An Evaluation of Laboratory and Test Road Environments and Electric Vehicle Warning Sounds and Systems

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ABSTRACT

The number of electric vehicles on the road is increasing rapidly every year. Due to the decreased sound produced by these vehicles at low speeds, there is significant concern that pedestrians and bicyclists will be at increased risk of vehicle collisions. This is particularly true for those with vision impairment who cannot rely on visual cues to alert them of an approaching vehicle. This thesis explores pedestrian aural detectability of six electric vehicle additive sounds produced by two additive sound systems: a modified version of the factory equipped system and a prototype exciter transducer-based system. All additive sounds and systems were first evaluated for regulatory compliance at stationary, 10 km/h, and 20 km/h conditions and then pedestrian detectability was assessed using 16 blind folded participants and on-road drive by tests. Participant drive by tests were then replicated using 3D sound field recordings played in a high-fidelity immersive reality lab. Results were used to verify the accuracy of lab environment and its potential applicability to future testing. The exciter transducer acoustic warning system was found to created more uniform sound levels on the passenger and drivers' sides of the vehicle than the factory system but produced lower sound levels on the front side of the vehicle. Additive sound modulation rate was not determined to be a key differentiator in pedestrian detectability and low frequency emphasis sounds were found to have the highest level of pedestrian detectability. As expected, vehicle speed played a critical role in participant detection with the 20 km/h speed condition producing higher average detection distances. The immersive reality lab was found to not replicate on-road environment however a perceived linear offset was observed between the two environments.

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GENERAL AUDIENCE ABSTRACT

The number of electric vehicles on the road increases every year due to growing consumer demand for clean and sustainable transportation. Due to the decreased sound produced by these vehicles at low speeds there is significant concern that pedestrians and bicyclists will be at increased risk of vehicle collisions. This is particularly true for those with vision impairment who cannot rely on visual cues to alert them of an approaching vehicle. This thesis explores pedestrians' ability to detect six electric vehicle additive sounds produced by two sound systems: a modified version of the factory equipped system and a prototype system designed to produce uniform sound around the vehicle. All sounds and systems were evaluated see if they met current regulations at stationary, 10 km/h, and 20 km/h conditions. Pedestrians' ability to detect the vehicle was assessed using 16 blind folded participants and on-road tests where participants were asked to press a button when they heard an approaching vehicle. Participant drive by tests were then replicated using recordings taken on the same section of road and played in a lab environment. Results were used to see if the lab environment matched the results seen on the road. The prototype system created more uniform sound levels on the passenger and drivers' sides of the vehicle than the factory system but consistently produced lower sound levels on the front side of the vehicle. Sound modulation rate was not determined to be a key differentiator in pedestrian detectability and low frequency emphasis sounds were found to be the most easily detected by pedestrians. As expected, vehicle speed played a critical role in participant detection with the 20 km/h speed condition producing higher detection distances. The lab environment was found to not replicate on-road environment however similar offsets and sound ordering was observed between the two environments. Further work will be needed assess and correct this disagreement.

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List of Abbreviations

Abbreviation	Definition
AM	Amplitude Modulation
ANOVA	Analysis of Variance
ASPIRE	Acoustics Signal Processing and Immersive Reality
AVAS	Acoustic Vehicle Alert System
CDC	Center for Disease Control and Prevention
DAQ	Data Acquisition System
DAS	Data Acquisition System
DAW	Digital Audio Workstation
DGPS	Differential Global Positioning System
EU	European Union
EV	Electric Vehicle
EVADER	Electric Vehicle Alert for Detection and Emergency Response
FM	Frequency Modulation
FMVSS	Federal Motor Vehicle Safety Standard
GBD	Global Burden of Disease
GM	General Motors
GVWR	Gross Vehicle Weight Rating
HE	Hybrid Electric
HEV	Hybrid Electric Vehicle
IABP	The International Agency for Blindness Prevention
ICE	Internal Combustion Engine
IVSS	Intelligent Vehicle Safety Systems
MIDI	Musical Instrument Digital Interface
NHTSA	National Highway Traffic Safety Administration
OEM	Original Equipment Manufacture
PSEA	Pedestrian Safety Enhancement Act
SAE	Society Automotive Engineers
SPL	Sound Pressure Level
UN	United Nations
UNECE	United Nations Economic Commission for Europe
VTTI	Virginia Tech Transportation Institute

Introduction

This introductory chapter aims to acquaint the reader with the magnitude of the hazards posed to the visually impaired by electric vehicles (EVs), and review previous research done in this field.

Motivation

Electric Vehicle Growth and Hazards

Due to advances in technology, governmental pressures and environmental concerns electric vehicles (EVs), are soaring in popularity all around the world [1]. EV's can travel further and be recharged more quickly and conveniently than in the past, which has gained them increased popularity as a practical and environmental alternative to internal combustion engine (ICE) vehicles. Being more environmentally friendly and cost effective, it is no surprise globally EV sales are growing at rates 3 to 8 times higher than internal combustion engine vehicles in the light duty passenger car category [2]. In a recent study by PEW research center "about four-in-ten Americans (39%) say that the next time they purchase a vehicle, they are at least somewhat likely to seriously consider electric" this number is likely to rise as awareness of electric vehicles increases and manufactures come out with more vehicle options [3]. Growth rates are compounded with new governmental initiatives aimed at requiring new passenger and midsized vehicles to be electric. Most notable of these initiatives is the International Zero Emission Vehicle Alliance where 18 different countries, states, and provinces have come together and agreed to require all new passenger vehicles to be zero emission by at latest 2050 [4]. Of the 18 members of the alliance, seven -British Columbia, California, Canada, the Netherlands, Norway, the United Kingdom, and Quebec - have agreed on earlier goals [4]. It has no longer become a question of if electric vehicles will be the future of transportation, but how long it will take for them to be the main source of transportation.

There are a variety of differences between EVs and ICE vehicles besides the environmental benefits mentioned above, but most pertinent to this research is the fact that EVs make significantly less noise than their ICE counterparts. Vehicle noise sources can be divided into three main categories: wind noise, tire noise, and drivetrain noise. The wind and tire noise are often grouped together and are common between both electric vehicles and their ICE vehicle counterparts. Wind and tire noise sources are the dominant factor for pedestrian vehicle detection

when the vehicle is at speeds greater than 20mph and there is little difference between pedestrian detection of electric vehicles and ICE vehicles at these speeds [5]. At lower speeds common in pedestrian heavy environments such as parking lots and city streets the relative significance of drivetrain noise increases, and noise levels of EVs drop below ICE vehicles. This can range anywhere from 20 dBA at 0 km/h to 6dBA at 10 km/h, according to a Japanese study aimed at assessing the acoustic difference between EVs and ICE vehicles, and the necessity of additive noise devices on electric vehicles[6,7].

Pedestrian Hazards

Decreased audibility of electric vehicles has been a cause for concern for pedestrian groups who believe there will be an increase in accidents due to vehicles being more difficult to hear. Of these pedestrian groups those who are visually impaired, or blind have been especially worried. People navigate based on information they have gained from their environment such as curbs, sloped curb ramps, audible warnings, and traffic sounds [5]. Navigation becomes more difficult when fewer of these cues are available. For example, at an unprotected intersection there may not be a ramped curb or audible warning from a crosswalk button; a visually impaired pedestrian must rely on their sense of hearing to orientate themselves and decide if it is safe to cross the road. These decisions become much more difficult as the noise from a vehicle decreases as it does with an EV. There is concern that as the percentage of EVs on the road increases it will become significantly more difficult for pedestrians to navigate safely and there will be an increase in pedestrian collisions. These fears are corroborated by a recent survey in Australia, a country who at the time did not have EV additive noise requirements, which found a staggering 35 percent of visually impaired pedestrians have had a collision or near collision with an electric vehicle [8].

Regulatory Action

Due to these concerns, regulations have been put into place in many countries requiring electric vehicles to meet certain noise requirements to safely operate on public roads. Globally there are two main regulatory bodies that have set the pace for global regulation: the National Highway and Traffic Safety Administration in the United States and the Economic Commission for Europe of the United Nations (UNECE) in Europe. The United States has established the Federal Motor Vehicle Safety Standards (FMVSS) *No. 141, Minimum Sound Requirements for Hybrid and Electric Vehicles* requiring auto manufactures to comply with the new regulations by

2018 [9]. The UN established *UN R138 Uniform provisions concerning the approval of Quiet Road Transport Vehicles with regard to their reduced audibility* and required manufactures to comply with the regulation by 2016 [10]. These regulations have been used around the world by countries implementing EV noise requirements with national regulations being either based upon one of these two regulations or the direct application of one of these two regulations[11]. The use of these regulations is summarized in Figure 1.

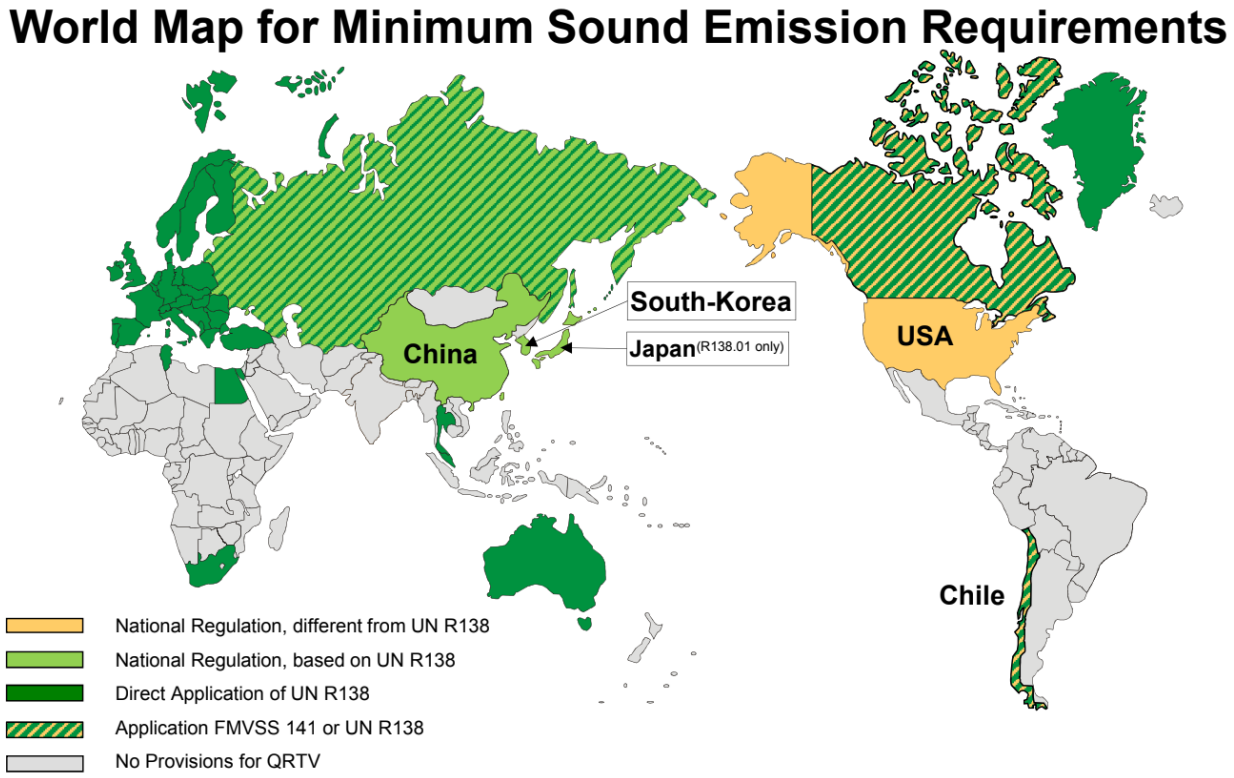

Figure 1 World Map for Minimum Sound Emission Requirements [11]

Production Solutions

Manufactures have addressed quiet vehicle regulations by designing additive noise systems into their vehicles that emit noise when the vehicle is moving within the regulatory speed region. These systems generally consist of one or more speakers mounted underneath the vehicle and an amplifier that plays additive sounds. The sounds are designed to augment the desired personality of the vehicle while providing the volume and frequency content to meet regulations. For example, according to an article by Shift the Porsche Taycan embodies "the essence of control, speed, and power into a sound" and the Chevy Volt has an "enigmatic yet mysterious hum that all spas play to distract us from the chaos of the outside world and provide us an aural cushion on which to rest our weary souls" [12]. These production solutions are

effective at meeting regulatory limits ,but have been critiqued for adding excessive noise pollution to their surroundings [13]. This is at least partially due to the increased volume required from single point source sound generation systems. Since the lowest volume measurement location around the vehicle is used to meet regulatory requirements, the volume of the total additive sound must be raised, causing some locations around the vehicle to be louder than necessary.

A common way of assessing the effectiveness of these warning systems is by conducting on road participant drive by tests [14]. Participants are seated adjacent to a test road and given a way of indicating when they hear a vehicle approaching, this is typically a handheld button to press. A test vehicle is then driven down the test road while playing different warning noises. The distance and speed of the vehicle is recorded, as are the participants button presses. This allows researchers to detect the distance of the vehicle was when the button was pressed and if a possible collision would have occurred. This testing methodology provides a good metric at assessing the effectiveness of additive sounds, but is time intensive, less controlled, and susceptible to noise and weather disruptions that cause tests to need to be redone. These interruptions and alterations in testing environment lead to increased cost and time spent on the test road as well as heightened variation between testing groups.

Research Goals

Our research aims to address the following key concepts in the field of EV additive sound.

1. Analyze and quantify the effect that different additive sound frequency content and modulation speed have on pedestrian vehicle detection.
2. Design and verify a prototype additive sound generation system to explore if it can provide a more uniform sound around the test vehicle and lower maximum sound pressure level.
3. Compare and contrast the new additive sound system with the factory sound system in stationary, drive by, and participant drive by tests.
4. Compare on road participant tests with participant tests done in a laboratory environment. Validate or invalidate the virtual acoustic testing environment and procedure.

Review of Literature

Problem Assessment

To determine the necessity of additive noise systems in electric vehicles the following topics were researched and reviewed.

Prevalence and Growth of Vision Impairment

To assess the magnitude of vision impairment both globally and in the United States, statistics of vision impairment and blindness were reviewed. This was done to see the percentage of people that will be potentially affected by the lower sound levels of electric vehicles.

According to The International Agency for Blindness Prevention (IABP), globally blindness and vision impairment are not uniform, but rather corelated to numerous factors such age, gender, and region. The prevalence of blindness and vision impairment increases with age, with cataracts, presbyopia, age-related macular degeneration, and glaucoma being the main causes for vision deterioration [15]. Vision impairment is also not uniform across genders. Women are 12 percent more likely to have some sort of vision impairment and 8 percent more likely to be blind. This is due to three main factors: women have a longer life expectancy, are more prone to vision impairments such as cataracts and trachomatous trichiasis, and in certain countries women have less access to health care and vision treatments. Blindness and vision impairment are also much more prevalent in certain regions of the world than others "the GBD super regions Southeast Asia, East Asia and Oceania and South Asia are home to 52% of the world's population yet have 64% of the global burden of vision loss. Conversely, the High-income region has 14% of the global population, yet is home to only 7% of the global burden of people who are vision impaired."

Despite medical care and treatment, the United States still has a large population of people with vision impairments. This population is steadily growing and is expected to grow to 8.96 million people by 2050 [16]. According to the Center of Disease Control (CDC) approximately "12 million people 40 years and over in the United States have vision impairment, including 1 million who are blind, 3 million who have vision impairment after correction, and 8 million who have vision impairment due to uncorrected refractive error". Eye impairment does not only affect adults, in fact about 6.8% of children in the United States under the age of 18 have vision problems and 3% are blind or visually impaired even when wearing glasses or contacts. The severity of vision impairment is enlarged due to peoples' inability/unwillingness to

visit an eye doctor. In fact, “an estimated 93 million adults in the United States are at high risk for serious vision loss, but only half visited an eye doctor in the past 12 months”.

With better nutrition and health care, the average life expectancy of humans is growing globally each year. However, eye care and vision treatment are not growing at the same rate. This causes there to be a larger older population which is more likely to be visually impaired. Consequently, a larger number of people each year have some form of vision impairment develop.

Increased Dangers Posed by EVs

The necessity of electric vehicle pedestrian warning systems for EVs and hybrid electric (HE) vehicles were originally proposed by pedestrian safety advocacy groups and the National Federation of the Blind. NHTSA then substantiated the need for these regulations by examining pedestrian crash statistics initially in 2009 and then again in 2011 when more accident data was available. In 2011, NHTSA performed a background study evaluating the number of automotive accidents involving pedestrians and cyclists. The study “was conducted on a total of 24,297 HE and 1,001,100 ICE Honda and Toyota selected vehicles in 16 States. A total of 186 and 5,699 HE and ICE vehicles respectively were involved in pedestrian crashes. A total of 116 and 3,052 HE and ICE vehicles respectively were involved in bicycle crashes” [17]. Extrapolating these crash statistics to the general population of EVs and ICE vehicles NHTSA concluded that hybrid electric vehicles were about 35% more likely to be involved in pedestrian crashes, and 57% more likely to be involved in a cyclist crash compared to an ICE vehicle. The study compared the probability of a vehicle being in an accident using an odds ratio (OR) and found that HE vehicles were the most likely to be involved in pedestrian crashes “with speed limits of 35 mph and lower (OR = 1.39), during low-speed maneuvers (OR = 1.66) and when the crash is on the roadway (OR = 1.50).” This study helped to strengthen the case for minimum sound requirements for electric vehicles in the United States and was used as justification for regulations globally.

More recently in 2018 Vision Australia and Monash University Accident Research Centre conducted a study aimed to gauge the level of risk quiet vehicles posed to the visually impaired [8]. The research consisted of a literature review from the past ten years, a focus group workshop and a community survey. The focus group workshop, and the community survey give insight into the experiences of the visually impaired and the level of risk they experience due to electric vehicles. The focus group workshop concluded that in general there was increased

concern when navigating roadways due to the reduced noise level of electric vehicles, but these concerns can be partially alleviated with orientation and mobility training. These trainings help to develop "strategies to establish routine, using other sensory modalities – such as hearing and touch, and the ability to identify markers in the environment" which allow for the pedestrian to navigate more efficiently and safely. The community survey was conducted with 246 participants across Australia of which 75% reported that they walk daily or almost daily, 42% reported that they mainly walk unassisted. "Of the total participant sample, 35% reported having experienced either a collision or near-collision with an electric / hybrid vehicle. Of this 35%, 14% reported at least one collision, 77% reported at least one near-collision, with a further 9% reported having experienced at least one collision and one near-collision." Additionally, 74% of respondents had reduced confidence navigating walkways and crossing roads with the increase of quiet vehicles on the road. Respondents also reported that they felt that countermeasures such as additive sounds on electric vehicles and increased awareness to the public of the risks posed to visually impaired by EVs would be the most effective at reducing the risk towards the visually impaired.

Regulations

In this section the main regulations governing EV additive sounds will be reviewed: FMVSS No. 141, "Minimum sound for hybrid and electric vehicles" and Regulation No 138 of the UNECE "Uniform provisions concerning the approval of Quiet Road Transport Vehicles with regard to their reduced audibility."

FMVSS No. 141, "Minimum sound for hybrid and electric vehicles"

In the United States EV additive sound regulations were initiated in 2010, with the US Pedestrian Safety Enhancement Act (PSEA) [18]. This law addressed the following three requirements:

1. Determine the minimum level of sound emitted from a motor vehicle that is necessary to provide blind and other pedestrians with the information needed to reasonably detect a nearby electric or hybrid vehicle operating at or below the cross-over speed, if any.
2. Determine the performance requirements for an alert sound that is recognizable to a pedestrian as a motor vehicle in operation
3. Consider the overall community noise impact.

With these requirements FMVSS No. 141, “Minimum sound for hybrid and electric vehicles” was established. Auto manufactures were originally required to have all new vehicles comply with this standard by 2018, however due to auto maker petitions the following compliance schedules were established: “50 percent of light HEVs manufactured between September 1, 2019 and August 31, 2020, and all light HEVs manufactured on or after September 1, 2020 must comply with the FMVSS 141” [19].

FMVSS 141 applies to-

1. Electric vehicles with a gross vehicle weight rating (GVWR) of 4,536 Kg or less that are passenger cars, multipurpose passenger vehicles, trucks, or buses;
2. Hybrid vehicles with a gross vehicle weight rating (GVWR) of 4,536 Kg or less that are passenger cars, multi-purpose passenger vehicles, trucks, or buses; and
3. Electric vehicles and hybrid vehicles that are low speed vehicles.

