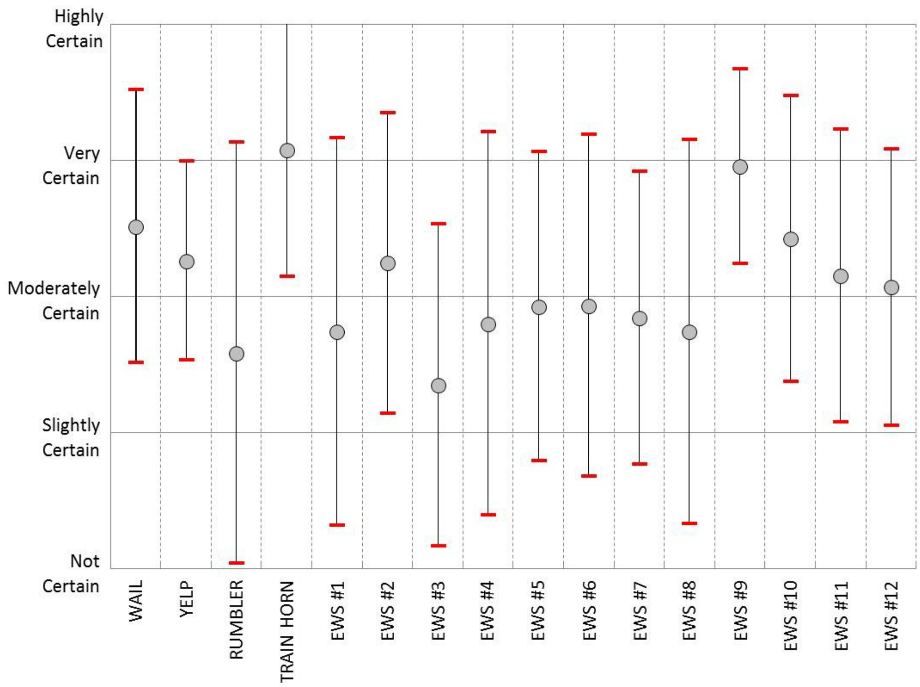

Figure 20. EWS Certainty of Source Identification Rating (Average +/- Standard Deviations)

2.3.2 Sense of Urgency

The sense of urgency that each signal caused is shown in Figure 21. This figure shows the average rating and plus and minus one standard deviation. The sense of urgency is thought to be one of the most important metrics to assess the effectiveness of the EWS as the primary purpose of the EWS is to cause the listener to take action and move away from the tracks. Figure 21 shows that there is not a significant difference among most of the EWS sounds. The rumbler, in fact, is shown to be one of the least effective signals. EWS #2, #3, and #12 are shown to cause a relatively low sense of urgency compared to the train horn. EWS #1, #4, and #6 are slightly higher than the train horn. EWS #9, which was one of the better performing signals for identification as a train source create a slightly higher sense of urgency than the train horn. The individual survey results for the sense of urgency results were also broken into demographics of sex and age as shown in Appendix A. The rumbler scored lowest generally. Even within a single demographic, the results varied widely.

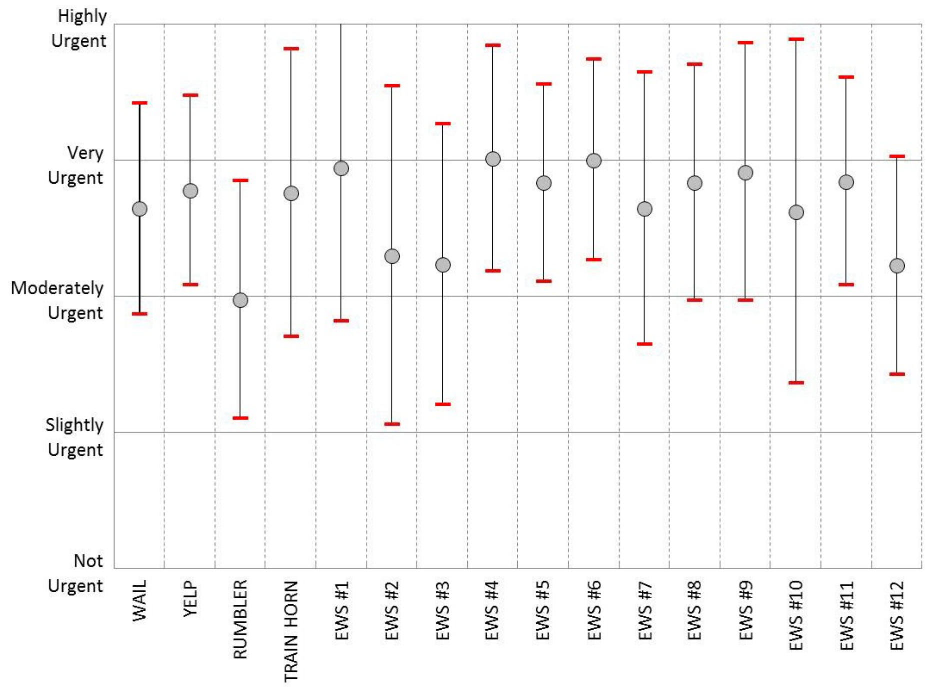

Figure 21. EWS Urgency Ratings
(Average +/- Standard Deviation)

2.3.3 Startle

Figure 22 presents the ratings for the EWS sounds startled the listener. Causing startle can have both positive and negative effects regarding safety. Listeners that were startled indicated a quick and rapid response to the EWS, which is desirable; however, it also could indicate a sense of confusion and a limitation towards responding to the sound with a desired action (i.e., leaving the tracks). Results for the sense of urgency compared to startling the listeners provided very similar responses to these two questions. Figure 23 shows the annoyance rating of various EWSs and EWS #9 has a relatively lower annoyance level in addition to a better detectability and higher sense of urgency.

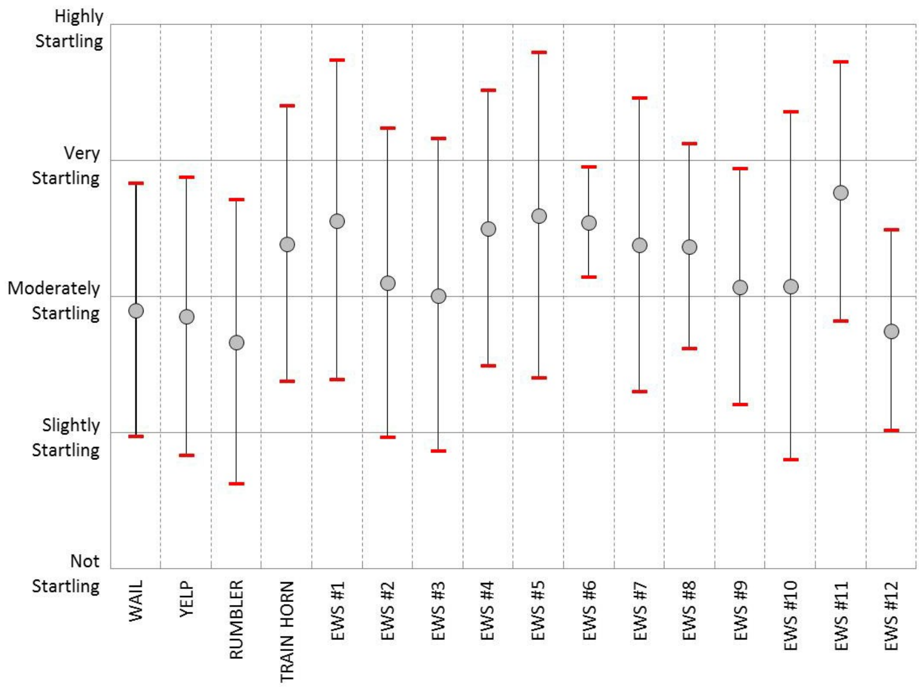

Figure 22. EWS Startling Effect Rating (Average +/- Standard Deviation)

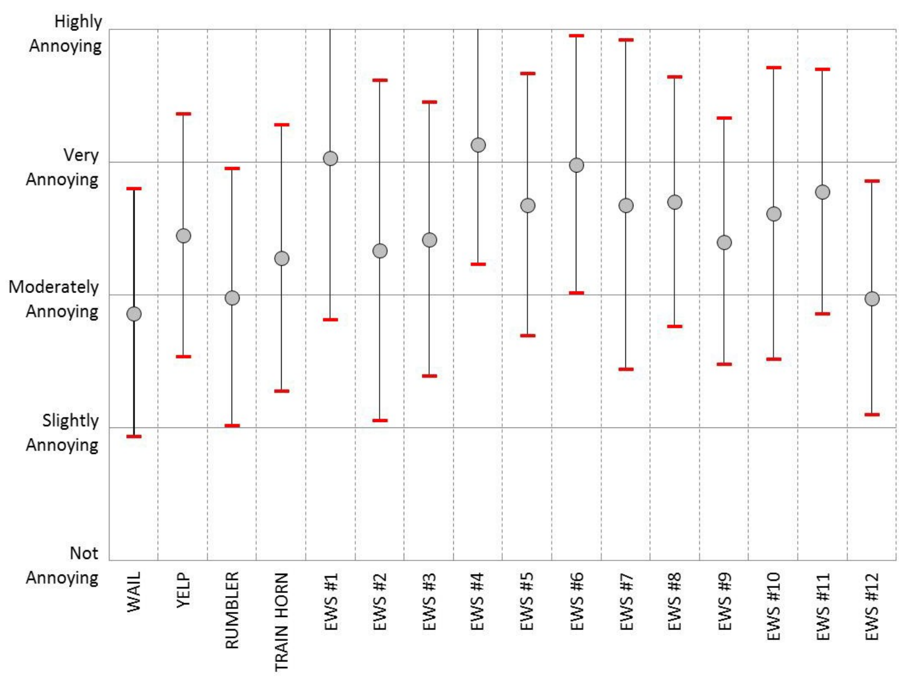

Figure 23. EWS Annoyance Rating (Average +/- Standard Deviation)

2.3.4 Music and Background Noise Masking

The detectability of the different signals with music masking is shown in Figure 24. The detectability with the pink noise background is shown in Figure 25. Relative differences in detectability compared to the baseline train horn are shown in Figure 26. For reference, if a particular EWS can be heard or the need to take action occurs 6 dB lower than the standard train horn; this means that the EWS would be effective when the train is twice the distance away.

Therefore, if the standard horn was audible when the train was 400 feet away, the new EWS would be audible when the train was 800 feet away. Doubling the distance of the train will also double the amount of time trespassers and railroad workers have to vacate the tracks.

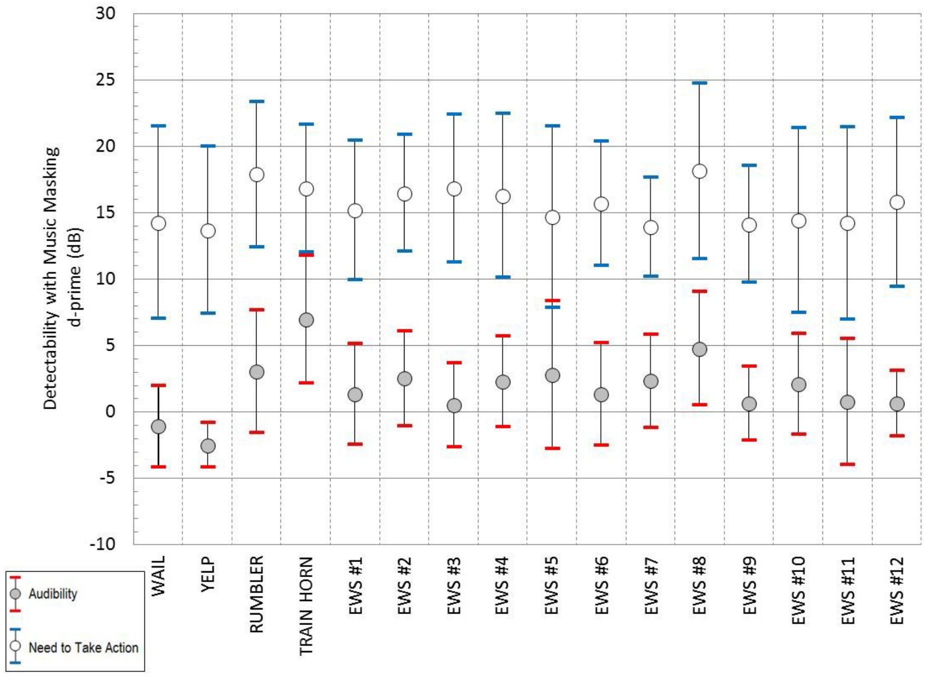

Figure 24. EWS Detectability with Music Masking (Average +/- Standard Deviation)

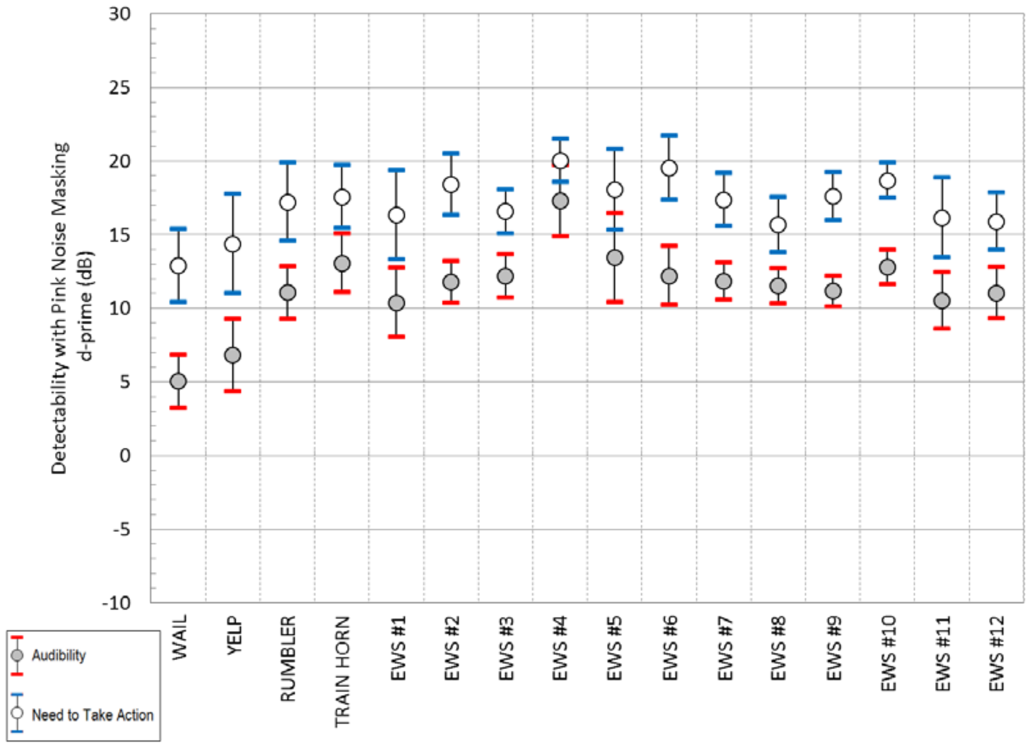

Figure 25. EWS Detectability with Pink Noise Masking (Average +/- Standard Deviation)