FMVSS 141 evaluates vehicles at five vehicle speed conditions: stationary to speeds up to 10 km/h, speeds greater than 0 km/h and less than 20 km/h, speeds from 20 to 30 km/h, speeds from 30 to 32 km/h and in reverse [20]. There are two ways manufacturers can meet the FMVSS No. 141 regulation. The first way is to meet A-weighted sound pressure level requirements for four nonadjacent one-third octave bands spanning no fewer than 9 of the 13 bands from 315 to 5,000 Hz. In the second method an additive sound must meet A-weighted sound pressure levels in two nonadjacent one-third octave bands from 315 to 3,150 Hz and meet a calculated band sum requirement, if it meets a minimum A-weighted sound pressure level in each band and a band sum requirement. Of the two bands used to meet the requirement, one of the two one-third octave bands must be from 315 to 800 Hz and the other must be from 1,000 to 3,150 Hz. Tables showing the A weighted sound pressure levels for both the four band and two band options can be found in appendix 1 and 2 respectively. In addition to meeting the octave band requirements, additive sounds must change in volume to indicate a change in vehicle speed.

Regulation No 138 of the UNECE "Uniform provisions concerning the approval of Quiet Road Transport Vehicles with regard to their reduced audibility".

Following the United States' decision to implement quiet vehicle additive sound laws the European parliament and the Council of the European Union determined the need for AVASs in EVs due to the heightened risk posed to pedestrians [21]. In 2017 UNECE regulation No. 138 "Uniform provisions concerning the approval of Quiet Road Transport Vehicles with regard to their reduced audibility" was passed, and required manufactures to add AVAS to all new types of electric and hybrid vehicles by 2019, and to all new electric and hybrid vehicles by 2021[22]. This regulation was justified by the Electric Vehicle Alert for Detection and Emergency Response (eVADER) project. The eVADER project was sponsored by the EU and researched optimal additive sounds, signal performance verse acoustic landscape, and integration between IVSS, environment information and acoustic warning signal. This research determined what was included in the later proposed EV additive noise regulation.

Regulation No. 138 of the UNECE (UN R138) is either used directly or as the basis for regulations in most of the countries that have implemented regulations for minimum sound levels for electric vehicles. "This regulation applies to electrified vehicles of categories M and N which can be propelled in the normal mode, in reverse or at least one forward drive gear, without an internal combustion engine operating in respect to their audibility" [10,23].

UN R138 requires vehicles not meeting specified sound requirements to have additive sound devices to increase vehicle audibility. The regulation mandates vehicles have additive noise when travelling under 20 km/h that satisfy minimum SPLs in two one-third octave bands. Vehicles are evaluated by performing tests at both 10 and 20 km/h as well as when the vehicle is in reverse. A table summarizing these sound levels can be found in appendix 2. Additionally, it requires one of the satisfied bands to be below or within the 1600 Hz one-third octave band. To signify changing vehicle speed "At least one tone within the specified frequency range must vary proportionally with speed by an average of at least 0.8% per 1 km/h in the speed range from 5 to 20 km/h inclusive when driving in the forward direction" [24]. UN R138 is also unique in that it requires vehicles to emit noises below a maximum overall SPL of 75dBA.

EV Additive Noises

EV Warning Noise Characteristics and Blind Verse Sighted Participants

Since the blind and visually impaired are major stake holders in this research it is important to establish if similar results can be expected from visually impaired and non-visually impaired subjects during vehicle drive by tests and if it is appropriate to utilize more conveniently recruited non-visually impaired participants. It is also necessary to review past research on effective EV additive sounds to help guide the development of new potential additive sounds.

In a previous study done by Parizet et. al and sponsored by the eVADER project nine different EV additive sounds were assessed and compared to a quiet EV and a diesel vehicle using 100 sighted and 53 blind participants [25,26]. The goal of this study was to address if visually impaired pedestrians can detect vehicles faster than non-visually impaired pedestrians and to determine what additive sound characteristics are most efficient at increasing the audibility of electric vehicles. The study was conducted using recordings of an EV synthesized with the nine different additive sounds and a recording of a similar diesel vehicle. The additive sounds were "designed to differ in particular sound features such as FM, AM or the number of harmonics" and were developed to simulate the vehicle approaching from both the left and the right. Participants were then played recordings with overlayed background noise (simulating a wet or dry roadway) in a lab environment and asked to indicate as soon as possible if the vehicle was approaching from the left or the right. The response times for each vehicle were recorded. Through conducting a three factor ANOVA test (sighted verse blind, warnings sound used, and wet verse dry background noise) it was determined that there was a non-significant relationship between the reaction time and sighted verse blind participants. It was also concluded through the same ANOVA analysis that there was a statistically significant three-way interaction "indicating that the effect of the sounds differed for blind and sighted participants as a function of the background noise condition used". To determine the effect that different additive sound characteristics had on reaction time a three factor three level "ANOVA was performed on the mean individual reaction times of all participants (blind or sighted) and provided evidence for significant main effects for all three factors: Frequency modulation [$F(2, 974) = 173$, $p < .001$], number of harmonics [$F(2, 974) = 137.7$, $p < .001$], and amplitude modulation

[$F(2, 974) = 159.1$, $p < .001$], the effects sizes being quite similar for all three factors". Through this ANOVA analysis it was determined that the most ideal additive sound would contain the smallest number of harmonics, no frequency modulation and maximal amplitude modulation.

In another study done by Belenguer et al three different additive sounds were developed: an intermittent warning tone, a tone replicating an ICE, and a synthesized tone modeled off a Nissan EV additive sound [27]. A system was developed to monitor the background noise and play the additive sounds to volunteer pedestrians on different streets in Spain to allow for varied background noise levels. While the paper did address dynamically adjusting the noise levels to meet requirements with different background noise levels, the most pertinent to this research is the surveys conducted with participants in which they ranked the warning noises in terms of detectability, satisfaction, and preference. The intermittent warning tone was found to be the most detectible, followed by the ICE tone, and then the synthesized tone. Inversely, 84% of pedestrians found the synthesized tone to be the most preferable, followed by the ICE tone (14%), and then the intermittent tone (2%). The pedestrian's satisfaction with the additive sound was found to follow the same trend as their preference. This survey highlights the opposing requirements from an EV additive sounds and the subsequent conflict of developing a detectible additive sound that is also not annoying to pedestrians.

Past Work by Research Team

To efficiently develop additive sounds, conduct on-road participant tests, and evaluate test data past research conducted by Dr. Mike Roan of Virginia Tech and Dr. Luke Neurauter's of Virginia Tech Transportation Institute (VTTI) research team will be leveraged. These past works will be referenced and briefly summarized in this section.

Phase One Research Efforts

In 2015, the research team conducted a study to evaluate the appropriateness of the UNECE regulations. This was accomplished by recording the audio for four different vehicles at speeds of 10 and 20 km/h using methods described in UN R138. The acoustic measurements were then used to assess if the vehicles met regulations. The same vehicles were then used in participant drive by trials where participants were asked to press a handheld button when they heard a vehicle approaching and then release it when they felt it was safe to cross. This allowed for the research team to determine if participants were able to effectively hear an approaching vehicle and quantify the acoustics of the vehicle at the time of detection. With both sets of data

collected, the team was able to evaluate if the UNECE regulations were sufficient for alerting pedestrians and determine the acoustics at the time of detection [28,29].The results of these studies are summarized in the following two papers:

1. Roan, M., Neurauter, M. L., Moore, D., and Glaser, D., 2017, "Electric Vehicle Detectability: A Methods-Based Approach to Assess Artificial Noise Impact on the Ability of Pedestrians to Safely Detect Approaching Electric Vehicles," SAE Int. J. Veh. Dyn. Stab. NVH, **1**(2), pp. 352–361.
2. Neurauter, M. L., Roan, M., Song, M., Harwood, L., Moore, D., and Glaser, D., 2017, "Electric Vehicle Detectability by the Vision Impaired: Quantifying Impact of Vehicle Generated Acoustic Signatures on Minimum Detection Distances."

UNECE Vehicle Noise Testing

For this research, the following four vehicles were utilized:

1. 2011 Chevrolet Volt (EV, no additive sound)
2. 2014 Cadillac ELR (EV, production additive sound)
3. 2013 Toyota Prius (HEV, production additive sound)
4. 2013 Cadillac SRX (internal combustion engine)

The vehicles acoustics were evaluated by conducting drive by tests using the microphone set up laid out in UN R138 and displayed in Figure 2. Tests were conducted at 10 and 20 km/h as well as slowing from 20km/h to a stop. For each speed scenario audio, vehicle position and vehicle velocity were collected. The data collection system allowed these to be collected simultaneously so the vehicle's position was known for each audio measurement. The recordings were then trimmed to 10m before and after the microphones, and overall A weighted SPLs, A weighted 1/3 octave bands and average peak A weighted SPL was recorded for each vehicle. The drive by test audio was then examined and it was determined that all four vehicles met the UNECE requirements for both test speeds.

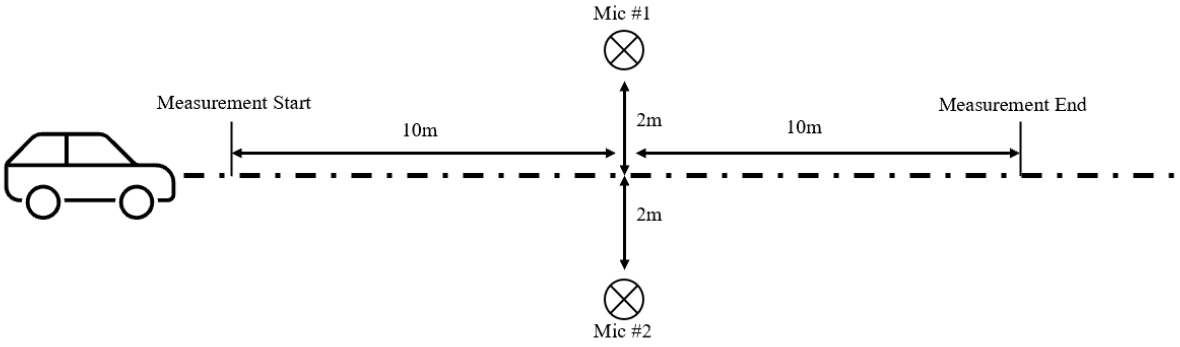

Figure 2 Vehicle Noise Testing Geometry

Pedestrian Drive by Testing

After the vehicles were evaluated to determine if they met the UNECE requirements, drive by tests were conducted to evaluate the distances at which pedestrians were able to hear an approaching vehicle, and when they felt that it was safe to cross the road. A total of 24 legally blind participants were recruited and divided into six groups. For these tests two different background noise levels (55dBA and 60 dBA), three speed conditions (10km/h, 20km/h and slowing from 20km/h to a stop), and the four vehicles described above were used. Each scenario was repeated three times resulting in 72 tests being conducted for each participant group.

Testing was conducted on an isolated, flat, and straight section of the VTTI Smart Road where there was low background noise. Six test sessions were conducted with one participant group being tested at a time. During each session participants were seated in barber chairs adjacent to the test road with a microphone placed over their head. The participants were blindfolded to eliminate the possibility of visual cues. This setup can be seen in Figure 3. A test vehicle was driven down the test road and participants were asked to press a handheld button when they heard the vehicle approaching and release it when they felt that it would be safe to cross the road as a pedestrian. The button presses were recorded using the same equipment that logged the vehicles position and the microphone data. This allowed the position of the vehicle and the acoustics that the participant was experiencing to be known at the time of detection.

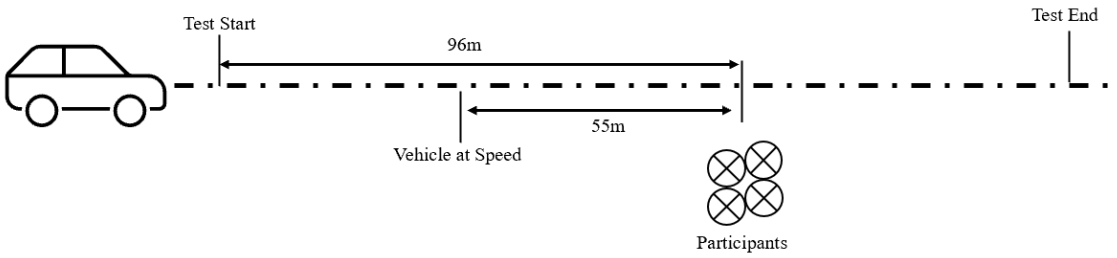

Figure 3 Participant Test Geometry

Phase One Results

Through the phase one testing it was found that all four vehicles had mean detection distances above the threshold suggested by NHTSA for both 10km/h and 20km/h. It was also found that there was a statistically significant difference in pedestrian detection distances between the ICE test vehicle and the other three test vehicles, and that the ICE vehicle was detected much more easily. There was not a large difference between the non-ICE vehicles. Detection distances were much bigger for 20km/h than 10 km/h, however this difference was the smallest for the Prius most likely due to smaller tire sizes. At 20km/h the detection distances were similar for all vehicles supporting the assumption that wind and tire noise play a leading role in vehicle noise at higher speeds. It was determined that the different levels of background noise had a significant impact on pedestrians' ability to detect the vehicles, with detection distances being lower for the higher level of background noise. "Detection distances fell approximately 33% for the 10 kph approach, ranging from a low of 29% for the SRX, to a high of 36% for the ELR. Similarly, the overall percentage drop in detection distances for 20 kph was approximately 29%, with a low of 21% for the SRX and a high of 35% for the Volt"[29].

Detection data was then analyzed to determine the extent and frequency of missed or late detection. While the extent of missed detections varied vehicle to vehicle, none of the test vehicles were immune to missed detections. The largest frequency of missed or late detections occurred at 10 km/h with 60dBA background noise. The Volt had the largest percentage of missed or late detection (41.7%), followed by the Prius and ELR (21.8%), and finally the SRX (10.1%). Missed detection varied significantly with the level of background noise. The "largest increase was observed for the ELR, with almost four times as many dilemma cases (7.1% at 55 dBA vs. 28.2% for 60 dBA). Neither the Prius nor the SRX were far behind, increasing by 3.3

and 3.5 times respectively. The Volt increased by approximately 2.9 times, resulting in the largest overall number of cases" [28].

Pedestrians' ability to detect when it was once again safe to cross the road was evaluated using the test case where the vehicle slowed from 20 km/h to stop, waited at a stop for 5s, and then continued moving. Results were categorized into three cases: "Miss, indicative of no or late responses; Early, indicative of a button release before the approaching vehicle came to a complete stop; and, while stopped, indicative of a button release following vehicle stop, but before the vehicle moved forward again (after 5s stoppage)." It was found that the Prius had the fewest number of missed cases (11.1%), followed by the ELR (33.3%), SRX (27.8%), and finally the Volt (38.9%).

Phase Two Research Efforts

In 2018 the team completed the second phase of EV additive sound research. In this phase the team evaluated only one vehicle: a Chevy Bolt. Two speakers were mounted to the front bumper of the Bolt and four different additive sounds were developed. The four additive sounds and a no sound case were then analyzed through stationary, drive by, and participant drive by tests. The tests were conducted in accordance with the FMVSS 141. From the participant tests probability of detection (Pd) curves were generated, allowing for the probability that a pedestrian would recognize a vehicle at a given distance to be assessed. The results of these studies are summarized in the following two papers:

1. Luke Neurauter, Michael Roan, Miao Song, Marty Miller, Eric Glenn, and Jacob Walters, 2020, Quiet Car Detectability Impact of Artificial Noise on Ability of Pedestrians to Safely Detect Approaching Electric Vehicles, #20-UT-078, Virginia Tech Transportation Institute.
2. Roan, M. J., Neurauter, L., Song, M., and Miller, M., 2021, "Probability of Detection of Electric Vehicles with and without Added Warning Sounds," J. Acoust. Soc. Am., **149**(1), pp. 599–611.

Stationary Tests

To evaluate each warning noises' compliance to FMVSS 141, stationary tests were conducted in accordance with the FMVSS 141 procedure and can be seen in Figure 4. The level of each warning noise was set to ensure that they met regulations. Due to the speakers mounted on the front bumper of the vehicle, it was found that "the overall A-weighted SPL in front of the

vehicle was 3–6 dBA above the lowest overall SPL for that sound"[14]. This was due to the test setup used for this phase which was inconsistent with the equipment that would be used in a production vehicle.

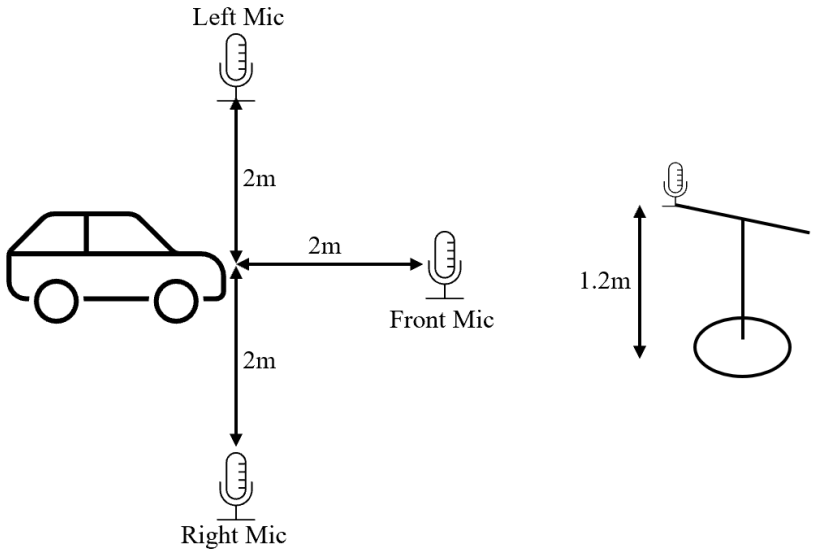

Figure 4 Stationary Test Geometry

Drive by Tests

Drive by tests were then conducted for each of the four additive sounds and the no noise condition at speeds of 10 and 20 km/h with the vehicle moving from the left to the right. These tests were conducted using methods similar to the FMVSS procedure (not all approach speeds were considered) and this geometry can be seen in Figure 2 above. These tests were conducted using the same stretch of the VTTI Smart Road used in the first phase of testing. It was found that the peak A-weighted overall SPL occurred at approximately 10m from the microphones when an additive sound was played and at 9m for the no noise condition. This once again gives credence to the directionality of the test setup used. Similar to the first phase of testing, an increase of approximately 10 dBA was observed for the A-weighted overall SPLs for all test cases when comparing 10km/h drive by tests to the louder 20km/h tests.

Pedestrian Drive by Testing

Using the same test setup from phase one testing and shown in Figure 3, participant testing was conducted for each sound condition. Sixteen participants were recruited for the study and vision impairment and age requirements were not specified. The participants were split into test groups of four participants and one participant group was tested at a time. Participants were

seated adjacent to the test road, blindfolded, and given a handheld button which they pressed to indicate when they heard a vehicle approaching. The participants were asked to release the button when they felt it was safe to cross the road. Background noise at levels of 55 dBA and 60dBA were played from five loudspeakers surrounding the participants and tests were conducted for the five sound conditions (4 additive sounds and 1 no sound condition) and at vehicle approach speeds of 10km/h, 20 km/h, and slowing from 20km/h to a stop. Each speed, background noise level, and additive sound condition was repeated four times (two approaches from the left and two from the right) for a total of 120 trials per session.

Phase Two Results

Phase two was analyzed by looking at the probability that a pedestrian was able to detect a vehicle at a given distance, as well as looking at the mean detection distances. The probability of detection (Pd) gives a better indication of a pedestrian's ability to detect a vehicle at a given distance and the mean detection distances allowed for comparisons between phase two tests, phase one tests, and regulations. Probability of detection was analyzed through the generation of Pd curves which conveniently displayed Pd verse distance. "The data from a 4 m window that corresponds to the length of the vehicle are used to calculate Pd and probability of missed detection directly. While a vehicle is in a given range cell, there are a fixed number of samples of the listener's button presses (1 for detection, i.e., button pushed, and 0 for no detection, i.e., no vehicle present). The total number of button-push data points in the range cell gives the number of opportunities to make a decision. As the vehicle was always present in the range cell, the Pd is the number of 1's in the range cell divided by the number of opportunities. The number of missed detections is 1-Pd (i.e., the vehicle is present, but listeners did not detect it). Sliding the range cell along the data set and averaging across data sets for a given scenario gives Pd vs distance for that scenario." [14].

Through the Pd curves it was confirmed that there were higher rates of detection when the vehicle was moving at the faster 20km/h speed condition than the 10km/h speed. All additive sounds provided mean detection distances greater than those suggested by the NHTSA regulation. All sounds except one resulted in Pd of 100% at the NHTSA suggested minimum detection distance of 11m at a background level of 60 dBA and speed of 20 km/h. The one sound that did not reach 100% detection reached 95% detection probability at the NHTSA suggested minimum distance of 11m. This sound had the lowest energy in the 1250 and 1600 Hz

1/3 octave bands. The team also found that the test sound with significant dynamic amplitude shifts "provided a Pd that reached 100% for all of the scenarios except for the 10 kph approach in 60 dBA background, where it reached 0.87 at 5 m". This additive sound had the lowest overall energy and yet provided the greatest Pd at closer distances and lowest Pd at farther distances, suggesting it would be a good candidate noise to minimize annoyance and maximize nearby detection. The additive sound with the highest amount of low frequency content provided equivalent Pd at the 10km/h test speed, but higher levels of Pd, compared to other additive sounds, at the 20km/h test condition. This suggests it would be a good candidate to increase the detectability of a vehicle at faster speeds. Finally, it was found that the no sound base line condition never reached 100% Pd in any case.