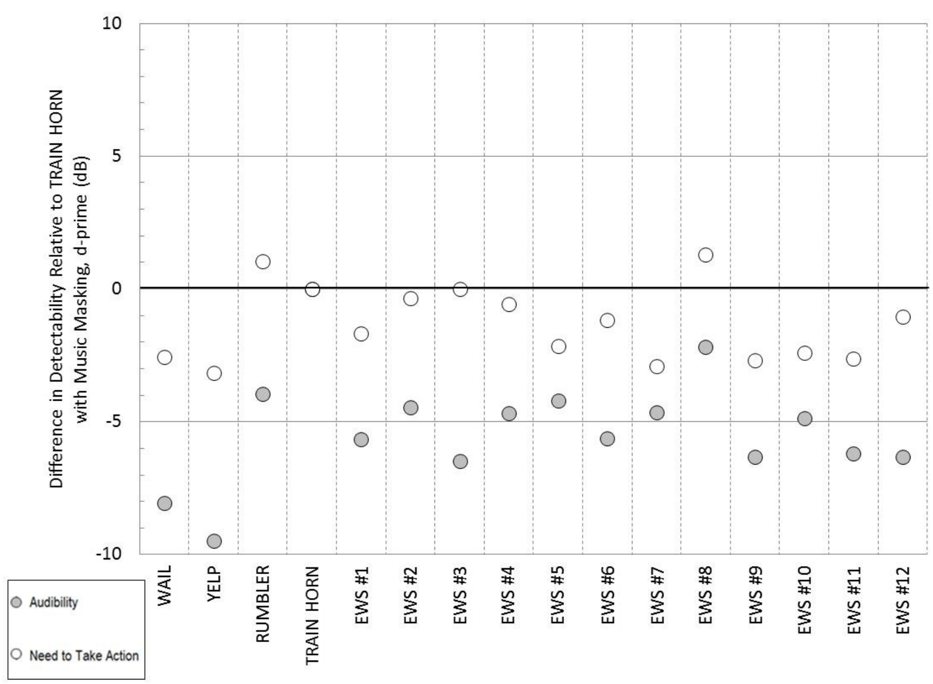

Figure 26. Difference in Detectability Relative to Train Horn with Music Masking

2.3.5 Detectability

The wail and yelp standard warning signals are shown to be audible at the lowest d-prime levels. The wail could be heard at a level approximately 8 dB lower and the yelp could be heard at a level approximately 10 dB lower than the standard train horn. Many of the candidate EWS sounds that were adaptations of the baseline train horn improved audibility by 5 dB or more compared to the standard train horn. Regarding the amplitude needed to take action, many of the EWS candidates were effective 1 to 3 dB lower than the standard train horn.

The average maximum range for audibility in Figure 24 is a d-prime of 6 dB. The mean noticeability occurs at d-prime of 16, with the mean maximum d-prime for actionable noticeability at a d-prime of 21. The National Park Service has determined that aircraft is audible in an outdoor recreational setting with a d-prime of 7 dB which is similar to these results (Rapoza, A. S., & Fleming, G. G., 2002).

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

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

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

The results in Figure 27 to Figure 29 indicate that EWS #9 is one of the most effective candidate EWSs as it performs well in the three most important categories. This EWS is a combination of both the analog and digital baseline which does not actually include a Doppler-effect, but rather, frequency modulation of the tones.

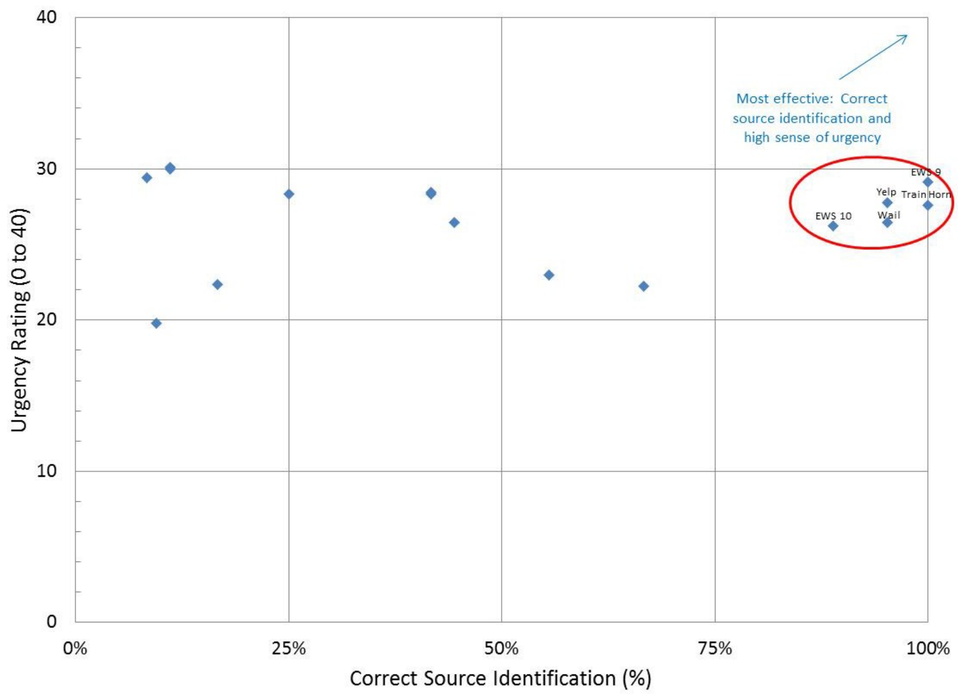

Figure 27. Correct Source Identification % vs. Urgency Rating

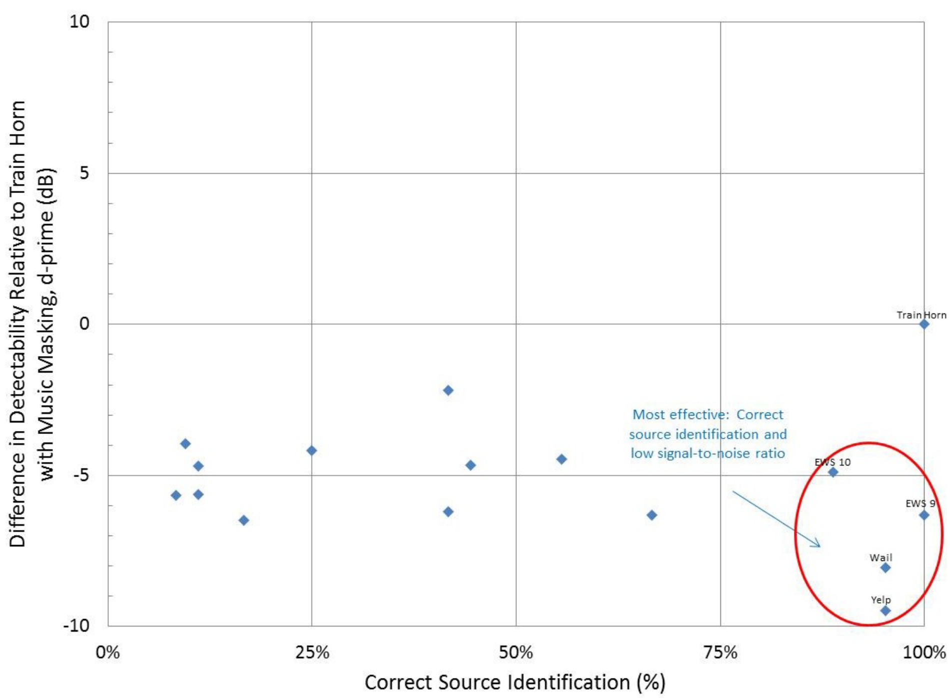

Figure 28. Correct Source Identification % vs. Difference in Detectability with Music Masking