Looking at mean detection distances it was found that while all scenarios met regulatory limits there was a large advantage to additive sound conditions when compared to the no sound condition. Possible pedestrian accidents "based on missed or close detections were rare, but not entirely absent for the additive sound conditions. Comparatively, approximately 30% of trials for the no sound condition fell within this possible strike window" [30]. Similar to the Pd curve analysis described above, mean detection distances were higher at 20km/h than 10km/h as tire and wind noise became the leading causes of noise at the higher speed. However, this was much less evident than in previous testing. Like phase one testing, "increasing background noise resulted in a measurable impact on mean detection distances. The average reduction across all conditions was approximately 33% and 28% for approach speeds of 10 km/h and 20 km/h, respectively." Pedestrians were able to detect the vehicle slowing from 20 km/h to a stop more easily when the vehicle had additive sound than the no sound condition. Indicating additive sound will make it easier for pedestrians to determine when it is safe to cross after a vehicle has passed.

Phase Three Research

This thesis covers the third phase of research done by this team; however, some initial work was conducted before I had joined the research team. This work will be briefly summarized in this section to give credit to those that completed the initial work on this project and to help orient the audience to recognize the work done by myself and the work done by others.

Phase Three Progress Prior to this Thesis

1. Funding for this study was secured through the Safety through Disruption (Safe-D) National University Transportation Center, a grant from the U.S. Department of Transportation – Office of the Assistant Secretary for Research and Technology, University Transportation Centers Program.
2. The test vehicle was provided by General Motors (GM) through connections formed during previous phases of testing between VTTI, GM, and my advisor Dr. Michael Roan.
3. The four new warning noises used for this phase of testing were developed by Dr. Michael Roan and were guided by the work done in previous phases of testing.
4. The new exciter transducer-based system used to generate the additive sounds was proposed by Dr. Michael Roan.

Methods and Equipment

Methods Overview

A general overview of the methods used to accomplish the research goals of this thesis is provided to help orient the audience. To maintain continuity between the current phase of testing and the past two phases of testing similar methods were be used. First, a prototype setup of the new exciter transducer-based warning system was constructed and tested. The factory pedestrian alert system was then be modified to allow for different warning noises and noise levels to be tested. Stationary testing was then conducted for each system using a variety of warning noises to evaluate how the two systems compared and if the warning noises met FMVSS 141 regulations. Participant drive by tests were used to evaluate on-road participant detection distances and enable comparisons between the different warning systems and sounds. A separate set of drive by tests was conducted without participants to evaluate FMVSS 141 compliance and to gather recordings to be played in an immersive reality lab. Finally, in lab tests were conducted using the drive by recordings. These results were used to verify the immersive reality environment against the on-road participant tests.

Test Vehicle and Test Sites

A 2018 Chevy Bolt (EV) was used for the experiments presented in this thesis. This vehicle was sent to VTTI by GM for this additive sound testing and was the same test vehicle

used in the second phase of testing detailed above. This vehicle came with a production additive sound system, and all previous additive noise systems from phase two had been removed.

Testing was conducted at three different locations. Stationary vehicle measurements were initially conducted in a VTTI garage bay and then verified on the VTTI Smart Road. Drive by measurements, drive by participant measurements, and interior vehicle measurements were conducted on the VTTI Smart Road and the virtual environment lab tests were conducted in the Virginia Tech Acoustics Signal Processing and Immersive Reality lab (ASPIRE lab).

The Smart Road is a closed test track located at VTTI in Blacksburg Va. that is remotely located and free from traffic noise and other distractions. To maintain continuity with previous phases of testing, the same section of the Smart Road used in previous phases of testing was used. This section of road was free from excessive background noise, flat, straight, and had a surface consistent with typical Virginia roadways. A google maps screenshot of the test site is provided in Figure 5

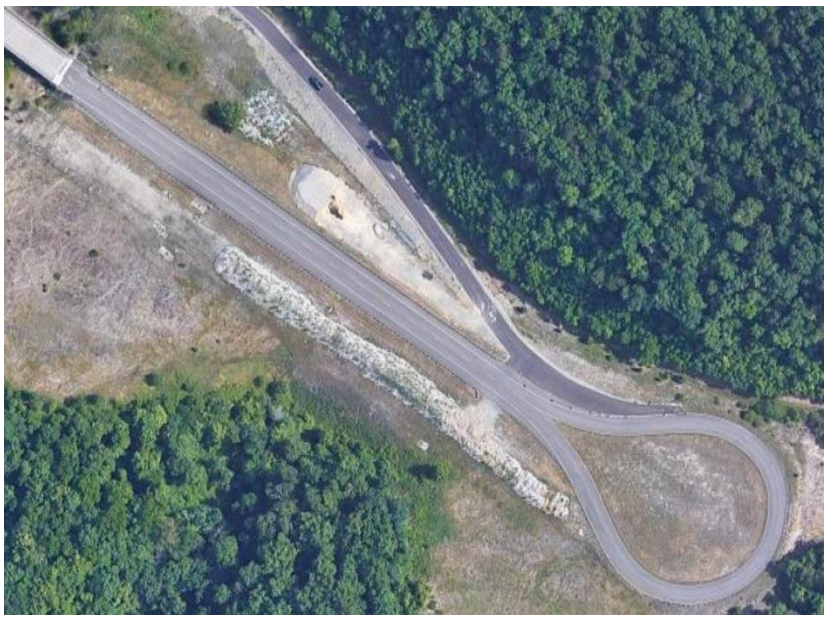

Figure 5 VTTI Smart Road test site sourced from Google Maps.

The ASPIRE lab is a spatial acoustic immersive reality facility. The immersive reality lab consists of a semi anechoic chamber with 58 loudspeakers mounted around the lab. A spatial recording can then be mapped to each of the 58 loudspeakers and amplified to recreate the sound field that was experienced when the recording was taken. This allows for the listener to experience the audio as if they were at the site of the recording. This process is accomplished by first taking a four-channel sound field recording with a sound field microphone located where it

is desired to have the audio replicated in the lab. This recording is then included in a Reaper project which first uses the Harpex signal processing algorithm to extract the maximum amount of spatial information from the sound field recording [31]. Next the Ambix decoder is used to decode optimized signal from the Harpex algorithm to be mapped to the 58 speakers around the lab [32]. This decoder uses the specific distances and angles from the "sweet spot" in the lab (where the audio should replicate what was experienced by the sound field microphone) to determine the necessary output from each speaker. This ambisonic system creates " a smooth, stable and continuous sphere of sound" around the "sweet spot" in the lab allowing the listener to experience the audio from all directions as it was recorded by the sound field microphone [33]. Pictures of the lab are shown below in Figure 6.

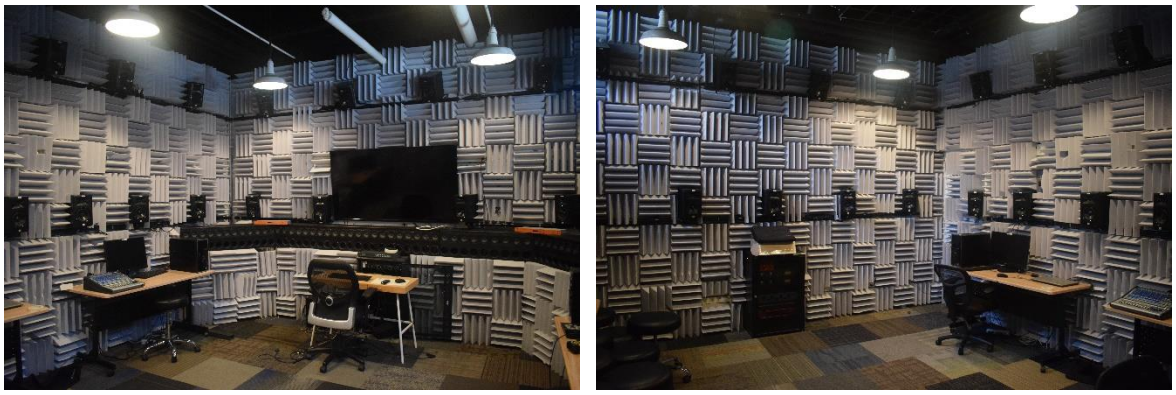

Figure 6 ASPIRE Lab

Reaper Digital Audio Workstation

The Reaper digital audio workstation (DAW) was used to develop additive sounds, play audio to the vehicle sound systems, play recordings in the ASPIRE lab, develop and play background noise, and record participant responses in the ASPIRE lab. "REAPER is a complete digital audio production application for computers, offering a full multitrack audio and MIDI recording, editing, processing, mixing and mastering toolset" [34].

Three different types of Reaper projects were created for this research. First, a project was created to play the different warning noises to the vehicle. This project had a track for each warning noise and speaker configuration and allowed the different warnings to be played at specified volume levels. This allowed for the volume of each additive sound to be set and saved for subsequent testing. The second Reaper project was created to allow background noise to be

played around participants during both on-road and in lab participant testing. This project filtered white noise to have frequency content equivalent to what is typically experienced by pedestrians in an urban environment. It also allowed the volume of each background noise speaker to be adjusted to maintain a uniform level at each participants location. The final set of Reaper projects was used in lab testing to play sound field recordings in the ASPIRE lab and record participant button presses. One project was created for each test scenario and each project contained the sound field recording, time synchronized vehicle distance, and a track for each participant's button to be recorded. These Reaper projects will be referred to throughout the description of each testing phase.

Participants and Recruitment

Participants were recruited by VTTIs recruitment team for both on-road and in lab drive by testing. 20 Virginia Tech students were recruited and split into 5 groups of 4 students. One group was deemed the pilot group and used for a test session to validate experimental procedures. Students were compensated 60 dollars for the first on-road session and 90 dollars for the second in lab session. This was done to incentivize participants to return for the second session and reduce the amount variation due to using different participants. Prior to on-road tests the participants were required to fill out informed consent documents and take a hearing test. Participant were briefed on their duties before each testing session and asked to fill out a survey at the end of the trial.

Data Collection Systems

For this thesis a variety of measurement equipment was utilized to collect acoustic, vehicle position and participant response data. These systems will be summarized in this section and referenced in subsequent sections.

Acoustic Data Collection Systems

Two acoustic data collection systems were used in this thesis. The first system was used to collect overall A-weighted SPLs and A-weighted 1/3 octave band levels for the following tests: stationary vehicle tests, drive by vehicle tests, participant on-road drive by tests, participant lab tests, sound-field calibration tests. This system consisted of the following major components:

1. Four G.R.A.S. 46AQ TEDS microphones
2. National Instruments cDAQ-9171
3. Lenovo IdeaPad 320 Laptop
4. National Instruments LabVIEW software
5. National Instruments LabVIEW Acoustics and Vibrations Measurement Suite

The G.R.A.S. 46AQ TEDS microphones were sampled at 50kHz and passed through an A-weighted filter and sound level meter to calculate overall SPL (0.125 s exponential averaging) and 1/3 octave band SPLs. Overall SPL and 1/3 octave band calculations were recorded using the Lenovo IdeaPad 320 Laptop with the LabVIEW software, and both saved on the PC and transmitted over ethernet to the VTTI DAS (described below) at a rate of 10 Hz (when vehicle distance data needed to be collected). The G.R.A.S. 46AQ TEDS microphones were calibrated before each test with a G.R.A.S. 42AA pistonphone calibrator (114dB at 250Hz) and were corrected using a G.R.A.S. ZC0002K barometer. This system uses many of the same components used in phase two of testing. This system is shown in Figure 7.

The second acoustic data collection system was used to record sound field recordings to be played back in the lab participant tests. The major components of this system are:

1. Core Sound Tetra Mic sound field microphone
2. Roland R-44 Audio Recorder

The Core Sound Tetra Mic was sampled at 48KHz using the audio recorder. The audio recorder saved data to a SD card as a four channel .wav file. This system is shown below in Figure 7.

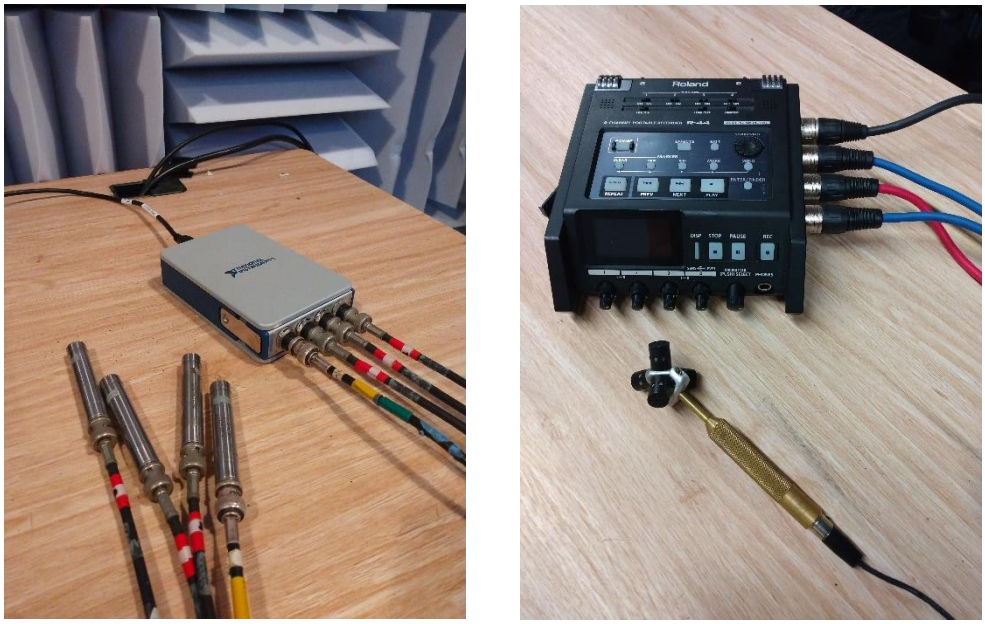

Figure 7 Left Acoustic Data Collection System. Right Sound Field Data Collection System.

VTTI Next Gen DAS

For vehicle position, participant response, and acoustic data collection, a modified VTTI DAS system was utilized. This system was developed by VTTI and recorded position and velocity using a differential global positioning system (DGPS). Acoustic data was sent to the DAS over ethernet from the acoustic measurement system described above. Participant response data was collected using four handheld buttons that were given to each participant. The DAS recorded when each button was pressed which could be later mapped to the vehicles distance at that point in time. Using this system, vehicle position, vehicle velocity, participant button presses, A weighted overall SPL and 1/3 octave band levels were all able to be recorded simultaneously. The transmitter and receiver were calibrated before each test to help ensure base-to-vehicle distance and speed accuracy. This system was the same system used in phase two testing.

ASPIRE Lab Participant Response Module

To maintain continuity between the participant tests conducted on the VTTI Smart Road and in the ASPIRE Lab, hardware was constructed to record participant responses in the ASPIRE Lab using handheld buttons. This was accomplished by wiring four handheld buttons to a joystick board which was recognized as a MIDI device by Reaper. This module can be seen to the Right in Figure 8. Reaper was then set up to record the input of this MIDI device as a zero whenever the button was not pressed, and a 1 when the button was pressed. This allowed the time in the recording when each participant pressed the button to be precisely determined.

Figure 8 Participant Response Module and Participant Buttons

Additive Sound Systems

One of the significant issues with phase two testing was that the additive sounds were much louder in the front of the vehicle than they were on the sides of the vehicle. Due to the way that these additive sounds are evaluated to meet regulations, the additive sounds need to be raised until the lowest microphone met regulatory requirements. This caused the vehicle to be louder than it would be if a more uniform sound emitting method was used. In this phase of testing a new sound generation system was proposed and tested. This system was evaluated to see if it could provide a uniform sound field around the vehicle and thus lower the level of noise pollution emitted to the environment. In addition to this new system the factory speaker system was modified to be able to play different additive sounds. This allowed for the comparison of not only different additive sounds, but the two different sound generation systems.

Factory Sound System Modification

From the factory the Bolt is equipped with a single speaker mounted in the front driver side wheel well that is used to play additive sounds see Figure 9. These additive sounds are controlled by the cars internal computer and thus do not lend themselves to being easily changed.

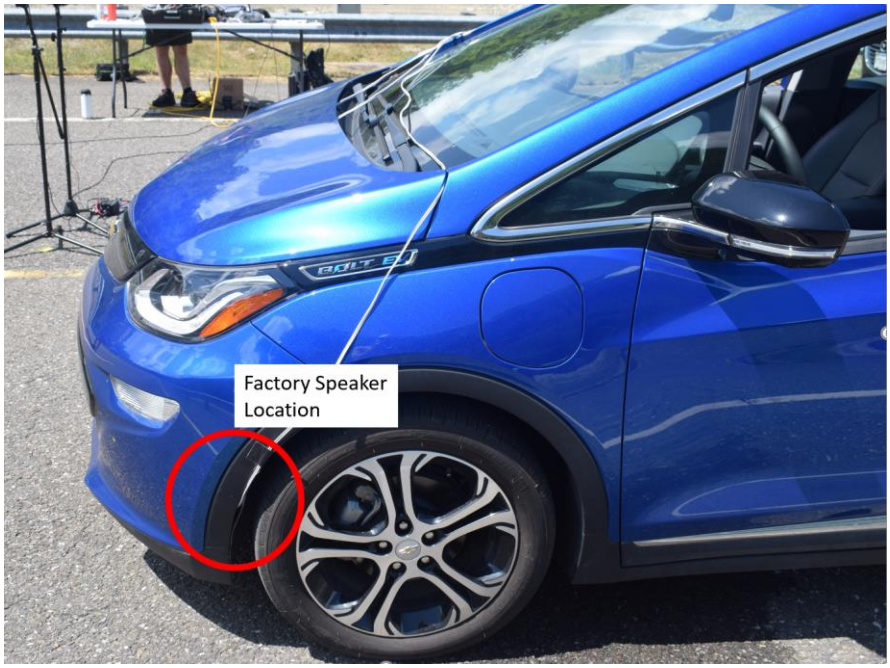

Figure 9 Factory Speaker Location

To be able to get around this system, the factory speaker was unplugged from the cars computer and external wires were connected to the speaker. The wires were fed from the speaker to the interior of the vehicle and the plastic shielding was replaced in the factory configuration, this can be seen above in Figure 9. A FX Audio FX-502A HiFi audio amplifier was selected and connected to the factory speaker via the externally routed wires. This amplifier has two channels and can provide 50W per channel. This allowed different additive sounds to be played to the factory speaker from a Lenovo S540 IdeaPad laptop computer. A diagram of this solution can be found in Figure 10.

Figure 10 Factory Speaker Diagram

Exciter Sound System

To achieve a uniform sound field around the vehicle, bonded acoustic exciters or tactile transducers were selected as a potential solution. It was proposed that bonding these exciters to the inside of the Bolts body panels would turn the body panels into large speakers that would allow for the selected additive sounds to propagate uniformly around the vehicle. A simplified schematic showing this concept is shown below in Figure 11. These exciters would allow the sound to propagate from the surface of the body panel rather than from behind it, while still being out of sight. The surface used to emit the sound will also be much larger (the entire body panel verse the speaker diaphragm), and due to the complex nature of the geometry of the body panels it was expected that the numerous vibrational modes of the panel will allow for sufficient frequency content from the panel to be transmitted.

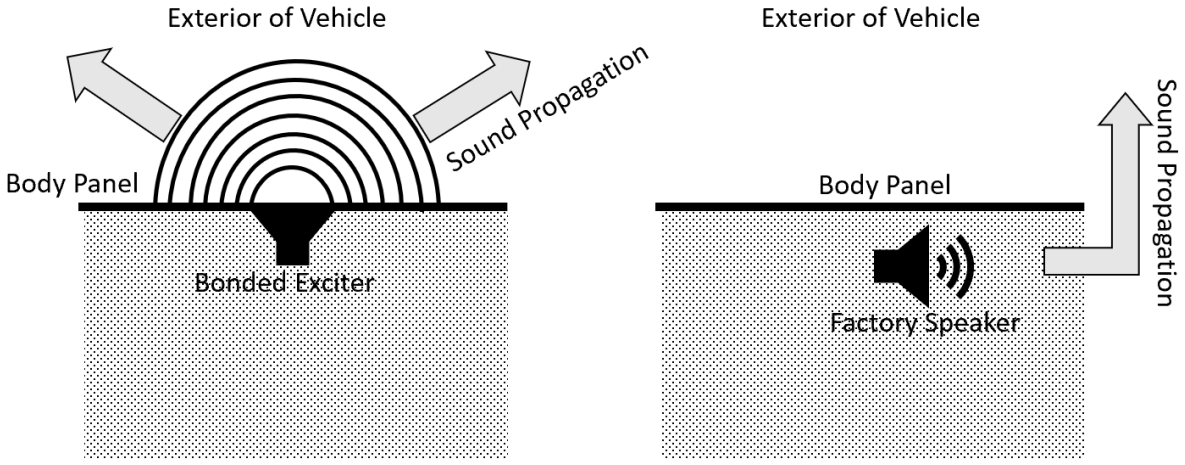

Figure 11 Speaker comparison

To preliminarily validate the application of exciters as a method of generating acoustic alerts for pedestrian alert systems, two Dayton Audio daex32QMB-4 40W 4-ohm exciters were ordered and were driven with the same FX Audio FX-502A HiFi audio amplifier. This setup can be seen in 12. The following three test vehicles were used to preliminarily test the system: a 2010 Honda fit (short hood), 2018 Chevy Bolt (medium hood), and 2014 Mazda 3 (longer hood). Three microphones were set up around the test vehicle, as shown in Figure 4, and the exciter was placed on the outside hood of test vehicle. Due to the single use nature of the bonding elements the exciters were not bonded to the hood, but rather placed on the outside of the panel and relied on gravity to hold them in place. The sound quality from the unbonded exciter sounded qualitatively similar to a factory solution and it was assumed that when bonded, the exciters

would produce better sound quality. For this testing one and two exciter solutions were considered and only the relative sound levels around the vehicle were of interest. A picture of a one exciter solution on the 2014 Mazda 3 is shown in Figure 13. Microphones were set up in accordance with FMVSS 141 stationary testing protocols as shown in Figure 4 and each vehicle was tested in a large garage bay at VTTI. For each vehicle, overall A-weighted SPLs within approximately 1-2 dBA of each other at each microphone location were obtained. When compared to the 3-6 dBA difference seen in phase two testing and a subjective confirmation of sound quality from the research team, it was decided that bonded exciters provided an adequate solution for a uniform sound generation system that can easily be applied to the hood of a variety of test vehicles.

Figure 12 Exciter Diagram

Figure 13 2014 Mazda 3 One Exciter

Testing was then conducted to determine the optimal location to mount the exciters on the Bolt to accomplish a uniform sound field around the vehicle while maintaining OEM appearance and relative ease of application. The hood of the vehicle was selected as the best location to mount the exciter as it provides a large panel that is easily accessed, is locationally

closest the front of the vehicle, and provided good results in preliminary testing. Due to the geometry of the hood and the structural supports, the response to excitation varied significantly with the location of the exciters Figure 15. Modeling the vibrational response of the hood was not practical and the placement of the exciters was determined by monitoring the A weighted overall SPL at the three microphones shown in Figure 14. The transducers were placed on the top of the hood with consideration to the structural geometry on the bottom of the hood. A selection of warning noises was played from the amplifier and the A weighted overall SPL was monitored. Through placing the exciters at different locations, the optimum configuration was determined to be two exciters placed on either side of the main hood support Figure 15. This provided the best sound quality, most uniform sound dispersion, and highest overall A weighted SPL.

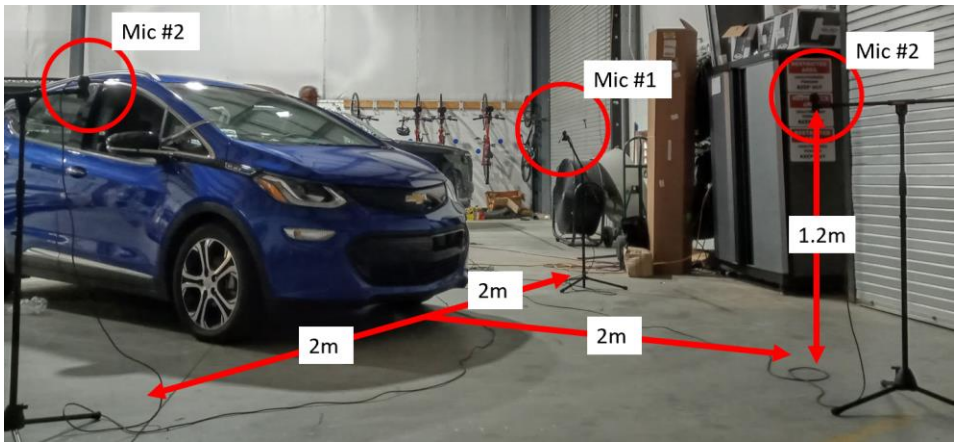

Figure 14 Exciter placement test geometry

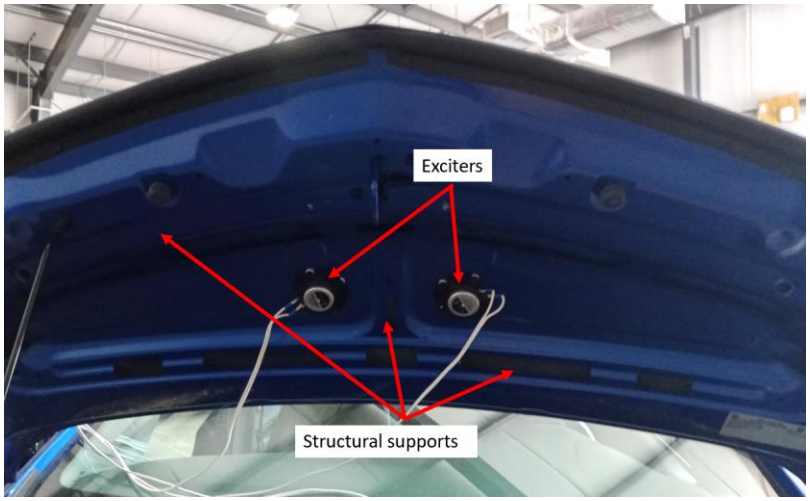

Figure 15 Exciter Placement

Combined System

To be able to efficiently test with both the exciter-transducer system and the factory modified system, a Solupeak P2 loudspeaker selector control box was installed after the FX Audio FX-502A HiFi audio amplifier. The two selectable outputs were routed to the exciter transducer system and the factory modified system. The selector box was then mounted to the dashboard of the Bolt in front of the passenger's seat. This allowed the desired speaker system to be selected by the researcher with a simple toggle switch during stationary and drive by testing. This final combined configuration is shown in Figure 16. With this modification, the researcher could select a test configuration in the Reaper project, flip the toggle switch and the correct additive sound would be played from the desired system at the correct volume. This modification reduced the amount of time needed to switch between speaker systems and decreased the likelihood that the sound was played from the wrong speaker.

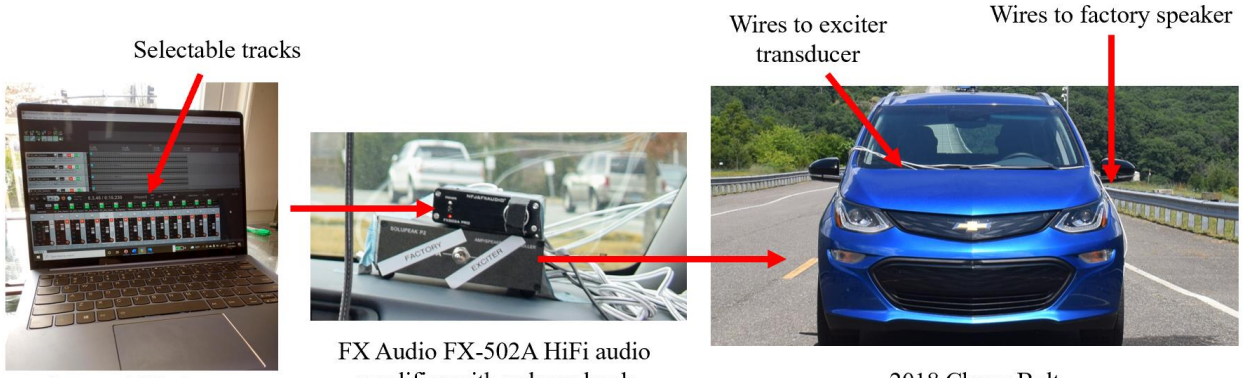

Figure 16 Combined Exciter and Factory Configuration

Background Noise Sound System

During participant tests both in the ASPIRE lab and on the Smart Road, background noise was played around the participants to simulate the noise pedestrians experience on typical roadways. This was done to allow for results to be more broadly applied to real life scenarios. Leveraging the typical roadway noise spectrum developed by NHTSA during initial FMVSS 141 testing and used in both previous phases of testing, white noise was filtered to provide frequency content equivalent to what is experienced by pedestrian in a typical urban environment [9]. This was accomplished using the Reaper DAW. First the standard white noise plugin was used to generate gaussian white noise. Then, the noise was filtered using Reapers standard equalizer plugin. The background noise was broadcast by a Focusrite Scarlett 18i20 USB Audio Interface

to five JBL LSR308 loudspeakers set up around the participants and a subwoofer directly behind the participants. As suggested by NHTSA, a background noise level of 55 dBA was maintained for the duration of each testing session. Unlike previous phases of testing where both 55dBA and 60dBA levels were considered, only a background noise level of 55 dBA was used for this testing. This was due to the primary comparison of interest being between the two different noise systems and the different warning noises rather than the background noise levels. When monitored with microphones over the top of each participant's head, this setup allowed for the background level to be maintained within 1 dBA of the desired 55dBA background noise level at each participants location.

For on-road testing the same speaker positions used in previous phases of testing were used and can be seen in Figure 17. Due to the constraints provided by the limited room in the lab, the spacing of the background speakers was condensed for lab testing. This geometry can be seen in Figure 18. An example of the background noise spectrum taken during session 1 of on-road testing can be seen in Figure 19.

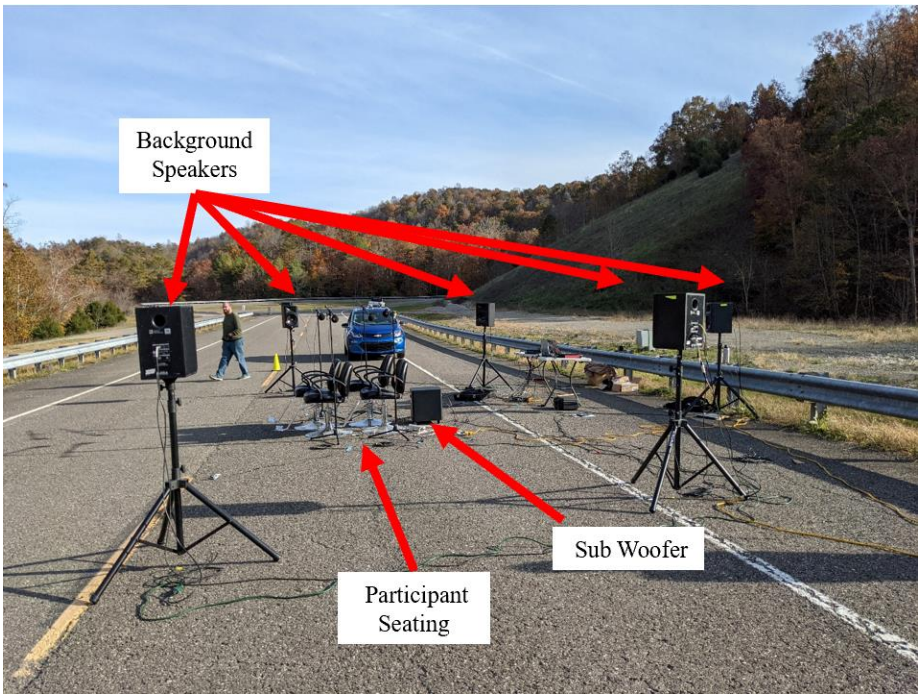

Figure 17 On Road Participant Background Noise Setup

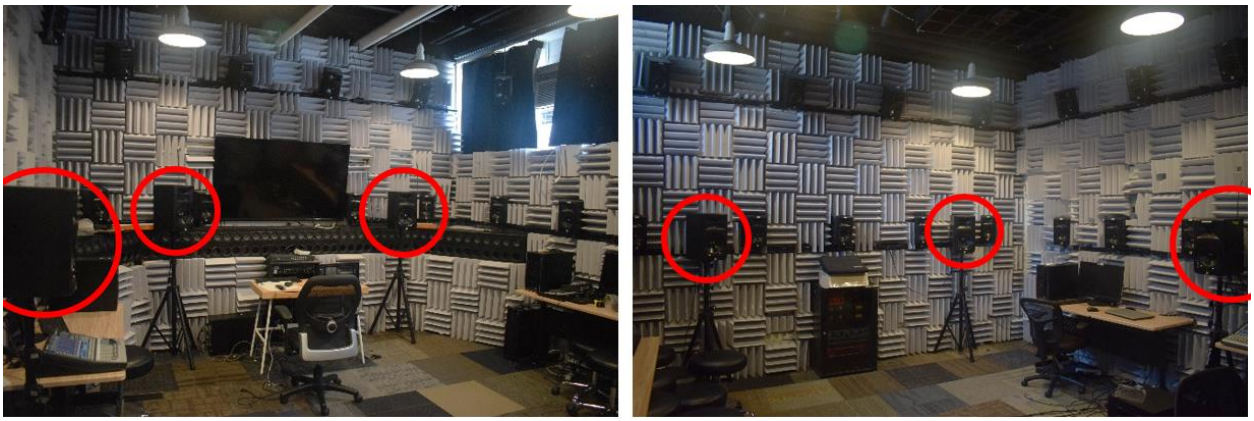

Figure 18 Lab Background Noise Setup (Rear Speaker Shown Twice)

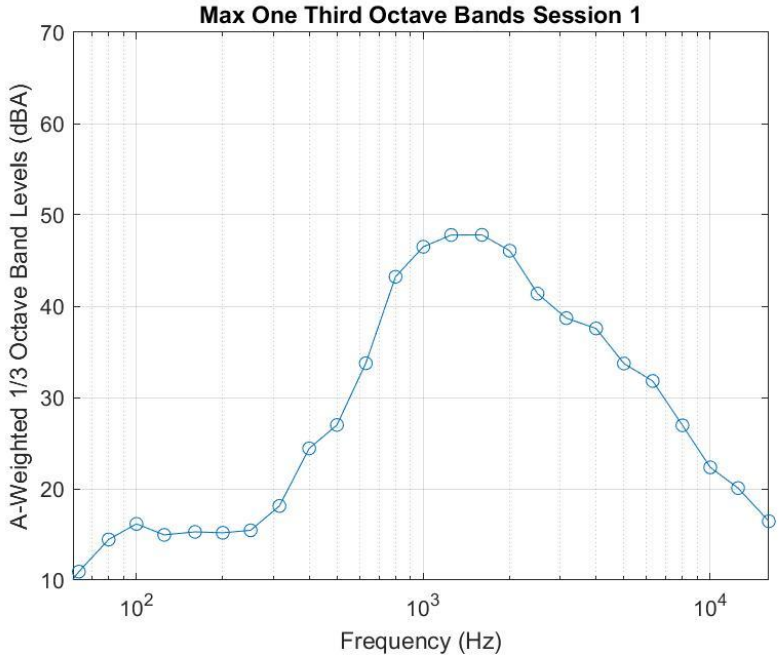

Figure 19 Background Noise 1/3 Octave Band Levels On-Road Session #1

Additive Sound Design

Four new additive sounds, one sound from the second phase of testing and a recording of the factory test vehicle additive sound were used for additive noise solutions in this round of testing. The no sound condition was included as a baseline. These sounds were developed by Dr. Mike Roan prior to me joining the research team. The sound characteristics of each additive sound are detailed below.

Guided by the past phases of testing and reviewed literature, four new additive sounds were developed. Two different frequency contents and two modulation levels were considered to create four new additive sounds. For the first two additive sounds a low frequency emphasis base

sound was used. This base sound was then modulated at a frequency of 1Hz and 2 Hz to create additive sounds LF 1Hz and LF 2 Hz. Similarly, the other two additive sounds were created using a high frequency emphasis base sound also modulated at a frequency of 1Hz and 2 Hz to create additive sounds HF 1Hz and HF 2 Hz. These additive sounds were decided upon to allow for the comparison of high and low frequency emphasis additive sounds and different levels of amplitude modulation. In addition to these new additive sounds a high performing additive sound from phase two of testing was included. This sound will be referred to as FP and had a mid-frequency emphasis and low amplitude modulation. The last additive sound was a recording of the factory sound that came with the Bolt. This sound will be referred to as Factory and had a mid-frequency emphasis and a low amplitude modulation.

Experimental Methods

To evaluate and compare the two additive sound systems (factory and exciter) stationary and drive by tests were conducted on the smart road. Drive by tests were then repeated in the ASPIRE lab to give a comparison between on-road and in lab result.

Stationary Tests

Stationary tests were used to accomplish two main goals. First, they were used to set the levels for the warning noises, and secondly, they were used to verify if the test noises satisfied FMVSS 141 standards when played through each speaker configuration. A summary of the test scenarios considered is provided in **Error! Reference source not found.**

Additive sound	Speaker	Total Number of Test Conditions
LF 1Hz	Factory Speaker or Exciter	12
LF 2Hz		
HF 1Hz		
HF 2Hz		
FP		
Factory		

Table 1 Stationary Test Scenarios

To set the additive sound levels, the FX Audio FX-502A HiFi audio amplifier was set to the middle of its volume range and securely taped in place. The Lenovo S540 IdeaPad was set to a volume level in the middle of its range (60) and used to play each additive sound. Volume

settings were in the middle of each devices' range were used to avoid distortion while allowing for the volume to be played at an adequate level. With the level of amplification for the amplifier and computer fixed, the volume for the additive sounds could be adjusted and then saved using Reaper. This allowed the volume of each configuration to be set and then be played at the same level for subsequent testing sessions.

Testing was conducted on the Smart Road with the vehicle parked in the middle of the lane. Three G.R.A.S. 46AQ TEDS microphones were calibrated and set up around the front of the vehicle with a microphone on the left, right, and front of the vehicle. The microphones were setup at a height of 1.2m and 2m from the center of the vehicles front bumper this is the same geometry shown in Figure 14. For each additive sound and speaker configuration, the additive sound was played and the overall A-weighted SPL at each microphone was monitored. The volume of the additive sound was adjusted until the lowest of the three microphones overall A-weighted SPL averaged a constant 50 dBA. For each test the overall A-weighted SPL and the A-weighted 1/3 octave bands were recorded.

Drive by Verification and Sound Field Data Collection

To verify compliance to FMVSS 141 and to collect sound field recordings to be played in the ASPIRE lab drive by tests were conducted using methods consistent with FMVSS 141. For these tests 52 different conditions were considered and are summarized in Table 2

Additive sound	Speaker	Approach Speed	Approach Direction	Total Number of Test Conditions
LF 1Hz	Factory Speaker or Exciter	10 or 20 km/h	Left or right	52
LF 2Hz				
HF 1Hz				
HF 2Hz				
FP				
Factory				
No sound	No speaker			

Table 2 Drive by Test Scenarios

To verify the compliance to FMVSS 141 drive by tests two G.R.A.S. 46AQ microphones were calibrated and set up on either side of the test road 2m from the center of the road and at a height of 1.2m. This geometry is seen in Figure 20. The background noise was recorded prior to the testing session and tests were halted if conditions arose that caused inconsistent background noise such as planes, trains, excessive wind, etc. The test vehicle was driven from 100m before the microphones to 100m after the microphones. The vehicle maintained the constant test speed (within .5 km/h of the target speed) from the 100m starting point until 10 m after the microphones as this was the test envelope of interest. Speed, distance, A-weighted overall SPL, and A-weighted 1/3 octave band data was recorded using the DAS and audio recording setup detailed above. It is important to note that only the 10 km/h and 20 km/h test conditions were of interest for this study.

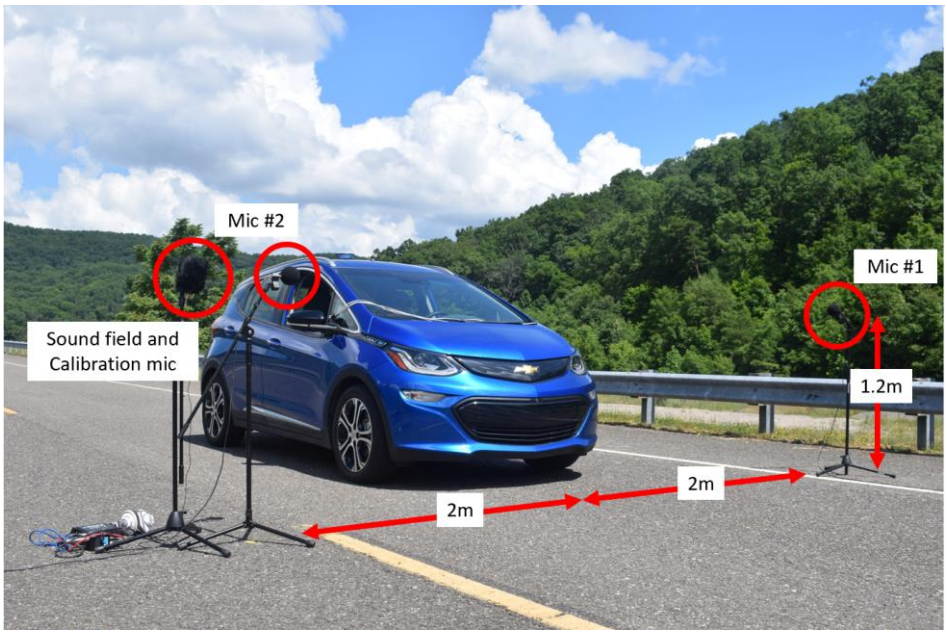

Figure 20 Drive by Test Geometry

During this testing session sound field recordings and calibration audio were captured to be used for participant testing in the ASPIRE Lab. The sound field microphone was set up adjacent to the test road at the location and height of where participants would be seated during on-road participant testing see Figure 20Figure 20. This microphone captured the three-dimensional audio a participant would be experiencing if they were on the test road during this simulated traffic scenario. A separate G.R.A.S. 46AQ microphone was calibrated and set up next to the sound field microphone to be used as a calibrated reference for the SPL at the location of

the sound field microphone. The data from the calibrated reference was collected with the DAS system and thus was aligned with vehicle distance. For each testing run data collection was first started on the sound field audio recorder and then the DAS system. This ensured that the sound field recording was longer than the data collected using the DAS and thus could be trimmed to match the distance, A-weighted SPL and A-weighted 1/3 octave band data.