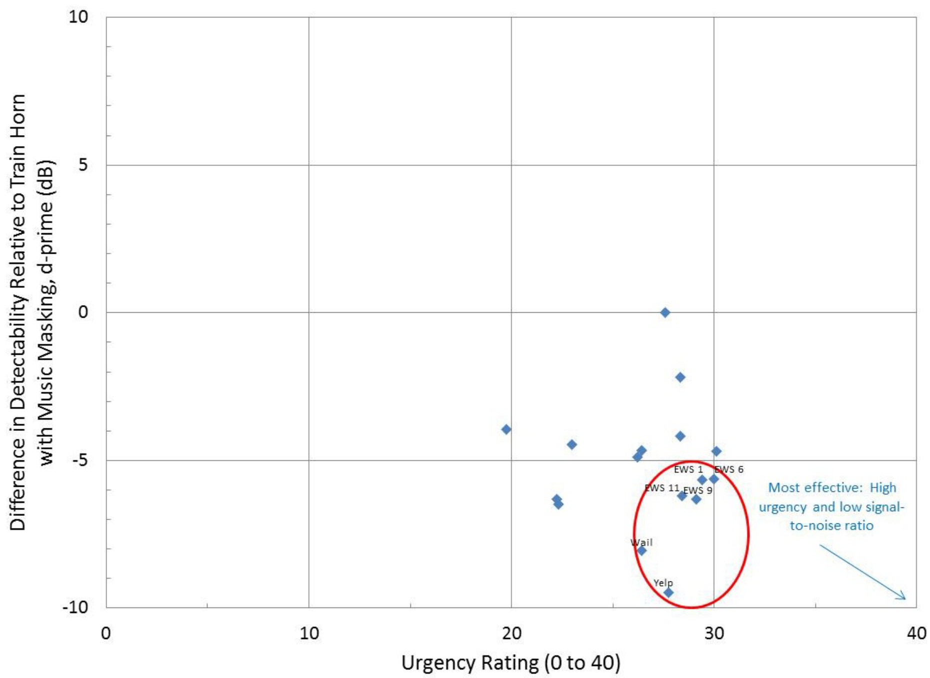

Figure 29. Urgency Rating vs. Difference in Detectability with Music Masking

3. Reaction Time Literature Review

A critical aspect of the design of a secondary EWS is to provide sufficient notice to trespassers to enable them to vacate the railroad right-of-way prior to the train arriving. The previous Phase 1 work assumed 2.5 seconds to notice and begin reacting (a commonly quoted time) to a warning signal, followed by 5 seconds to vacate the right-of-way.

The 5 second time was the author's estimate for a healthy person to vacate a single-track right-of-way. Given those assumptions the minimum distance a train needs to be noticed can be calculated as shown in Figure 30. For example, a 40-mph train needs to be noticed by a trespasser when it is 450 ft. away for the trespasser to vacate the tracks prior to the train arriving, assuming the train is not slowing down.

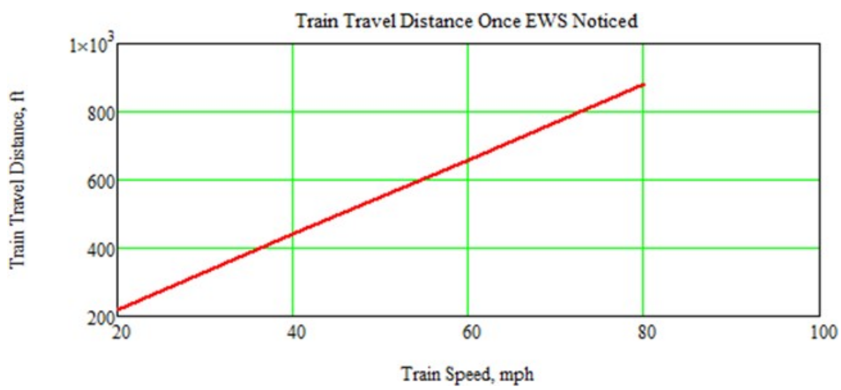

Figure 30. Minimum Train Distance Once Noticed for Trespassers to Vacate the Right-of-way with a 7.5 Second Total Reaction Time

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 ft. forward of the locomotive. Initial assumptions are that the EWS must meet the same requirements. Referring to Table 1, an EWS that develops the maximum of 110 dBA at 100 ft. forward of the locomotive will attenuate to 96 dBA at 500 ft. An EWS developing 96 dBA sound level at 100 ft. attenuates to 82 dBA at 500 ft. away. These sound level reductions are based on standard spherical sound propagation, where sound in dB is reduced by: $20\log\frac{r2}{r1}$

where r2 is the new distance (500 ft.) and r1 is the reference distance from the source (100 ft.).

Table 1. 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 levels of 90 dBA. A recent study showed that teenagers chose to listen to music at higher levels with earbuds approaching 90 dBA at the highest selected levels (Portnuff, C. D. F., Fligor, B. J., & Arehart, K. H., 2011). From Figure 31, the mean listening levels are shown to increase with ambient sound level. 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.

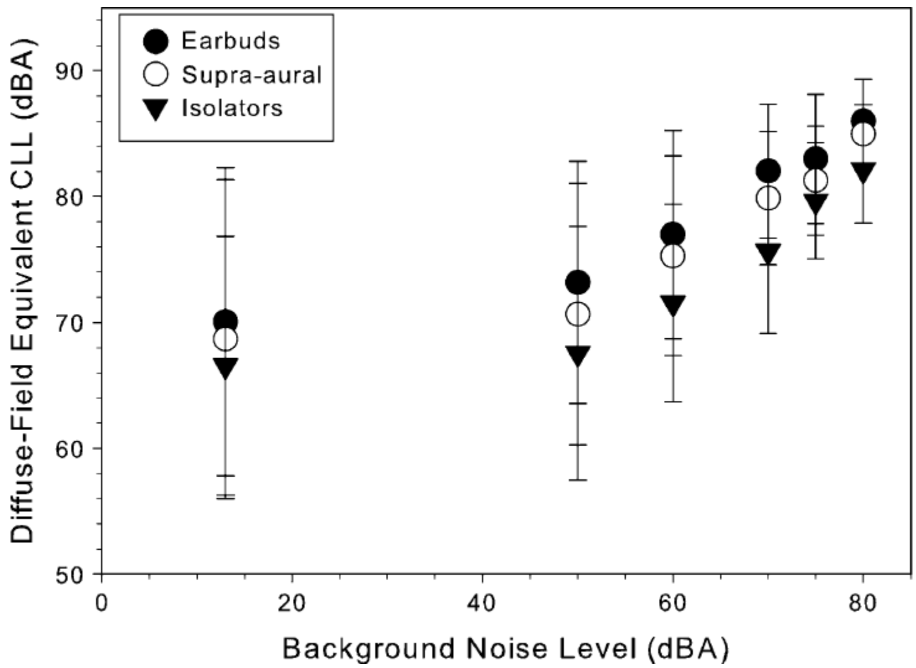

Figure 31. Chosen Listening Levels for 29 Teenagers as a Function of Background Noise (Portnuff, C. D. F., Fligor, B. J., & Arehart, K. H., 2011)

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 ft. away when noticed. Only a 20-mph train or slower could be avoided from Figure 30. Alternatively, to achieve this sound level at 450 ft., the horn would need to generate 118 dBA at 100 ft.

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 right-of-way. A key aspect of that is the reaction time and physical egress time to vacate the right-of-way. This task attempts to define these parameters based on a literature search.

This literature review assesses whether the assumed warning time of 7.5 seconds—2.5 second perception/reaction time and 5 second movement time is sufficient. The most applicable literature about warning time is reviewed which primarily comes from outside the railroad industry.

3.1 Components of Reaction Time

According to Woodson, Tillman, & 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. It is also noted that a simple reaction time to a surprising event is likely to increase the reaction time by around half a second. This gives a reaction time of approximately 11.05 seconds; however, it is 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 to produce response options.

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

3.2 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 right-of-way. 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, R. H., & Matthias, J. S., 1983). The range for perception-reaction time in Hay (1982) is given as 0.5–3 seconds, but the origin of those numbers is uncited. Olson & 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 have to perform response selection in an unfamiliar environment, it is not a particularly close analog.

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 to program the movement mentally. A need to select among multiple responses increases this stage, while practice decreases it.