For testing in the ASPIRE lab it was necessary to trim the sound field recordings to start when the Bolt was 100m away from the sound field microphone and end the recording when the Bolt was 10 m past the sound field microphone. This was done to ensure a consistent experimental envelope between on-road and in lab participant tests. Trimming was accomplished by first synchronizing the data recorded using the DAS and the sound field recordings. Once synchronized, distance recorded by the DAS was used to isolate the data within the test envelope. To time synchronize these two separate systems, before the vehicle started the trial, a clap was used to create an overall SPL impulse in each system. This allowed the peak of this impulse to be aligned in post processing. With this peak aligned, data from the DAS was matched to the sound field recordings. The data from each system was then processed to start at 100m before the microphones and end 10m after the microphones. A .wav file was created both for the sound field recording and corresponding vehicle distance during each test. These .wav files were then added to the lab testing reaper files allowing the distance data to be aligned to the sound field track in Reaper. Using the in-lab participant response module, the point in the track where each participant recognized the approaching vehicle was also recorded. Since each track was synchronized the distance of detection could be determined in post processing. An example of one of these projects is shown in Figure 21.

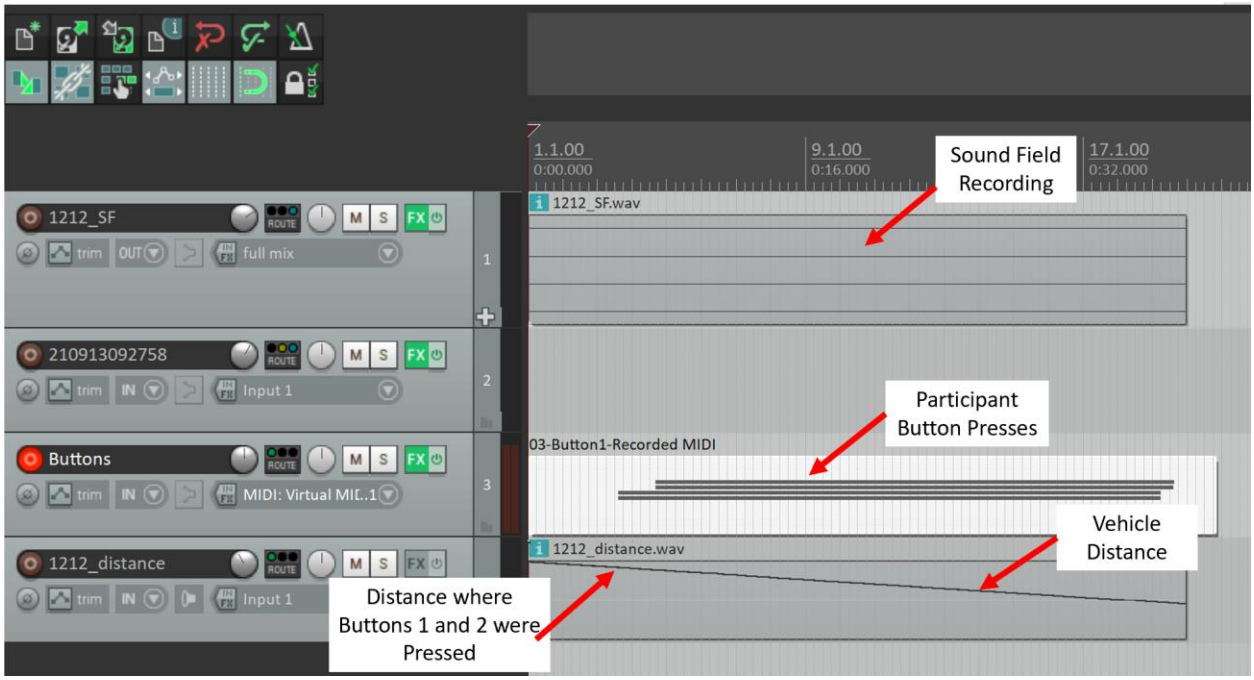

Figure 21 Lab Testing Reaper Project Example

It was discovered after conducting these tests that the volume on the Lenovo 540s laptop was mistakenly set to 54 instead of 60 as intended. This would have resulted in the volume that the car played the additive sound to be slightly lower than desired. Due to financial and timing constraints it was impractical to redo this session of testing. To correct this error the computer amplifier was characterized by playing each additive sound from a speaker in an anechoic chamber. The average overall A-weighted SPL of each additive sound was recorded at volume levels of 54 and 60. The average difference between these two volume levels determined to be 1.4 dBA. For testing in the ASPIRE Lab the magnitude of the peak Overall A-weighted SPL was scaled to reflect the volume difference. With this adjustment, the in-lab peak should match the peak recorded during drive by tests within the variation seen between runs of the same additive sound configuration. While not ideal, with adjustment it is expected that this shift will not impact the results of in lab testing.

On Road Participant Tests

On road participants testing was conducted on the Smart Road using methods consistent with past phases of research. These sessions were used to determine the distance that participants were able to detect the Bolt when surrounded by background noise at the level of a typical urban environment. During each session the 52 conditions shown in **Error! Reference source not**

found. were evaluated. Background noise was broadcasted by a Focusrite Scarlett 18i20 USB Audio Interface, five JBL LSR308 loudspeakers set up around the participants, and a subwoofer directly behind the participants. This system is discussed in more detailed above.

Additive sound	Speaker	Approach Speed	Approach Direction	Background Noise Level	Total Number of Test Conditions
LF 1Hz	Factory Speaker or Exciter	10 or 20 km/h	Left or right	55 dBA	52
LF 2Hz					
HF 1Hz					
HF 2Hz					
FP					
Factory					
No sound	No speaker				

Table 3 On-road Participant Test Scenarios

One pilot session and four test sessions were conducted with each session lasting approximately two hours. The pilot session was used to test the experimental procedures and make sure all experimenters were familiar with how to perform their specific role. For each session four participants were set up in barber chairs adjacent to the testing road and four G.R.A.S. 46AQ TEDS microphones were calibrated and set up over the top of each participant's head. These microphones served to monitor the background noise to ensure it maintained a 55dBA level at each participant's location and to record the A-weighted overall SPL and 1/3 octave band measurements that the participant was experiencing. This setup is seen in Figure 22. Participants were blindfolded to eliminate visual cuing and to allow results to be applied to visually impaired participants. Participants were told they were to simulate a pedestrian waiting to cross the road and that they were seated on the corner of a simulated intersection. The participants were given a handheld button and asked to press it when they heard a vehicle approaching and release it when they felt it was safe to cross the intersection. The wind direction and speed were monitored through a mobile weather station and were recorded prior to each test. Testing was halted if abnormal noise conditions such as trains, planes, or wind speeds above 7 mph arose. The following data was collected for each test using the DAS system: overall A

weighted SPL and 1/3 octave bands above each participant's head, vehicle distance, and vehicle speed. Test sessions were ordered to minimize the effects of participants' learned behaviors. Test orders can be seen in appendix 3.

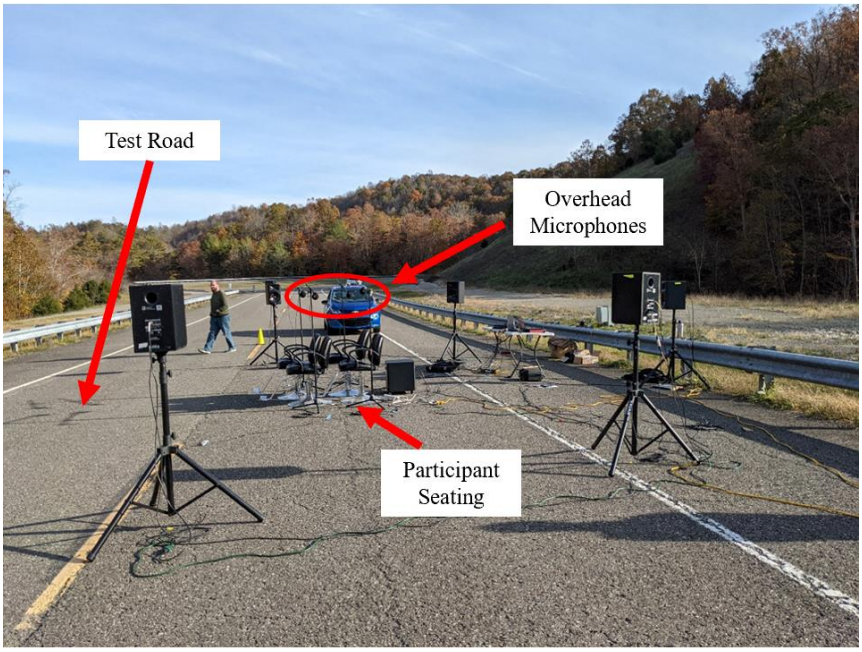

Figure 22 On Road Participant Setup

The following test procedure was used for on-road participant testing:

1. The microphones above each participant's head were calibrated.
2. A background noise measurement was taken without additional background noise.
3. The background noise was turned on and adjusted until the overall A weighted SPL at each participant's head was 55 dBA.
4. The DGPS on the research vehicle was calibrated and zeroed to insure 0m was even with the participant's location.
5. The research vehicle was driven to either the left of right side of the test road and setup 100m away from the participants.
6. Data collection was started on the DAS and National Instruments DAQ systems.
7. The desired speaker was selected using the dash mounted speaker selector.
8. The desired additive sound was played from the Reaper project at the level determined through stationary testing.
9. The wind speed and noise conditions were checked for abnormalities.

10. The driver was signaled and accelerated the research vehicle to the desired test speed. The research vehicle remained at this speed until it had traveled 10m past the participants.
11. Steps 6-10 were repeated for each test condition.

The background noise levels for each test condition are provided below in Table 4.

	Overall A-weighted SPL dBA
Session #1	33.9
Session #2	35.2
Session #3	39.1
Session #4	35.6

Table 4 On-road Background Noise Levels

In Lab Participant Tests

Using the sound field recordings taken on the Smart Road, participant tests were repeated in the ASPIRE Lab. The same set of participants were utilized although different seating arrangements and session groups were necessary to accommodate participant scheduling. The 52 test scenarios used on the Smart Road were repeated and are presented in **Error! Reference source not found.**.

To prepare the ASPIRE Lab for Participant testing all equipment that was not necessary for testing was turned off to minimize in lab background noise and raise the signal to noise ratio. The lab was cleared out to both make room for participants and the needed research personnel and create as anechoic an environment as possible. The background noise was measured in the lab with all equipment turned off and all the necessary equipment turned on and was found to have an overall A-weighted SPL of 32.9dBA and 33.6dBA respectively.

As discussed above, Reaper projects for each testing scenario were constructed containing tracks for the sound field recording, corresponding vehicle distance, participant input, and speaker mapping for the ASPIRE Lab. When each Reaper project was opened and played, the audio from the sound field recording was broadcast by the speakers in the lab and the participants' responses were recorded in the Reaper project. The project was then saved and the distance at which the participants detected the vehicle was determined through post processing the data.

It was necessary to match volume of the recording in the lab to the volume of the approaching research vehicle on the Smart Road to create as accurate of a representation of the drive by test as possible. This was accomplished by setting up a single G.R.A.S. 46AQ microphone in the ASPIRE Lab at the center of where the participants would be seated. This microphone was calibrated and then used to monitor the overall A-weighted SPL throughout a sound field recording playback. The peak overall A-weighted SPL was then compared to the peak overall A-weighted SPL measured by the calibration microphone on the Smart Road. The volume of each sound field track was adjusted until it matched the peak seen on the Smart Road.

To allow for the most accurate comparison between the two environments as possible, testing in the ASPIRE lab was designed to closely mimic testing done on the Smart Road. Two pilot studies (two participants per study) were conducted to test lab procedures and then four test sessions were conducted to gather the data presented in this thesis. For each session the participants were seated on four stools in the center of the ASPIRE lab; the center of this seating arrangement was used to determine the measurements for the speaker mapping in Reaper and provides the most realistic acoustic experience. Since the acoustics vary depending on the distance from this location, participants were seated as closely together as possible. This arrangement can be seen in Figure 23. Test sessions were conducted using the same ordering utilized for on-road tests.

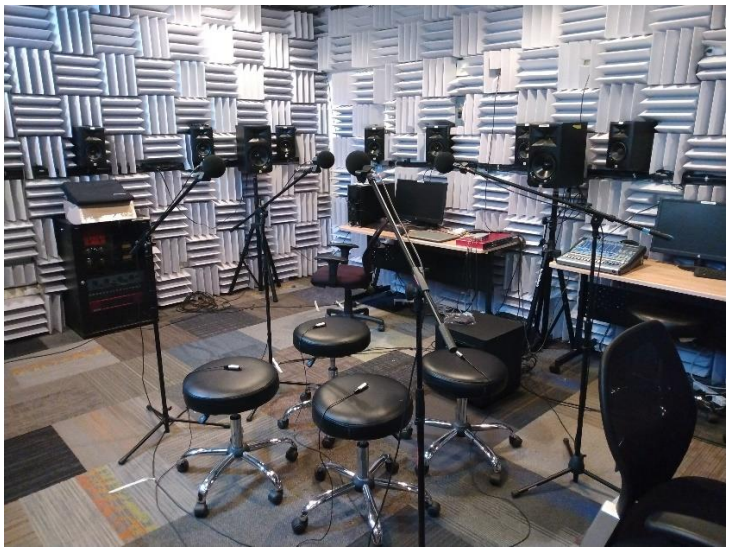

Figure 23 Lab Participant Setup

The following test procedure was used for in-lab participant testing:

1. The microphones above each participant's head were calibrated.
2. A background noise measurement was taken without additional background noise.
3. The background noise was turned on and adjusted until the overall A weighted SPL at each participant's head was 55 dBA.
4. The desired Reaper project was opened.
5. Acoustic data collection was started using the National Instruments DAQ system.
6. The Reaper project was recorded (playing the recording while simultaneously collecting participant response data).
7. The Reaper project was stopped, saved, and closed.
8. Steps 4-7 were repeated for each test condition.

In Vehicle Noise Level Test

To quantify potential driver and passenger annoyance, tests were conducted to evaluate the sound levels at the driver and passengers' head locations in the research vehicle. These measurements were collected on the Smart Road by setting up the National Instruments DAQ system inside the vehicle with a microphone placed near where both the driver and passengers' head would be located. This setup can be seen in Figure 24. For each test scenario, the desired sound was played, the vehicle was brought up to speed, and 10 second measurements were taken with the vehicle maintaining a steady speed. Tests were conducted for each of the test scenarios shown in Table 5. These tests were designed to help quantify differing interior noise levels caused by the two speaker systems and the six different additive sounds.

Figure 24 Interior Vehicle Measurement Setup

Sound	Speaker	Approach Speed	Total Number of Test Conditions
LF 1Hz	Factory Speaker or Exciter	10 or 20 km/h	26
LF 2Hz			
HF 1Hz			
HF 2Hz			
FP			
Factory			
No sound	No speaker		

Table 5 In Vehicle Test Scenarios

Results

Stationary Tests

Five second segments of stationary test recordings are shown below in Figures 25-36. The purple line on the 1/3 octave band plots denotes the limits for the four-band NHTSA alert requirements. To meet this requirement, four bands must exceed this threshold spanning 9 of the 13 1/3 octave bands. To meet the two-band requirement, two non-adjacent 1/3 octave band levels between 315 and 3150 Hz must be at or above 40dBA. One selected band must be below 1000Hz, and one must be at or above 1000Hz. The two bands used to meet this requirement must have a band sum of at least 44dBA as defined by FMVSS 141. For both the four band and two band alerts the location of the lowest overall A-weighted SPL (driver, front, or passenger) must be used to meet 1/3 octave band requirements.

Of the sound and speaker combinations used in this study only FP from the exciter, FP from the factory speaker, and the factory noise from the factory speaker met both the band sum and 1/3 octave band requirements (i.e., FMVSS 141 compliant). All the additive sounds met the band sum requirement. This was surprising, as LF 1Hz, LF 2Hz, HF 1Hz, and HF 2Hz additive sounds were all designed to have sufficient frequency content to meet the two-band requirement. This suggests that both the amplifier/speaker combinations either attenuated the signal in the necessary frequency regions or that the additive sounds needed more frequency content in these regions. This could have been resolved by either raising the volume of the additive sounds or by tuning each sounds' frequency content to meet the regulations. As the additive sounds were inputs to this thesis, the later was not an option. Raising the volume was also not desired as it was deemed more appropriate to compare the additive sounds at equal minimum overall A-weighted SPL than to adjust each sound to meet regulations and have widely varying volumes. Except for the HF 1Hz and HF 2Hz additive sounds, all additive sounds had the lowest overall A-weighted SPL in the front of the vehicle. HF 1Hz and HF 2Hz had the lowest level on the passenger side of the vehicle followed by the front of the vehicle which was approximately 2dBA lower. This means that the overall A-weighted SPL coming towards the participants from the front of the vehicle should be approximately the same for each additive sound. The overall A-weighted SPL will start to vary more as the vehicle starts to pass the participants and the sound coming from the sides of the vehicle becomes a more dominant source of noise.

These tests also showed that the bonded exciter did a good job at creating uniform sound at the passenger and driver sides of the vehicle but produced a lower A-weighted SPL at the front of the vehicle. The overall A-weighted SPL at the front of the vehicle ranged from 6.6 to 12.1 dBA lower than the highest A-weighted SPL. These results varied significantly from the initial testing done in the VTTI garage bay. It is likely that reflections in the garage bay artificially created more uniform sound levels around the vehicle. When the vehicle was tested in its final configuration on the Smart Road, and these reflections were no longer present and less uniform overall A-weighted SPLs were observed. When used with the FP and Factory sounds the exciter was able to produce more uniform overall A-weighted SPLs around the vehicle than the factory speaker. As these were the sounds that were FMVSS compliant it suggests that the exciter may be more effective at creating a uniform sound field around the vehicle when used in conjunction with broader frequency content non-modulating additive sounds. Average overall A-weighted SPL are shown in Table 6.

	Driver	**Front**	**Passenger**	**Sound**	**Speaker**	**SPL Range dBA**
Overall A-weighted SPL (dBA)	61.6	49.5	59.5	LF 1Hz	Exciter	12.1
	61.9	49.9	59.8	LF 2Hz		12.0
	58.9	49.7	54.6	HF 1Hz		9.1
	59.1	50.1	54.8	HF 2Hz		9.0
	55.9	49.9	56.4	FP		6.6
	56.9	50.2	57.0	Factory		6.8
	55.9	49.8	51.1	LF 1Hz	Factory	6.1
	55.8	49.8	51.3	LF 2Hz		5.9
	55.6	51.7	49.9	HF 1Hz		5.6
	55.2	52.1	50.3	HF 2Hz		4.9
	61.3	49.7	52.2	FP		11.6
	61.2	50.2	50.9	Factory		11.0

Table 6 Average A-weighted SPL Stationary Test

LF 1Hz from the exciter had the highest overall A-weighted SPL on the driver's side of the vehicle followed by the passenger side which was approximately 2.1dBA lower and finally the front of the vehicle which was 12.1 dBA below the highest microphone. This sound had the most frequency content in the 400 and 500Hz 1/3 octave bands. As seen in the overall SPL plot the signal modulated at 2Hz with an amplitude of approximately 2.15 dBA. This warning sound was not FMVSS 141 compliant.

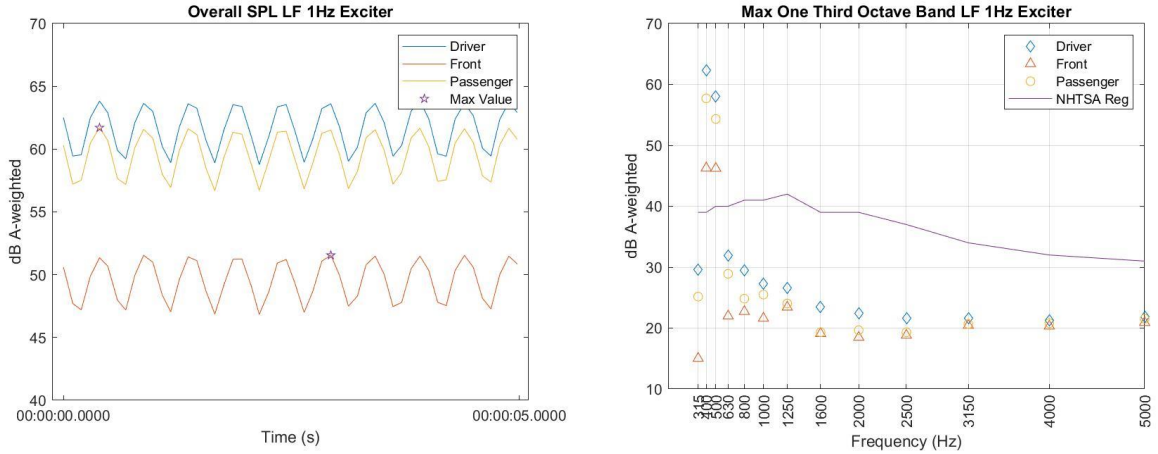

Figure 25 Overall A-weighted SPL and 1/3 Octave Bands LF 1Hz Exciter

LF 2Hz from the exciter had the highest overall A-weighted SPL on the driver's side of the vehicle followed by the passenger side of the vehicle which was approximately 2.1dBA lower and finally the front of the vehicle which was 12 dBA below the highest microphone. Similarly, to the LF 1Hz this sound had the most frequency content in the 400 and 500Hz 1/3 octave bands. As seen in the overall SPL plot the signal modulated at 4Hz with an amplitude of approximately 1 dBA. This sound was also not FMVSS compliant.

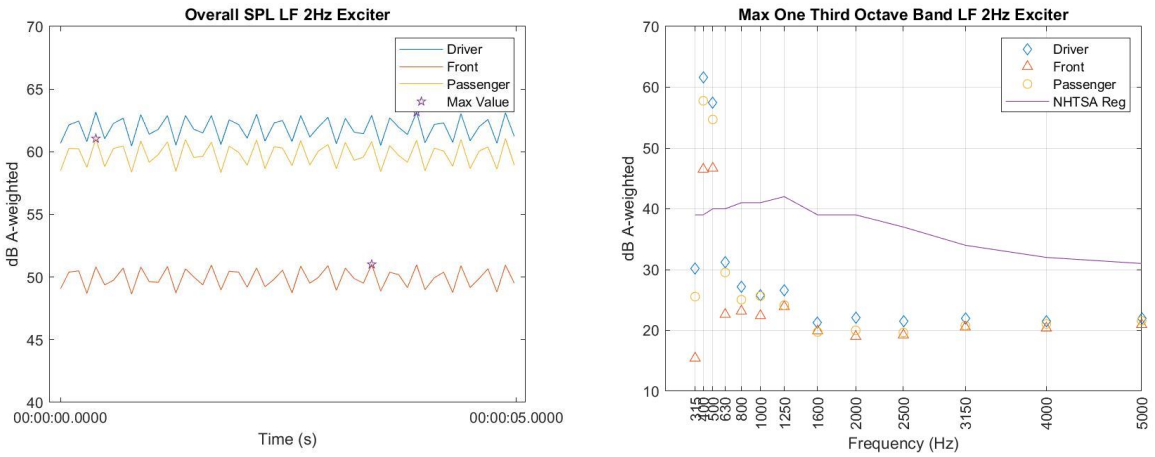

Figure 26 Overall A-weighted SPL and 1/3 Octave Bands LF 2Hz Exciter

HF 1Hz from the exciter had the highest overall A-weighted SPL on the driver's side of the vehicle followed by the passenger side which was approximately 4.3 dBA lower and finally the front of the vehicle which was 9.1 dBA below the highest microphone. This additive sound differed from the low frequency emphasis additive sounds in that the separation between the highest and lowest microphones was lower and yet there was more separation between the passenger and driver sides of the vehicle. This sound had the most frequency content in the 1250 to 2500Hz 1/3 octave bands which was a broader range than seen with the low frequency emphasis additive sounds. As seen in the overall SPL plot the signal modulated at 2Hz with an amplitude of approximately 2.2 dBA. This sound was also not FMVSS compliant.

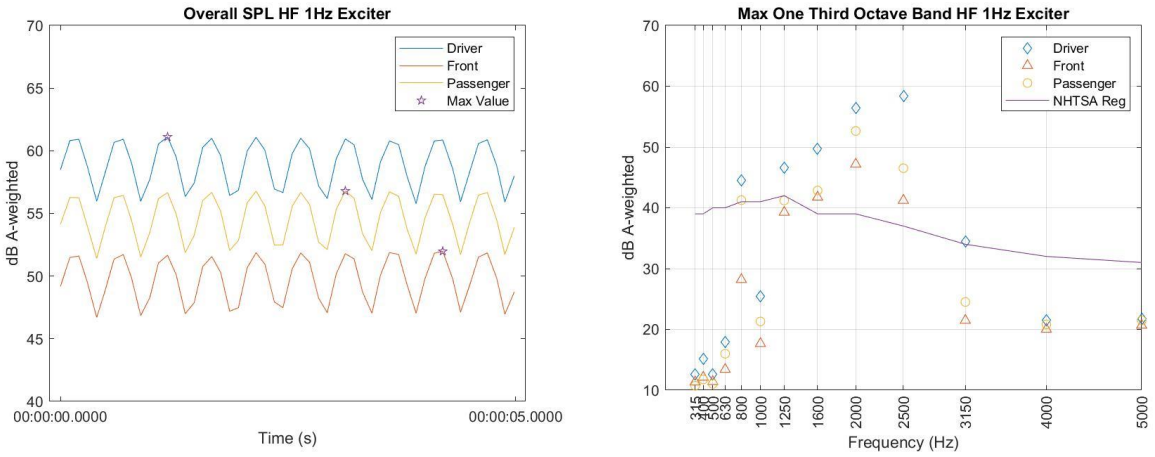

Figure 27 Overall A-weighted SPL and 1/3 Octave Bands HF 1Hz Exciter

HF 2Hz from the exciter had the highest overall A-weighted SPL on the driver's side of the vehicle followed by the passenger side of the vehicle which was approximately 4.3 dBA lower and finally the front of the vehicle which was 9 dBA below the highest microphone. Like HF 1Hz shown above, this additive sound differed from the low frequency emphasis additive sounds in that the separation between the highest and lowest microphones was lower and yet there was more separation between the passenger and driver sides of the vehicle. This sound had the most frequency content in the 1250 to 2500Hz 1/3 octave bands which was a broader range than seen with the low frequency emphasis additive sounds. As seen in the overall SPL plot the signal modulated at 4Hz with an amplitude of approximately 1.2 dBA. This sound was also not FMVSS compliant.

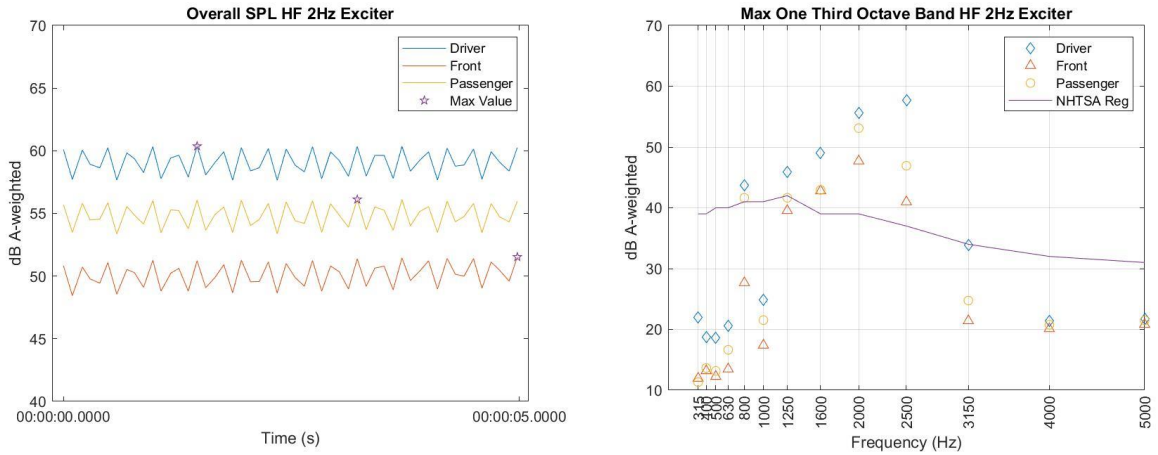

Figure 28 Overall A-weighted SPL and 1/3 Octave Bands HF 2Hz Exciter

FP from the exciter had very similar overall A-weighted SPL on the driver and passenger sides of the vehicle with the driver side being about 0.5 dBA lower. The front of the vehicle had the lowest level which was 6.6 dBA below the highest microphone. This sound did not have as distinct sinusoidal modulation as the previous signals but did display general periodic behavior at a frequency of 1Hz. This sound was compliant to FMVSS 141 regulations. 1/3 octave band data has been omitted due to it being a GM proprietary sound.

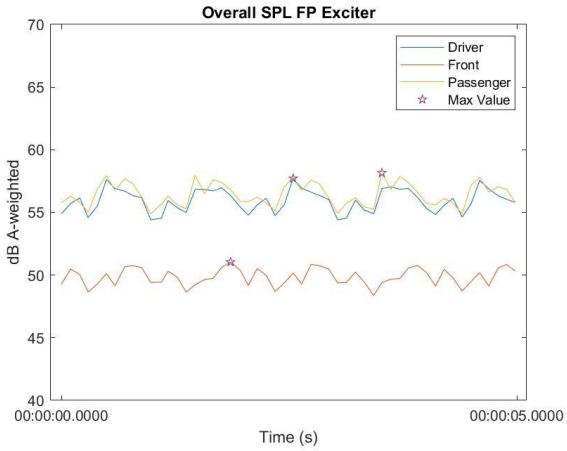

Figure 29 Overall A-weighted SPL FP Exciter

The factory noise was not periodic and had the most frequency content between the 500 and 1250 Hz 1/3 octave bands. Both the driver and passenger sides of the vehicle had similar overall A-weighted SPLs only differing by 0.1dBA. The front of the vehicle had the lowest overall level and was 6.8 dBA below the highest level. This configuration was very close to being FMVSS compliant but fell just short in the 630Hz band.

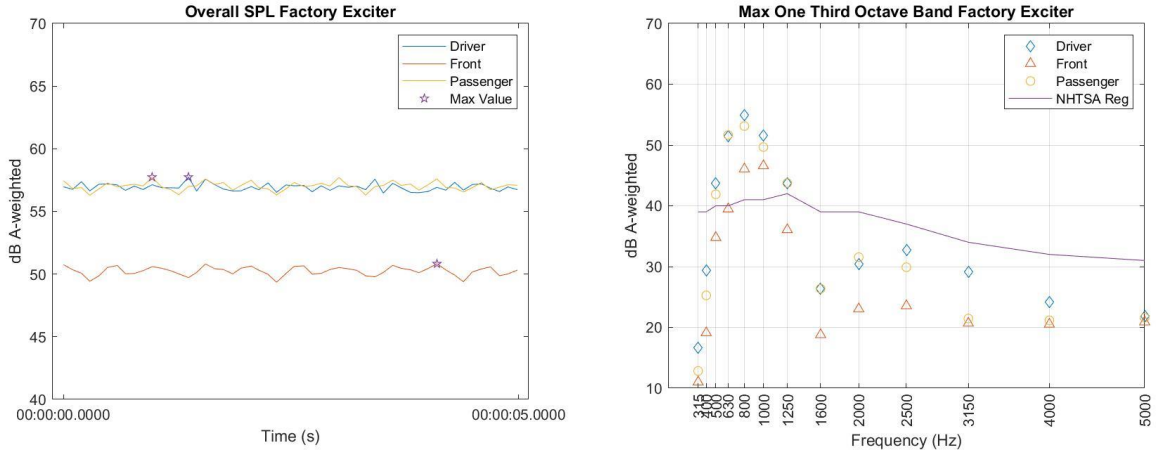

Figure 30 Overall A-weighted SPL and 1/3 Octave Bands Factory Exciter

LF 1Hz from the factory speaker exhibited similar frequency and overall A weighted SPL characteristics to the exciter configuration. This configuration had the highest level on the driver side of the vehicle and had similar levels on the front and passenger sides with the passenger side being 1.3 higher. The overall range between the highest and lowest microphones was less than seen with the exciter configuration with the difference between the highest and lowest microphones being 6.1dBA. This sound was also not FMVSS 141 compliant.

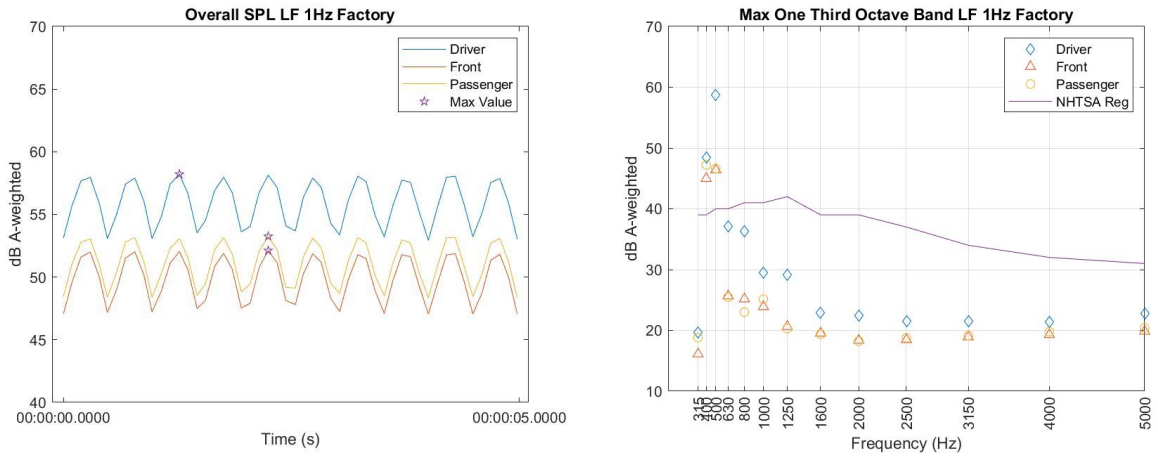

Figure 31 Overall A-weighted SPL and 1/3 Octave Bands LF 1Hz Factory

LF 2Hz from the factory speaker exhibited similar frequency and overall A weighted SPL characteristics to the exciter configuration. This configuration had the highest level on the driver side of the vehicle followed by the passenger and front of the vehicle with the passenger side being 1.5 dBA higher. The overall range between the highest and lowest microphones was less than seen with the exciter configuration with the difference between the highest and lowest microphones being 5.9 dBA. This sound was also not FMVSS 141 compliant.

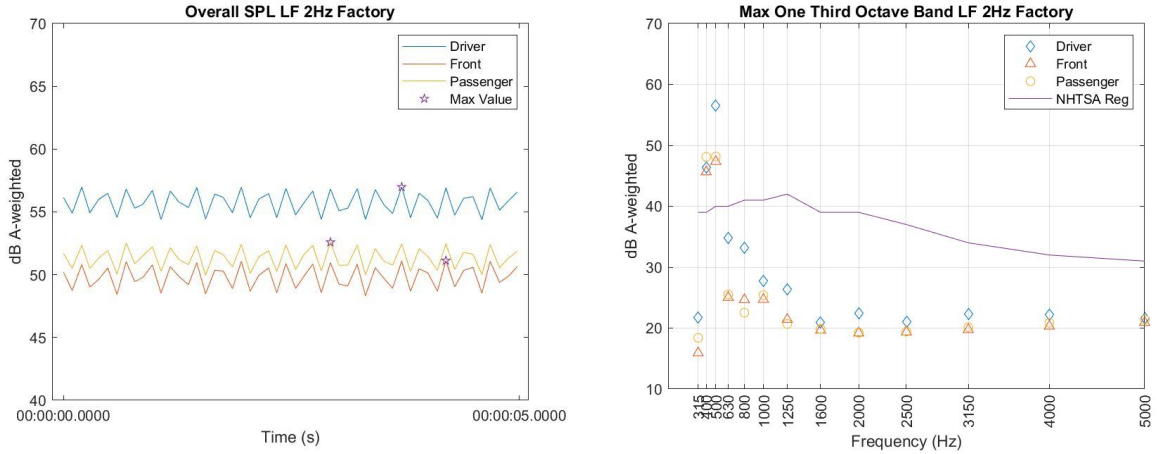

Figure 32 Overall A-weighted SPL and 1/3 Octave Bands LF 2Hz Factory

HF 1Hz from the factory speaker exhibited similar overall A weighted SPL characteristics to the exciter configuration but had lower 1/3 octave band levels particularly in the 1250 and 1600 Hz bands. This configuration had the highest level on the driver side of the vehicle followed by the front and then passenger sides with the front of the vehicle being 1.8

dBA higher. The overall range between the highest and lowest microphones was less than seen with the exciter configuration with the difference between the highest and lowest microphones being 5.6 dBA. This sound was also not FMVSS 141 compliant.

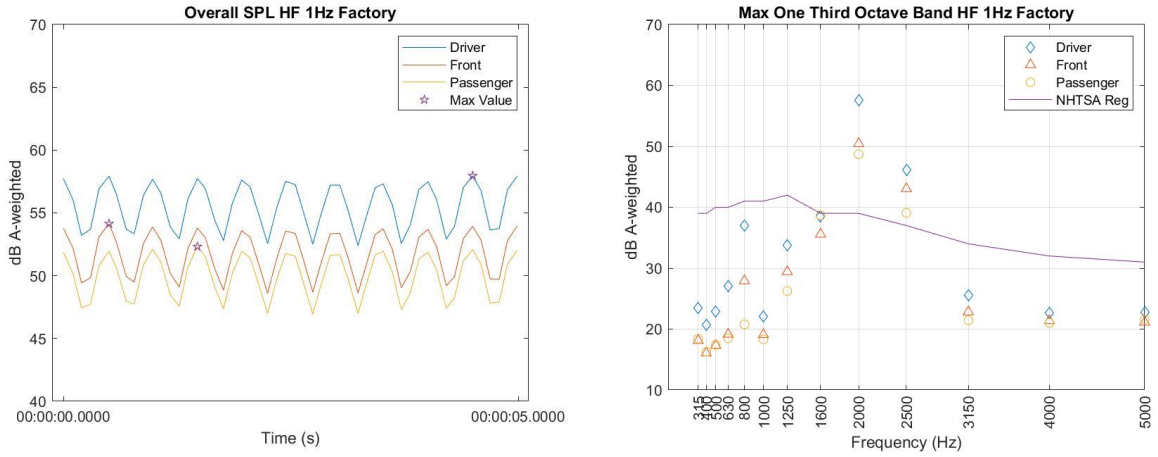

Figure 33 Overall A-weighted SPL and 1/3 Octave Bands HF 1Hz Factory

HF 2Hz from the factory speaker exhibited similar overall A weighted SPL characteristics to the exciter configuration but had lower 1/3 octave band levels particularly in the 1250 and 1600 Hz bands. This configuration had the highest level on the driver side of the vehicle followed by the front and then passenger sides with the front of the vehicle being 1.8 dBA higher. The overall range between the highest and lowest microphones was less than seen with the exciter configuration with the difference between the highest and lowest microphones being 4.9 dBA. This sound was also not FMVSS 141 compliant.

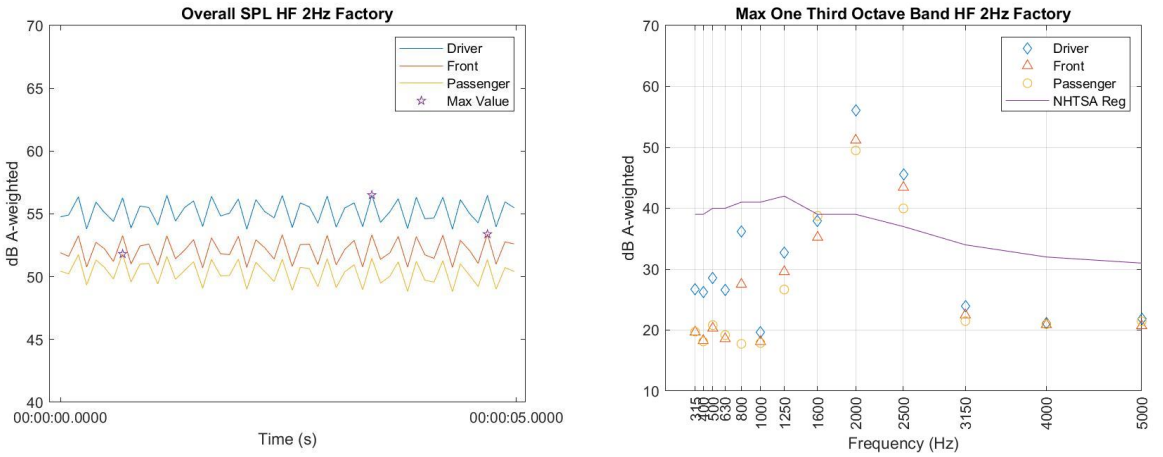

Figure 34 Overall A-weighted SPL and 1/3 Octave Bands HF 2Hz Factory

FP from the factory speaker exhibited similar overall A weighted SPL and frequency characteristics to the exciter configuration. The range between the highest and lowest microphones was much larger for this configuration with the driver side being highest at 11.6 dBA above the lowest microphone level. The front and passenger microphones were similar with the passenger microphone being 2.5dBA above the front. This sound was FMVSS compliant with the 2-band regulatory requirement. 1/3 octave band data has been omitted due to it being a GM proprietary sound.