Many reaction-time studies take place 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 analog for the conditions at issue is Suied, Susini, & McAdams (2008), which found a mean reaction time of 0.4 seconds 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 & McAdams, no response selection was necessary, while in the conditions at issue, the individual will 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 & 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 are unclear. Proulx & Pineau (1996) found a minimum reaction time to begin an evacuation to a fire alarm of 36 seconds and a maximum of 9 minutes and 46 seconds. 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.

3.3 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. The right-of-way itself is 25 feet wide, however, in cases with adjacent tracks, the minimum distance would be 20 feet to clear the tracks and a further 25 feet to clear the right-of-way.

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 second movement time.

3.4 Conclusion

The assumed time of 7.5 seconds can only be supported by tangentially related research, performed under circumstances that are not a close analog 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.

4. Institutional Review Board Protocol

Below is the protocol submitted and approved by the Institutional Review Board (IRB).

QNA is conducting a study on the potential use of EWS on trains. The standard AWD commonly used nowadays, generally referred to as a "train horn," creates a loud distinct sound that warns drivers and pedestrians of the approaching train. Light rail trains typically have several different audible warning devices, including an emergency signal. However, standard air-pressure train horns on FRA-compliant trains do not take advantage of modern technologies such as sirens or electronic acoustic sources; neither do they use the latest developments in EWS designs.

In the last few years, the widespread use of smart phones, iPads, and other portable electronic devices has hindered people's ability to clearly hear the standard horn. Many trespassers use headphones or earbuds to listen to music while crossing the railroads' right-of-way and this decreases their ability to hear/detect the standard horn sound. Modern electronic acoustic sources are essentially loudspeakers that can reproduce directive sounds. With the use of such devices on locomotives, an effective EWS can be developed to better warn railroad trespassers and railroad workers of oncoming trains and thus save lives.

4.1 Test Participants

For this study, researchers solicited 35 employees from both QNA and from HMMH—an internationally known company specializing in rail noise, vibration studies and evaluations. HMMH is near QNA and the two companies have worked together on several noise and vibration projects for more than two decades.

4.1.1 Requirements of Participation

As a participant of this study, subjects must read and sign the informed consent form prior to beginning the study. Then participants are asked to complete the daily activities and responsibilities associated with their job description. The session will be scheduled so as to minimize interferences with their job responsibilities. The QNA or HMMH staff will provide an overview of the study, expectations for participation, as well as answer any questions the subject may have about the study. No additional requirements are necessary to participate in this study.

4.1.2 Compensation

The subject's participation in the study will be funded on company time. If the subject is an employee of QNA or HMMH, these companies will provide compensation for their employees who choose to participate.

4.2 Equipment

The study requires a computer laptop running a programmed PowerPoint slide show. Researchers will equip each subject with a specific manufacturer and model of headphones. The study program will be calibrated to reproduce sounds at listening levels that will not exceed Occupational Safety and Health Administration (OSHA) occupational noise limits. The sound level output of the system will be calibrated to generate the maximum desired sound level at maximum laptop volume. By doing so, noise levels in excess of those intended cannot be physically reproduced by the system. Actual in-ear sound levels will be calibrated using a sound level meter to measure headphone output levels. There will be a calibration segment to allow the participants to lower the volume on the computer to comfortable listening levels if the maximum volume is disturbing.

4.3 Testing Procedures

The study will include the following procedures:

1) The participant will meet with one of the investigators. The participant will read and sign the consent form. The participant is welcome to ask any questions about the study, expectations, or other issues. The investigator will give the participant as much time as he/she needs before signing the consent form.
2) Once consented and questions are properly answered, the participant will be seated at a desk with a computer in an office. The investigator will provide instructions on how to begin and proceed with the study.
3) The participant will be asked to place the headphones on their head, with comfort in mind.
4) The study program will begin showing images of a fire engine, ambulance, train, police car, railroad track, grade crossing, and streets. These images are not emotion provoking. Rather, the research team chose neutral pictures of just the objects themselves. For example, researchers will show a fire engine, but not a fire engine at the scene of an accident.
5) The participant will press a button on the screen using the mouse to begin the study.
6) The participant will be instructed to press a button to listen to a sample warning signal up to 30 seconds in length. The sample warning signal will be calibrated to be less than 100 dBA. The participant will be informed that this is a typical sound level they will be exposed to during the survey. If this is acceptable, they will proceed with the survey. If unacceptable, they will be asked to lower the volume of the computer to generate sound at a more comfortable listening level. The amplitude that they select will be recorded and the reduced decibel level of the system will be known. The participant will be asked to not change the volume during the survey. Should the participant experience discomfort, they are encouraged to alert the investigator immediately. The participant will be reminded that if they want to end the survey at any time, they are free to do so, without any penalty.
7) Participants will be asked general demographic information including:
    a. Age range (i.e., 18–25, 26–35, 36–45, 46–55, 56–65, 66–75, 75+)
    b. Gender (i.e., male or female)
    c. Dominant hand (i.e., left, right or ambidextrous [research suggests that hearing preference may be linked to handedness])
    d. Any known hearing loss (i.e., none, slight, moderate or significant)

   e. How often do you wear headphones and listen to music outdoors (i.e., daily, weekly, monthly or less than once per month)?

8) The participant will then be played a low sound level (i.e., less than 70 dBA) recording of typical urban/suburban ambient noise.

9) Participants will listen to EWSs for up to 20 seconds and be asked the following questions after each sound is played:

   a. **Does the sound cause you to feel a sense of urgency to move?** A slider bar will allow the participant to select a response within the range of “no urgency,” “slightly urgent,” “moderately urgent,” “very urgent” or “highly urgent.” Values between 1 and 5 will be assigned to these responses. Non-integer (i.e., 3.4) values will be recorded.

   b. **Can you identify the source of the sound?** They will select 1 of 6 options by pressing a button. The options will be “train,” “police,” “fire engine,” “ambulance,” “car alarm” or “other.”

   c. **How certain are you about the source of the sound?** A slider bar will allow the participant to select a response within the range of “not certain,” “slightly certain,” “moderately certain,” “very certain” or “highly certain.” Values between 1 and 5 will be assigned to these responses. Non-integer (i.e., 3.4) values will be recorded.

   d. **Is the sound startling?** A slider bar will allow the participant to select a response within the range of “not startling,” “slightly startling,” “moderately startling,” “very startling” or “highly startling.” Values between 1 and 5 will be assigned to these responses. Non-integer (i.e., 3.4) values will be recorded.

   e. **Is this sound annoying?** A slider bar will allow the participant to select a response within the range of “not annoying,” “slightly annoying,” “moderately annoying,” “very annoying” or “highly annoying.” Values between 1 and 5 will be assigned to these responses. Non-integer (i.e., 3.4) values will be recorded.

10) Participants will be played a 60-second sound clip. The sound clip will include broadband random noise (pink noise) as masking noise and will ramp up in amplitude the EWS. The participant will watch a video of animals (i.e., neutral and non-emotion provoking) as a slight distraction. The participant will be asked to press a button at the moment they hear the warning signal through the masking noise. The survey will record the time it took the respondent to hear the noise. Based on the amplitudes of the masking noise and the warning signal, the detectability of the sound will be computed after the survey.

11) Participants will hear the next 60-second sound clip. The same procedure as described in #9 will be followed except the music (i.e., neutral and non-emotional) will be used as the background instead of random noise.

12) Participants will listen to up to 10 more EWSs, be asked the same questions, and be asked to determine when they can hear the sound through pink noise and/or music.

13) Participants will then be asked to listen to two different warning signals in an A/B comparison. Participants will be asked the following question:

a. **Which sound causes you to feel a greater sense of urgency to move?** A slider bar will allow the participant to select a response within the range of "Sound A: highly more urgent," "Sound A: slightly more urgent," "no difference," "Sound B: slightly more urgent," or "Sound B: highly more urgent." Values between +2 and -2 will be assigned to these responses. Non-integer (i.e., 0.5) values will be recorded.
b. **Which sound are you more certain about identifying its source?** A slider bar will allow the participant to select a response within the range of "Sound A: highly more certain," "Sound A: slightly more certain," "no difference," "Sound B: slightly more certain," or "Sound B: highly more certain." Values between +2 and -2 will be assigned to these responses. Non-integer (i.e., 0.5) values will be recorded.
c. **Which sound is more startling?** A slider bar will allow the participant to select a response within the range of "Sound A: highly more startling," "Sound A: slightly more startling," "no difference," "Sound B: slightly more startling," or "Sound B: highly more startling." Values between +2 and -2 will be assigned to these responses. Non-integer (i.e., 0.5) values will be recorded.

14) Participants will listen to up to 20 more A/B comparisons of EWSs and be asked the same questions.
15) The computer program will let the participant know that the study is complete. The investigator will answer any questions the subject may have about their participation.

4.4 Safety

Sounds included in this study will be reproduced at in-ear sound levels between 80 and 90 dBA, and will not exceed 100 dBA. The entire study is expected to take 30 minutes, including a maximum of up to 30 minutes of noise exposure to warning signals. Based on the maximum possible sound level (100 dBA) and the maximum duration of the survey (30 minutes), the 8-hour time-weighted average (TWA) noise exposure will be a maximum of 80 dBA. This conservative estimate is well below the OSHA 8-hour TWA noise limit of 85 dBA which would require the employer to institute a hearing conservation program and below the 8-hour TWA noise limit of 90 dBA which would require the employer to introduce hearing protection. Therefore, this survey is not anticipated to cause an adverse impact to the participants' noise exposure. If at any point in the study, the participant experiences discomfort, the investigator can adjust sound levels. If the participant wishes to discontinue the study, the investigator will immediately end the session without any consequences to the participant.

4.5 Data Management Plan

Participants will be assigned a unique number and each participant's data will be labeled with this number. The only permanent record of the individual's name will be on the consent forms. The consent forms do not contain the participant's number; therefore, at no point can the individual's name be linked to the participant number. A locked filing cabinet stored the consent forms.

Collected data will be labeled with the participant number only. This data will be stored on a secure, password-protected QNA or HMMH computer accessible only by the investigators. Participants will be informed that only the researchers have access to their data and that their identities will not be disclosed to outside parties in any form. No individual identifying information will be used in reports and/or publications.

5. Conclusion

This study indicates that there is a potential to create a more effective EWSs which meets the goals of increasing sense of urgency, reducing the signal-to-noise ratio at which detection occurs while maintaining the identification of the noise source and association of the EWS sound with that of a train.

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

The most effective candidate signal was shown to be a mix of the analog baseline standard train horn and digital baseline. It includes the analog signal of the fundamental horn tones and digital versions of all the harmonics which are modulated 2 percent at a modulation frequency of 15 Hz.

Additionally, amplitude modulation of +/- 6 dB at 10 Hz was applied to these harmonics.

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

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

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

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

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Appendix A.
Sense of Urgency Demographic Results