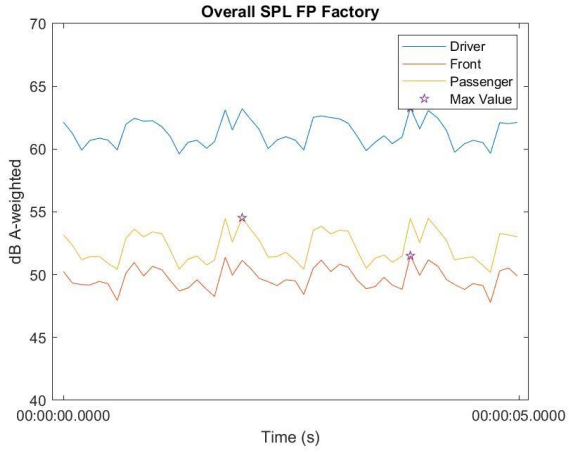

Figure 35 Overall A-weighted SPL FP Factory

The factory noise from the factory speaker exhibited similar overall A weighted SPL and frequency characteristics to the exciter configuration. The range between the highest and lowest microphones was much larger for this configuration with the driver side being highest at 11 dBA above the lowest microphone level. The front and passenger microphones were similar with the passenger microphone being 0.7 dBA above the front. This sound was compliant to FMVSS 141 regulations.

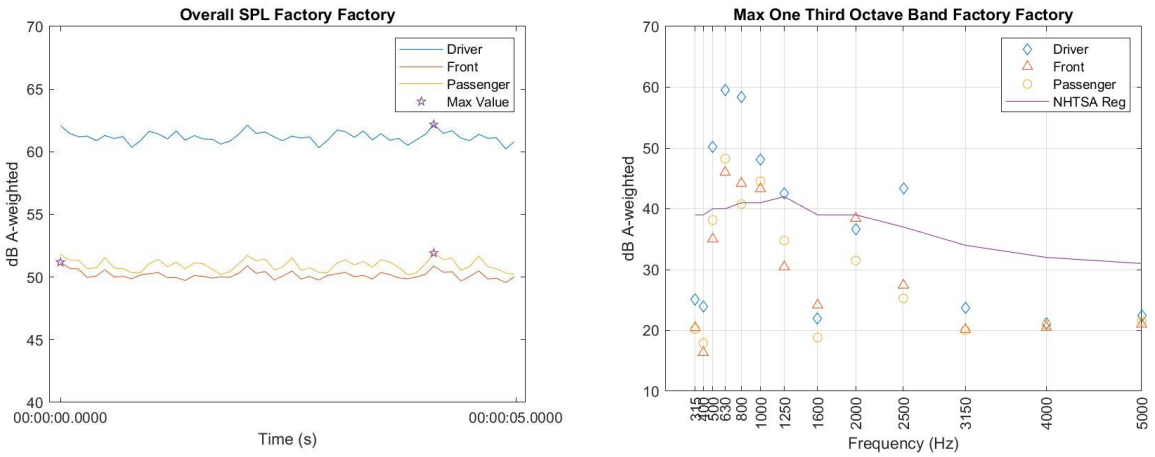

Figure 36 Overall A-weighted SPL and 1/3 Octave Bands Factory Factory

On Road Drive by Verification

On-road drive by tests were used to verify vehicle compliance to FMVSS 141 regulations. To evaluate compliance the two alert band test was utilized with a minimum A-weighted band level of 40dBA and band sum of 44dBA being used for 10km/h tests and a minimum A-weighted band level of 42dBA and band sum of 51dBA being used for 20km/h tests. The minimum overall A-weighted SPL of the passenger and driver side microphone readings were used to determine which side was used to meet FMVSS regulations. Maximum A-weighted 1/3 octave band levels during the vehicle pass by were determined for the side with the lower overall A-weighted SPL and were compared to FMVSS regulations for the given speed condition.

All additive sound solutions were able to exceed regulatory requirements for both the 10 and 20 km/h speed conditions. The no additive sound conditions were able to exceed regulatory requirements for all 20 km/h cases and the right approach direction at 10 km/h. Regulations were not met for the left approach direction at 10km/h.

It is worth noting that our test speeds were on the borderline of regulatory limits. Since the vehicle can be tested up to but not including the top speed for a regulatory limit it was deemed most appropriate to use the 0-10 km/h regulations for the 10 km/h test conditions and the 0-20km/h regulations for the 20km/h test conditions. While these speed ranges are not inclusive of the upper limit it was deemed more appropriate than testing at the slowest speed in the regulatory speed range.

Lab Playback Compared to On-road Recordings

Vehicle pass by audio in the ASPIRE Lab and on the Smart Road was compared by looking at both the overall A-weighted SPL and the A-weighted 1/3 octave bands. Acoustic measurements taken at the location of the sound field microphone on the Smart Road were compared to measurements taken at the center of the ASPIRE lab. If the lab environment replicated the on-road environment completely the acoustic measurements at these two locations should match. To make these comparisons, the measurements needed to first be synchronized to allow for the audio to be compared with the simulated vehicle distance in the lab matching the on-road vehicle distance. This was accomplished by first aligning the overall A-weighted SPL peaks and then plotting and trimming the in-lab data to align with on-road measurements.

Two plots showing characteristic signal alignment are shown below in Figure 37. As seen in these plots, in general good alignment was observed between the lab and on-road environments when looking at the overall A weighted SPL. The on-road and in lab overall A weighted SPLs seem to overlay well and match in shape and level. The overall SPL in the lab ramps up at the approximate same distance as seen on the Smart Road and peaks at a similar level. As previously noted, in-lab measurements were set to be slightly higher than the recordings completed on-road. This was done to accommodate the additive sound volume mistakenly being set slightly lower during recordings than during participant tests. This is seen below where the in-lab peak is slightly above the on-road peak. It was also observed that the overall A weighted SPL in the lab at the start of the recording, when there was no significant audio coming from the approaching vehicle, was higher in the lab than on the Smart Road. This was due to the on-road background noise on the Smart Road being captured in each sound field recording. This background noise was then played on top of the background noise in the lab raising the overall level.

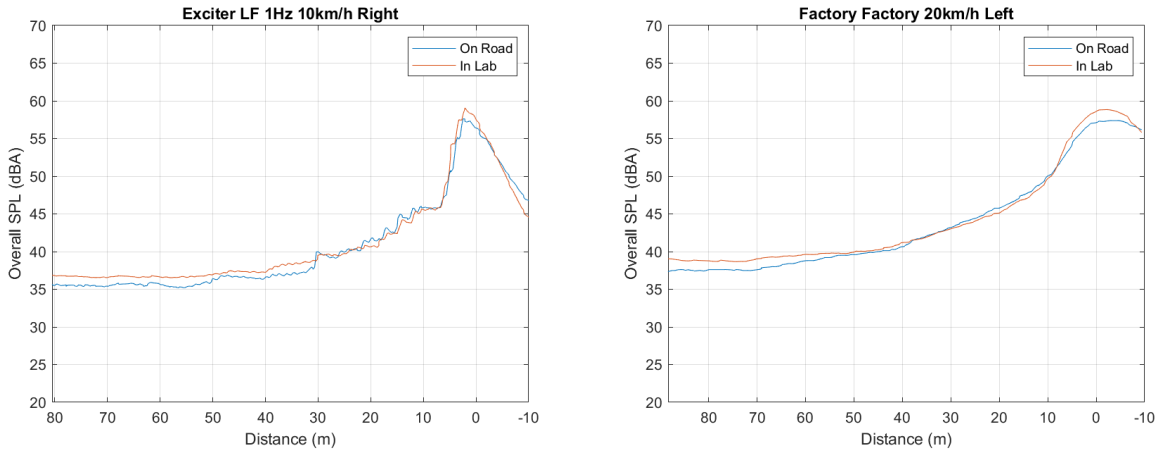

Figure 37 Overall A-Weighted SPL Lab vs. Road

Comparisons were also made using the 1/3 octave band data. For these comparisons road and lab octave band data was first aligned and then the 1/3 octave band levels on the road were subtracted from the 1/3 octave band level in the lab. This results in the ratio between the lab and the road being easily computed. To visualize these results, the octave band data was plotted as a surface. Two of plots characteristic of the results obtained and corresponding to the overall SPL results shown above are shown below in Figure 38. As seen in the plots, in the octave band levels from 20-315 Hz the lab typically had higher levels than were seen on the Smart Road. In the 1/3 octave bands from 400 to 1250 Hz the band levels in the lab initially start out very similar to those seen on the Smart Road as the vehicle is approaching and then the levels on the road exceed those seen in the lab as the vehicle gets closer to the microphone.

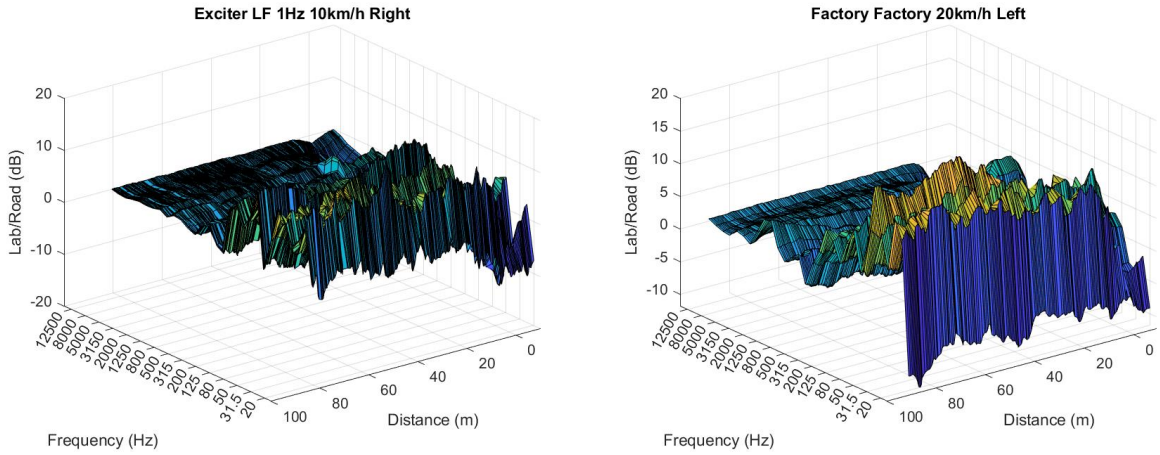

Figure 38 Lab to Road Ratio 1/3 Octave Bands

This analysis provides interesting insight into the differences in frequency content in the lab an on-road environments. It appears there is low/mid frequency resonation in the lab causing there to be more low frequency content than there should be to ideally replicate the recordings taken on-road. This could potentially have been from the lab not being as anechoic as necessary to prevent sound reflections from bouncing off the walls and equipment, causing higher band levels than on the road.

Participant Tests

On road participant tests were used to evaluate the performance of both the different sound systems and the additive sounds. Detection distance data was split by speed and environment and an ANOVA analysis ($\alpha = .05$) was completed using speaker, additive sound, direction, and participants as grouping variables. At 10 km/h approach speed statistically significant differences were observed for the speaker, sound, and participant with respective p values of $3.1 * 10^{-5}$, $1.9 * 10^{-53}$,and $4.1 * 10^{-33}$. Statistically insignificant differences were seen for the approach direction. At the 20 km/h approach speed statistically significant differences were observed for the additive sound, direction, and participant with respective p values of $3.2 * 10^{-9}$,0.02 ,and $7.8 * 10^{-35}$. Statistically insignificant differences were observed for the speaker.

Sound performance was evaluated statistically using a multiple comparison test and quantitatively using mean detection distances. At 10 km/h LF 1Hz and LF 2Hz from both the exciter and factory speaker had mean detection distances statistically different than all other additive sound and speaker combinations. For these test noises, mean detection distances ranged from a high of 70.4m (Factory LF 1Hz) to 56.0m (Exciter LF 1Hz). This performance was 3.5 times better than the lowest performing additive sound (Exciter HF 2Hz) which had a mean detection distance of 20.3m. HF 1Hz, HF 2Hz, and the Factory additive sounds had statistically similar performance to the no speaker and no sound configuration. The no speaker and no sound configuration had the second lowest performance with a mean detection distance of 22.1m. Despite the large variation of detection distances, all participants detected the vehicle at distances greater than the 5m suggested by the NHTSA. The average detection distance for all noise configurations was 39.8m with a standard deviation between configurations of 17.6m. The plot shown below in Figure 39 illustrates on-road sound performance at the 10 km/h speed condition. The error bars shown denote the standard error for each configuration.

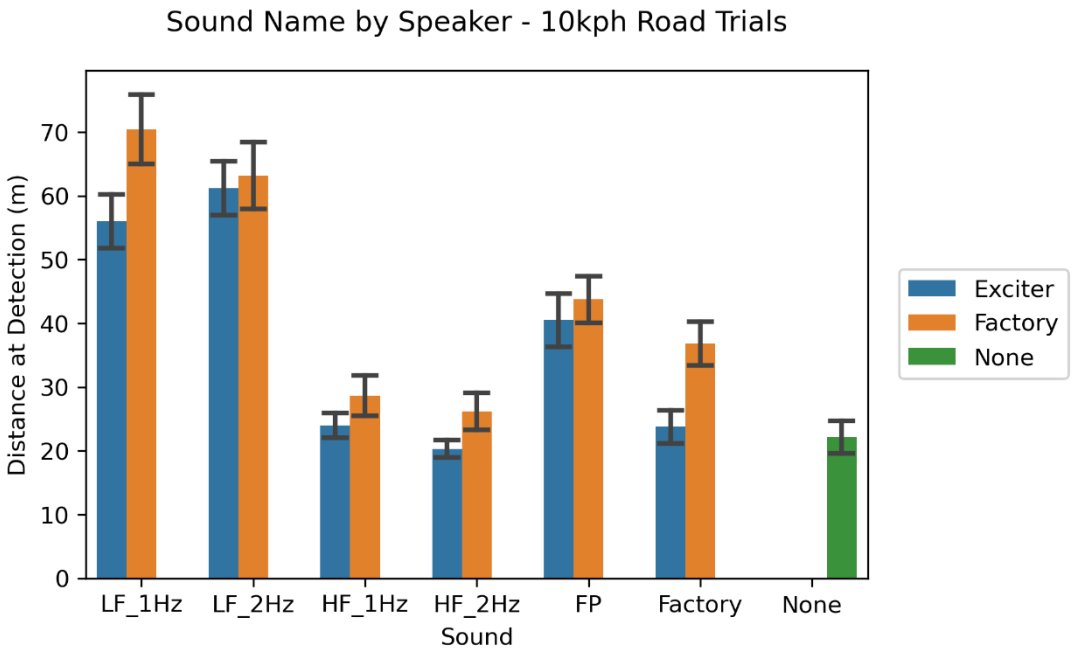

Figure 39 Exciter vs. Factory at 10 km/h

At 20 km/h low frequency sounds still had the best performance, but a less dramatic of a difference was observed. LF 1Hz from the factory speaker was the best performing low frequency noise with a mean detection distance of 72.6 and was the only configuration that was statistically different from all the non-low frequency emphasis additive sounds. LF 2 Hz from the exciter was the had the worst performance of the low frequency emphasis sounds with a mean detection distance of 65.8m and was only statistically different from HF 2Hz from the exciter, FP from the exciter, and the Factory noise from the exciter. Detection distances ranging from 49.2m to 56.0m were observed for non-low frequency additive sounds. LF 1Hz from the factory speaker was the only configuration to be statistically different than the no sound no speaker configuration. The average detection distance for all noise configurations was 58.0m with a standard deviation between configurations of 7.7m. This variation was significantly less than was observed at the 10km/h speed condition. The plot shown below in Figure 40 illustrates on-road sound performance at the 20 km/h speed condition. The error bars shown denote the standard error for each configuration.

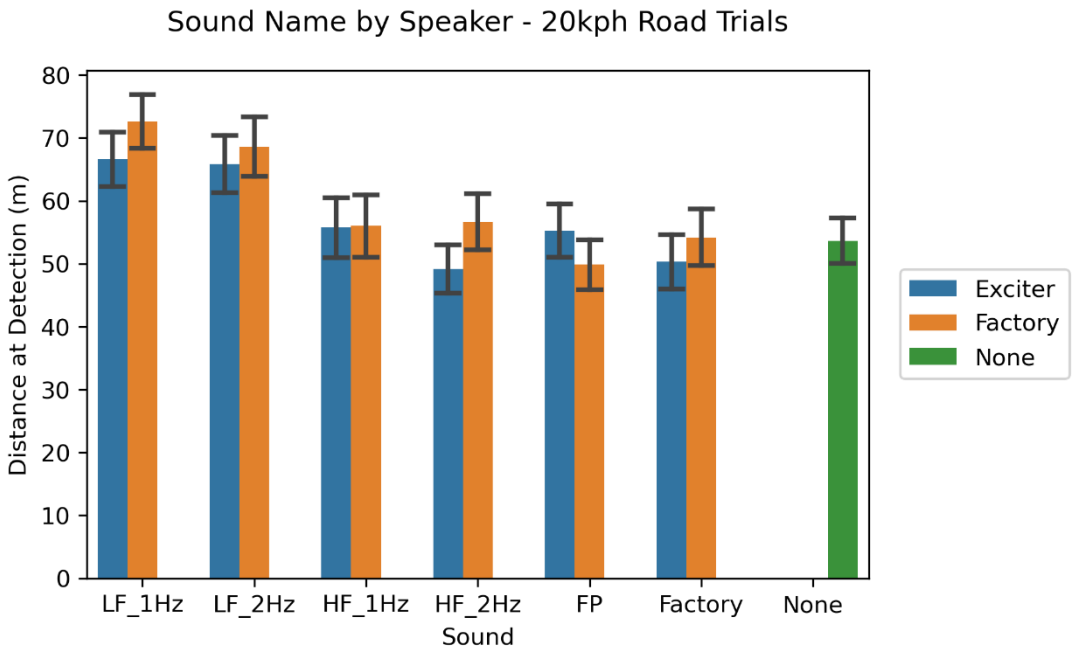

Figure 40 Exciter vs. Factory at 20 km/h

A significant difference was observed between the on-road and in lab environments. An ANOVA analysis was performed to compare the lab and on-road environments using the speaker, sound, speed, direction, participant, and environment as grouping variables and an alpha significance value of 0.05. When comparing the two environments a p value of $1.5 * 10^{-79}$ was obtained. This shows strong evidence that the lab environment varies significantly from the on-road environment. This was corroborated by comparing mean detection distances in the lab to those observed on the road. An average decrease in detection distance of 12.9m and 25.8m was observed in the lab environment at the 10 km/h and 20 km/h approach speeds respectively. Despite the significantly lower detection distances observed, similar performance ordering was seen in the lab environment. At the 10 km/h and 20 km/h approach speeds the low frequency additive sounds had the best performance. At 10km/h approach speed the FP and factory sound had the next best performance followed by the high frequency additive sounds and the no sound conditions. At the faster 20 km/h speeds all non-low frequency noises had similar performance. The decrease in average detection distances is shown below in Figure 41 which illustrates the average detection distances at both speed conditions for each environment.

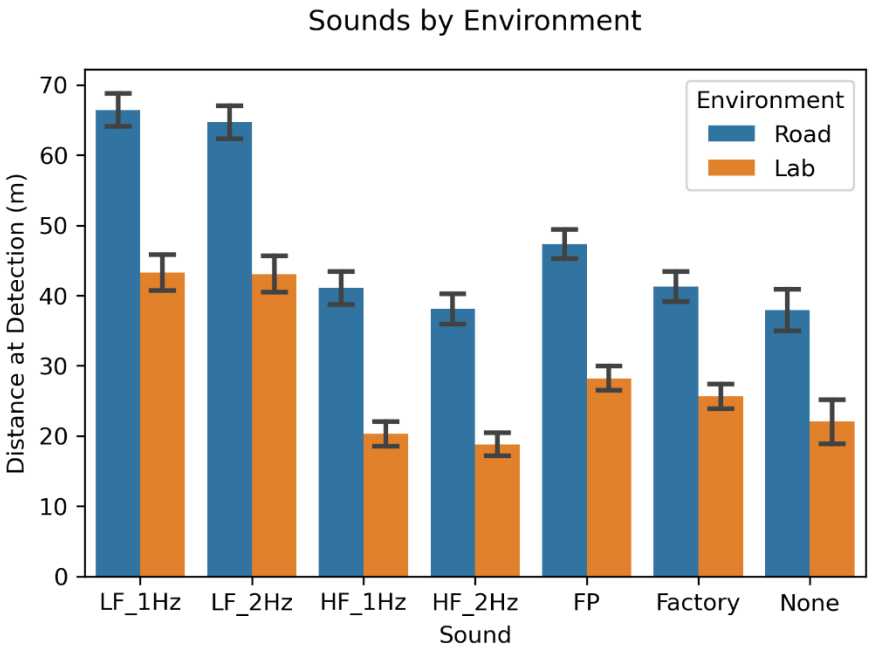

Figure 41 Road vs. Lab Detection Distances for All Speed Conditions

Interior Vehicle Measurements

At the 10 km/h approach speed minimal differences were observed between the overall A-weighted sound levels on the driver and passenger sides of the vehicle. The driver's side microphone was consistently higher by a negligible 0.15 dBA for the exciter configuration and the passenger microphone was 0.2dBA higher for the factory speaker. Similarly, a small difference was observed when comparing the interior noise levels produced by the factory speaker and the exciter transducer configurations. The largest difference was observed for the low frequency emphasis additive sounds where the exciter was approximately 1.5dBA louder than the factory speaker. The HF 1Hz and FP additive sounds had the lowest interior sound levels. These sound levels are shown below in Figure 42.