Emergency Warning Signal Sense of Urgency Survey

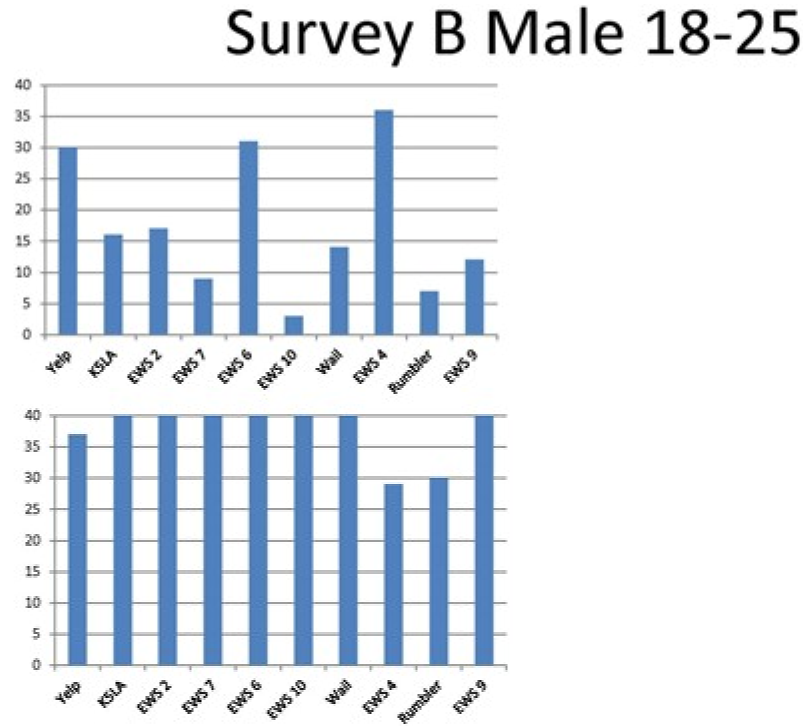

Figure A1. Survey B Male 18–25

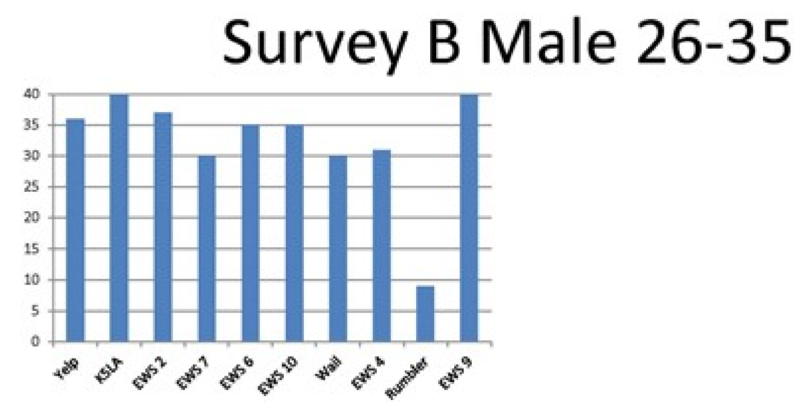

Figure A2. Survey B Male 26–35

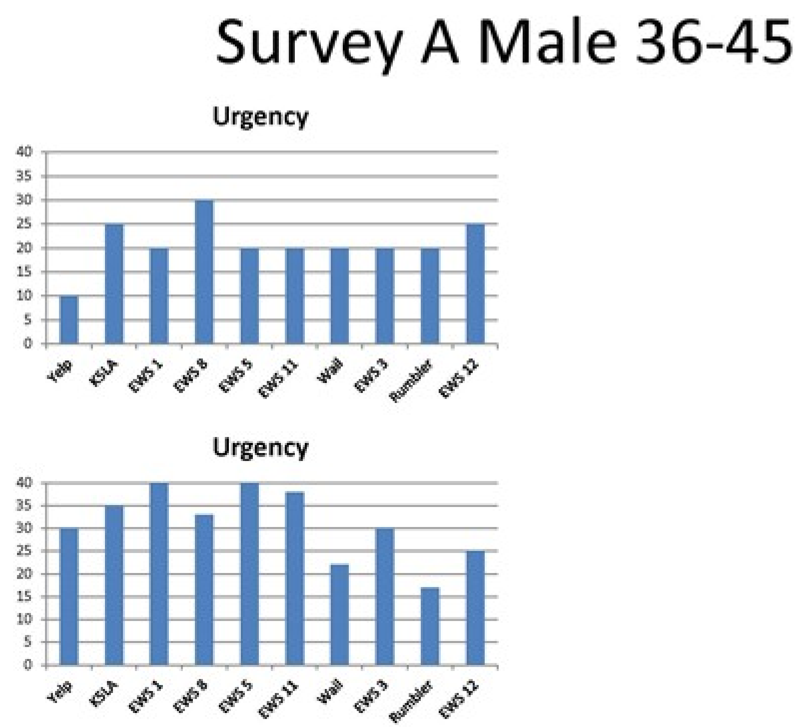

Figure A3. Survey A Male 36–45

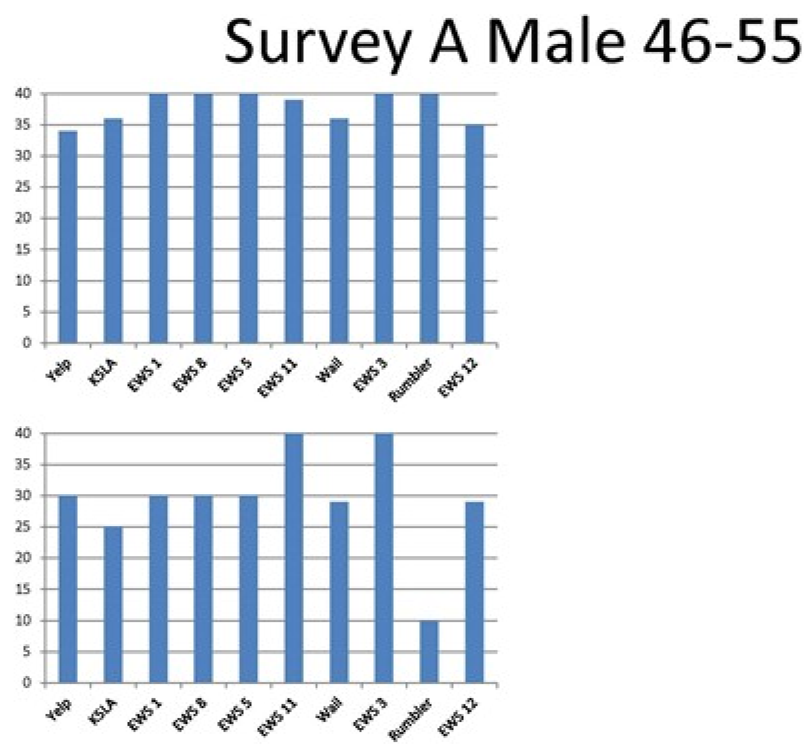

Figure A4. Survey A Male 46–55

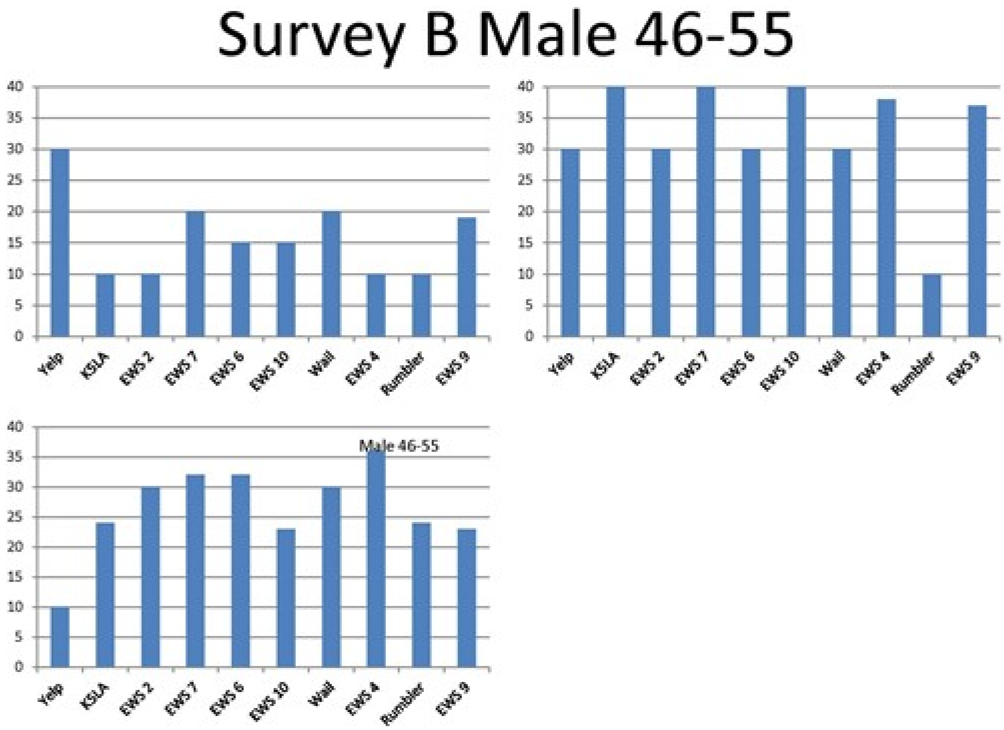

Figure A5. Survey B Male 46–55

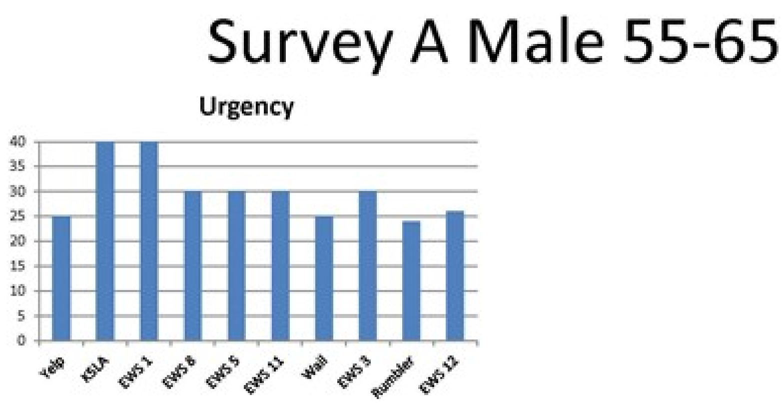

Figure A6. Survey A Male 55–65

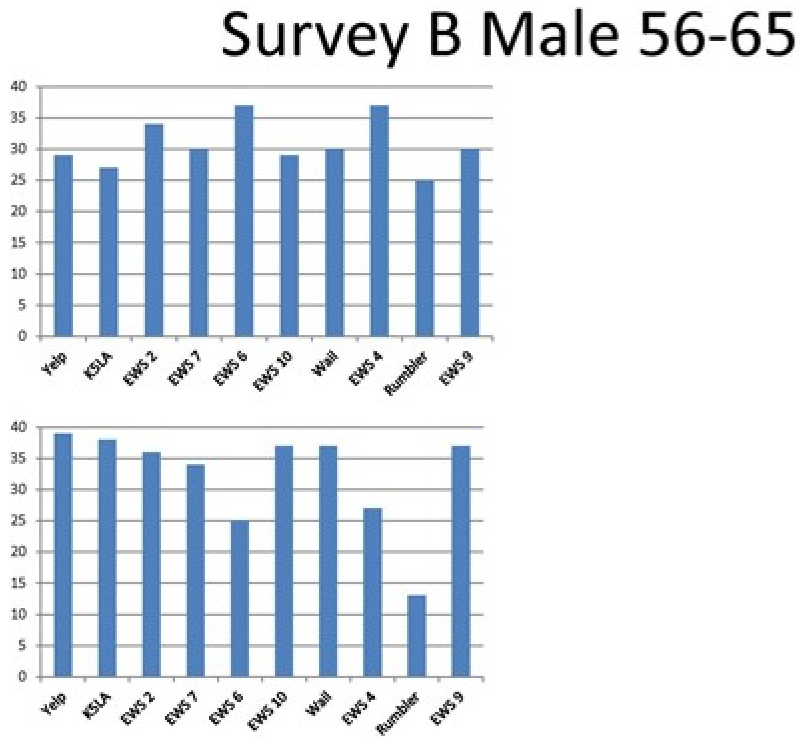

Figure A7. Survey B Male 56–65

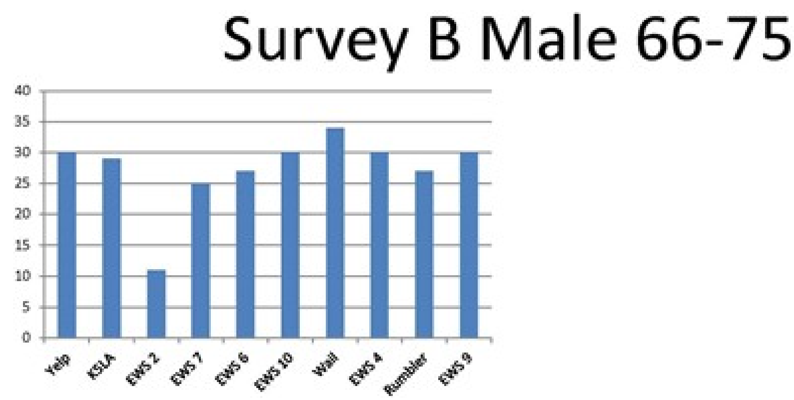

Figure A8. Survey B Male 66–75

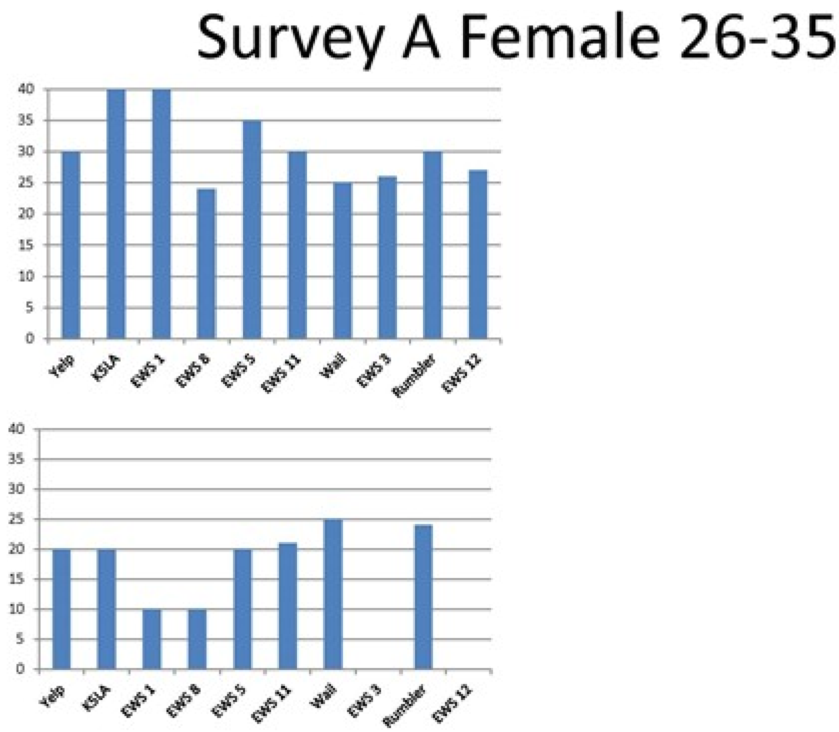

Figure A9. Survey A Female 26–35

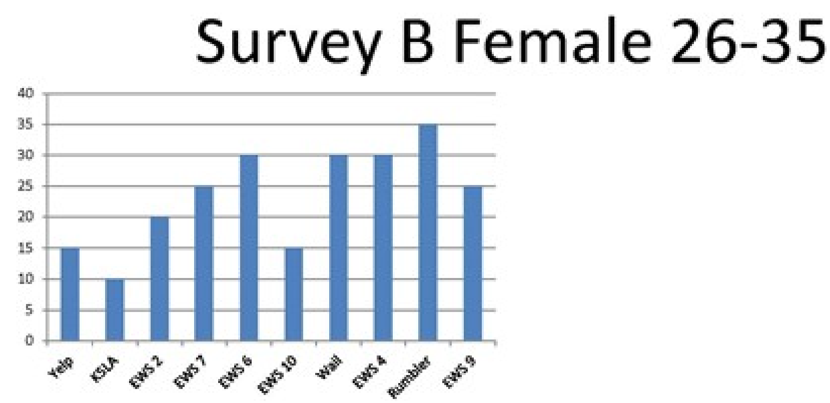

Figure A10. Survey B Female 26–35

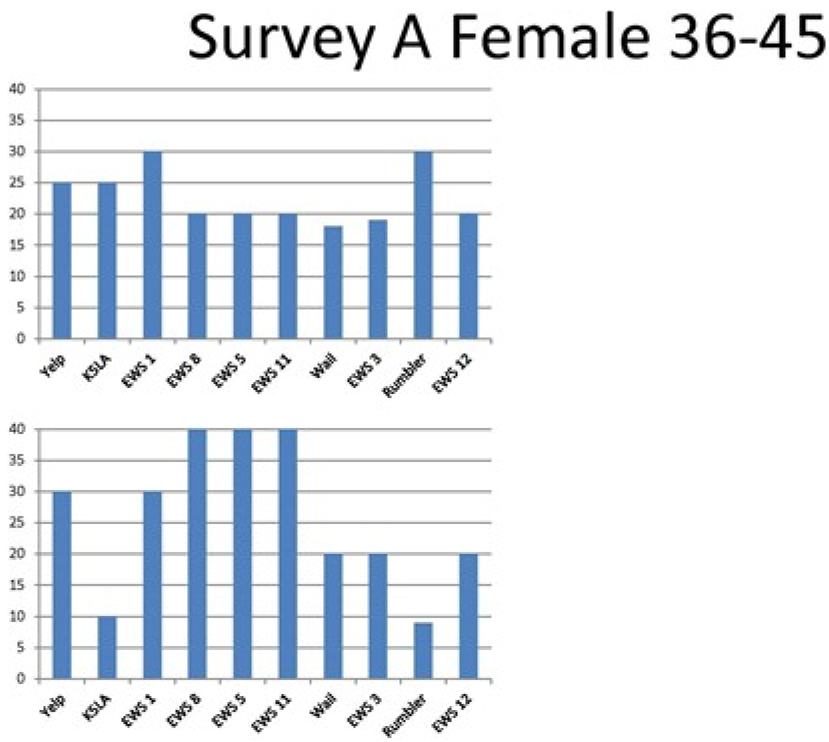

Figure A11. Survey A Female 36–45

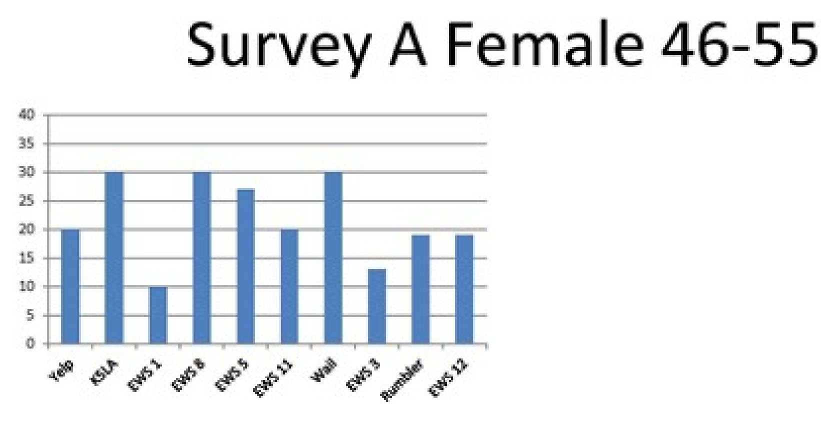

Figure A12. Survey A Female 46–55

Abbreviations and Acronyms

ACRONYMS	EXPLANATION
AWD	Acoustical Warning Device
ANC	Active Noise Cancellation
EWS	Emergency Warning Signal
FRA	Federal Railroad Administration
HMMH	Harris Miller Miller & Hanson Inc.
IRB	Institutional Review Board
OSHA	Occupational Safety and Health Administration
QNA	QinetiQ North America
TWA	Time-weighted Average
TTCI	Transportation Technology Center, Inc.