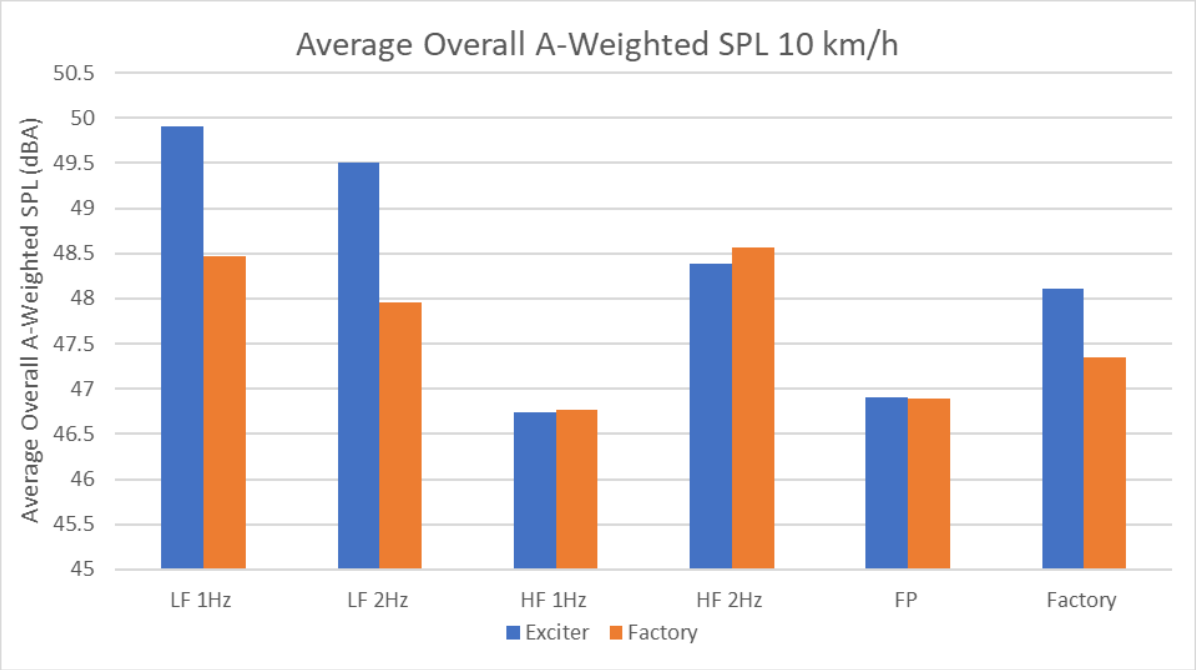

Figure 42 10 km/h Interior Vehicle Measurements

At the 20 km/h approach speed slightly higher and yet similarly minimal differences were observed between the overall A-weighted sound levels on the driver and passenger sides of the vehicle. The driver's side microphone was consistently higher by a negligible 0.8 dBA on average. Similarly, a small difference was observed when comparing the interior noise levels produced by the factory speaker and the exciter transducer configurations. The largest differences were observed for LF 1Hz and HF 1Hz where the exciter was approximately 1.2dBA louder than the factory speaker. These sound levels are shown below in Figure 43.

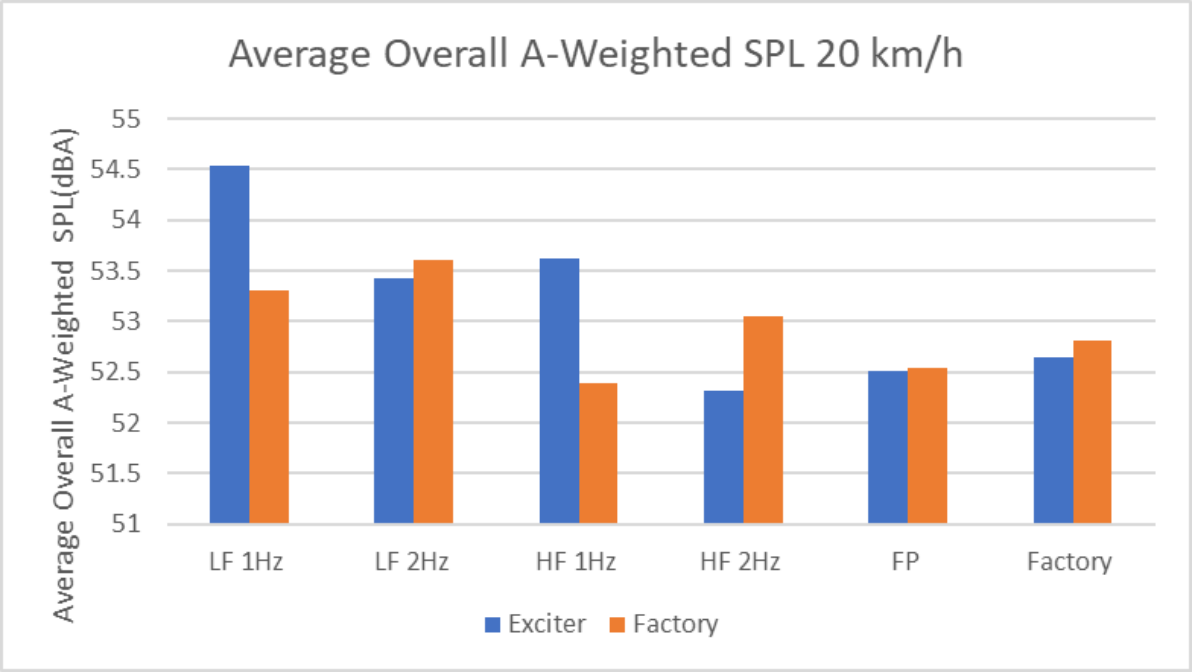

Figure 43 20 km/h Interior Vehicle Measurements

Discussion

Stationary testing results were particularly surprising as all additive sounds were designed to have sufficient frequency content to meet the two-band requirement. This suggests that the amplifier/speaker combinations either attenuated the signal in the necessary frequency regions or that the additive sounds needed more frequency content in these regions. This could have been resolved by either raising the volume of the additive sounds or by tuning each sounds' frequency content to meet the regulations. Raising the volume was not desired as it was deemed more appropriate to compare the additive sounds at equal minimum overall A-weighted SPL than to adjust each sound to meet regulations and have widely varying volumes. Except for the HF 1Hz and HF 2Hz additive sounds, all additive sounds had the lowest overall A-weighted SPL in the front of the vehicle. HF 1Hz and HF 2Hz had the lowest level on the passenger side of the vehicle followed by the front of the vehicle which was approximately 2dBA lower. The overall A-weighted SPL coming towards the participants from the front of the vehicle should be approximately the same for each additive sound. The overall A-weighted SPL will start to vary more as the vehicle starts to pass the participants and the sound coming from the sides of the vehicle becomes a more dominant source of noise.

The high frequency emphasis additive sounds consistently underperformed the other signals. This leads to several potential conclusions either the high frequency noise that participants associated with a vehicle did not project as far from the vehicle, the additive sound was not associated with an approaching vehicle by participants, or the additive sound was more effectively masked by the additive background noise. When the overall A-weighted SPL recorded without additive background noise was plotted for low and high frequency noises for the 10km/h speed condition (where the additive sound has the highest impact) it was observed that while there was some variation between trials and sounds both the low and high frequency emphasis sounds ramped up from the background noise level towards their peak value at approximately the same distance from the microphone and consistently before the no sound condition for the factory speaker. For exciter configurations the sound level ramped up earlier for the low frequency sound conditions followed by the high frequency sounds and then the no sound conditions. It was also observed that all additive sound conditions reached peak sound levels considerably higher than the no sound condition. Since low frequency sounds had higher detection for both the factory and exciter conditions it can be assumed that the earlier ramping up of the sound level for the exciter configurations is unlikely to be a significant factor in the detection differences observed. Since all additive sounds had higher sound levels during pass by than the no sound condition it seems likely that the high frequency additive sounds are simply not as recognizable as an approaching vehicle by pedestrians.

High and low emphasis additive sounds were originally chosen to explore the difference between the further propagation distances inherent of low frequency noises and the higher detectability of high frequency noises. This study showed that the low frequency was much more effective at alerting pedestrians of an oncoming vehicle than the high frequency additive sounds. This trend suggests that the theoretical longer propagation distance of the low frequency noise is more important than the increased detectability of the high frequency noise. Since A-weighted overall SPL and 1/3 octave bands were used to assess sound levels it is possible that the low frequency does propagate further, but since it is not weighted as heavily as the higher frequency content and thus does not permeate as heavily into the overall A-weighted SPL measurements mentioned above.

Stationary tests also showed that the bonded exciter did a good job at creating uniform sound at the passenger and driver sides of the vehicle but produced a lower A-weighted SPL at the front of the vehicle. The overall A-weighted SPL at the front of the vehicle ranged from 12.1 to 6.6 dBA lower than the highest A-weighted SPL. When used with the FP and Factory sounds the exciter was able to produce more uniform overall A-weighted SPLs around the vehicle than the factory speaker. As these were the sounds that were FMVSS compliant it suggests that the exciter may be more effective at creating a uniform sound field around the vehicle when used in conjunction with broader frequency content non-modulating additive sounds. Exciter performance would likely be able to be tuned by adjusting the location and number of bonded exciters used. Based on the results seen in this research an iterative approach of bonding exciters and checking vehicle performance in an outdoor anechoic environment would be more appropriate.

Drive by tests provided similar results to past phases of research. Additive sound solutions met FMVSS regulations more easily than the no sound condition. Additionally, at the higher approach speed of 20 km/h all configurations including the no sound conditions met regulatory requirements. Since approach speeds of 10 and 20 km/h were used to align with previous phases of testing, it was deemed most appropriate to use regulatory limits for 0-10km/h approach speeds for the 10 km/h drive by tests and regulatory limits for 10-20km/h approach speeds for the 20 km/h drive by tests. This meant that tests were conducted at the top end of the speed range rather than the lowest possible speed to meet regulations.

Participant testing in the lab environment was not able to replicate on-road tests as well as the team had initially hoped. The lab environment typically resulted in lower detection distances, but similar configuration ordering as seen on the Smart Road. In general, good alignment between the overall A-weighted SPL in the lab and smart road was observed, it is postulated that differing frequency content could be a potential cause for the differences observed. Another hypothesis is that participants were able to hear the vehicle before a noticeable signal was obtained by the sound field microphone. Since the sound field microphone has a self-noise floor of 19dBA, which is well below the background noise and vehicle acoustics this was deemed to be an unlikely cause of misalignment. Another potential cause could have been the sound field microphone’s spatial resolution, which was specified as 5 degrees or less by

the manufacture. While this would explain a slight misalignment between environments it does not explain the differences observed in this study.

Frequency analysis provided interesting insight into the causes of potential misalignment between the lab an on-road environments. It appears there is low/mid frequency resonation in the lab in the 20-315Hz region causing there to be more low frequency content than there should be to ideally replicate the recordings taken on-road. This could have been from the lab not being as anechoic as necessary to prevent sound reflections from bouncing off the walls and equipment, causing higher band levels than on the road. In the higher frequency regions (8-12.5 kHz) the on-road environment appears to initially be well represented shown by the ratio maintaining close to a 0 dB level. As the vehicle approaches the ratio dips below zero indicating that on-road levels are higher on-road than represented in the lab environment. As the recording levels were set based on the overall A-weighted SPL recorded in the lab, the frequency misalignment would permeate into the volume that each recording was set to. It also would show up in participants ability to effectively detect approaching vehicles in the lab environment since participants may cue based on different frequency signatures better than others.

Conclusions and Recommendations

On road testing shows the highest performing additive sounds were those with a low frequency emphasis (LF 1Hz and LF 2Hz). This is followed by those with broader frequency content around the 1 kHz 1/3 octave band and no modulation (FP and Factory). The high frequency additive sounds had similar performance to the no-sound condition, suggesting they were not effective at warning pedestrians of an approaching vehicle. These trends were seen in both the on-road and in lab studies.

Modulation rates did not have a large influence with both 1Hz and 2Hz rates, performing similarly for both low and high frequency emphasis additive sounds. This trend was corroborated by the FP and Factory noises outperforming the modulating high frequency sounds. Despite the large variation in detectability all configurations met NHTSA suggested minimum detection distances for drive by tests. Despite these sounds meeting regulations, it is recommended that future testing employ stationary-test compliant noises, for broader applicability to production vehicle sounds. To achieve standard compliance, the sounds used in this study could be modified by changing the base signals frequency content slightly to straddle the 1 kHz 1/3 octave band and

thus more easily meet the two-band regulatory requirement. Compliance would be verified with stationary tests to confirm the new signal meets requirements when paired with both systems.

This research focused primarily on the frequency content and modulation levels of additive sounds and tried to eliminate participant conditioning as much as possible. Conditioning is likely to play a role in participants, and pedestrians, abilities to detect an oncoming vehicle. As seen in this research some sounds, such as the HF 1Hz and HF 2Hz, are not easily recognized as an approaching vehicle. While there are scientific methods to design sounds for optimum detectability it is also important for participants to become trained to associate the different additive sounds with an approaching vehicle. This would be an interesting next phase of research. Testing could be conducted to train one group of participants to associate different warnings sounds with vehicles by playing them the additive sounds and drive by recordings in advance. Then, like this research, drive by tests could be conducted to compare the trained participants with a control group who had never heard the sounds before. These tests would either prove or disprove the importance of conditioning at risk pedestrians to the increasing danger of electric vehicles.

The exciter transducer configuration was able to create more uniform sound levels on the left and right sides of the vehicle than the factory speaker, but consistently had lower sound levels in the front of the vehicle. This suggests that the sound is projecting mostly to the sides of the vehicle rather than uniformly in all directions. A second step to further iterate on this prototype design would be to set up more microphones around the vehicles at varying distances and heights rather than relying on the setup outlined in regulatory requirements. Then an additive sound could be played, and the average overall A-weighted SPL could be used to plot the sound field around the vehicle. The results could then guide the placement of bonded excites to locations that would project sounds towards locations with lower sound levels. This would need be tuned using an iterative approach of bonding the exciters in different locations and then performing stationary testing to check the results. It would also be beneficial to have adjustable gain for each of the exciters to tailor spatial noise characteristics with directional consideration. Another potential solution could be a hybrid between a standard diaphragm speaker and the bonded exciters. This system would help to provide the advantages of the more uniform sound field provided by the exciter transducer, and the flatter frequency response of a diaphragm speaker. Panel structural dynamics and exciter placement, in addition to additive sound frequency content, influence spatial

and spectral sound propagation. Consequently, measuring and characterizing projected warning signatures at varying locations around the vehicle is imperative to efficient warning system design.

Both analytical and empirical methods would help guide design refinements related to spatial and spectral sound propagation. Analytical methods include flexible-body finite element analysis, depicting modes and forced operating deflections, influencing exciter placement. Empirical measures include inputted additive sound to sound-pressure-level frequency response, an objective characterization of end-to-end coupling would show spectral and spectral dependencies to system design. Given objective projected spatial and spectral characteristics, responses would likely influence additive sound design, and potentially additional filtering to invert aggregate structural-acoustic dynamics. While out of scope for this iteration of research it would be a good way to place the bonded exciters and design additive sound signals more scientifically.

For future testing it is recommended that all iteration of speaker and sound design be conducted outdoors in as semi anechoic environment as possible. When primary iterations of speaker design were conducted for this research, they were done in a large garage bay. The acoustic reflections produced by this environment altered the measurements taken and made the systems seem to produce more uniform sound levels than they did in later outdoor tests. This stopped further iterations of speaker design.

Further investigation is needed to verify the cause of the misalignment between the lab and road environments. It is recommended that the frequency characteristics of both the in lab and on-road environments be determined and compared. The determined frequency characteristics would highlight the frequency regions that differed between the two environments and guide modification to the lab to increase the perceived reality in the lab. From the 1/3 octave band data comparisons made in this research it appears that there may be more resonation than desired in the lab environment. Some potential modifications that may be necessary to reduce further reduce acoustic reflections and resonation in the lab could potentially be adding more acoustic damping to the ceiling and floor and moving as much necessary equipment as possible as well as the researcher out of the lab. This would allow for more acoustic dampening material to be added to lab and the number of screens and reflective surfaces to be minimized. Since the largest differences between the lab and on-road environments were observed in the lower frequency regions it seems probable

that there is resonation in these frequency regions. Once characterized this could be improved by adding bass traps to absorb and dissipate energy in these regions and flatten the overall frequency response in the lab. Iterative measure would likely be necessary until the frequency content measured on the road matches that measured in the lab.

It is likely that with acoustic reflections minimized that participant perceived directionality of approaching vehicles would be improved. With a reflective environment the participant is not only experiencing the acoustics from the source, but also all its reflected audio. This would make it more difficult to pinpoint where the source is and if it is approaching or receding. In the case of this research, it is possible that the reflections present in the lab made it more difficult for participants to pinpoint the vehicle audio and determine if it was an approaching danger. While not as easily improved, increased directionality could be provided by a larger lab environment. This would improve the spatial resolution of the environment and increase pedestrians' ability to detect vehicle movement and thus provide them with a more realistic experience of the vehicle drive by audio.

To improve the recordings used in the lab environment it would be recommended to upgrade the sound field microphone used to take on-road recordings. For this research a Core Sound 1st order ambisonic tetra mic was used to record all the audio played in the lab. For future efforts it would be recommended to use a newly released Core Sound 2nd order ambisonic octo microphone. This upgraded microphone is better at preserving perceptual cues required for a listener to precisely locate sound sources, provides a much larger "sweet spot" in the lab where audio sounds most realistic to listeners and can be used 50% farther away from the sound source while maintaining the same directivity index. These improved characteristics would improve the directionality of the source, provide all four participants with a more realistic experience in the lab, and provide participants with better cues to perceive the approaching vehicle.

Appendix

Appendix A FMVSS 141 Four Band SPL Levels

	Minimum Sound Pressure Level A weighted dB				
One-third octave band center frequency, Hz	Stationary and speeds under 10 kph	Speeds above 0 kph and under 20 kph	Speeds above 20 kph and under 30kph	Speeds 30-32 kph	Reverse 0 kph
315	39	45	52	56	42
400	39	44	51	55	41
500	40	46	52	57	43
630	40	46	53	57	43
800	41	47	53	58	44
1000	41	47	54	58	44
1250	42	48	54	59	45
1600	39	44	51	55	41
2000	39	45	51	55	42
2500	37	43	50	54	40
3150	34	40	47	51	37
4000	32	38	45	49	35
5000	31	36	43	47	33

Appendix B FMVSS 141 Two Band SPL Levels

	Sound Pressure Level A-weighted dBA	
Speed Condition	Minimum in Both Bands	Band Sum
Stationary and speeds under 10 kph	40	44
Speeds above 0 kph and under 20 kph	42	51
Speeds above 20 kph and under 30kph	47	57
30 kph	52	62
Reverse 0 kph	40	48

Appendix C Participant Testing Order

Session 1

Task Code	**Speaker**	**Sound**	**Speed**	**Direction**
1311	Exciter	HF_1Hz	10	Left
3722	None	None	20	Right
2421	Factory	HF_2Hz	20	Left
1212	Exciter	LF_2Hz	10	Right
1321	Exciter	HF_1Hz	20	Left
3712	None	None	10	Right

1211	Exciter	LF_2Hz	10	Left
1612	Exciter	Factory	10	Right
2311	Factory	HF_1Hz	10	Left
2612	Factory	Factory	10	Right
3721	None	None	20	Left
1122	Exciter	LF_1Hz	20	Right
2121	Factory	LF_1Hz	20	Left
1412	Exciter	HF_2Hz	10	Right
1121	Exciter	LF_1Hz	20	Left
2112	Factory	LF_1Hz	10	Right
1521	Exciter	FP	20	Left
1622	Exciter	Factory	20	Right
2111	Factory	LF_1Hz	10	Left
1222	Exciter	LF_2Hz	20	Right
1421	Exciter	HF_2Hz	20	Left
2122	Factory	LF_1Hz	20	Right
1621	Exciter	Factory	20	Left
1312	Exciter	HF_1Hz	10	Right
1411	Exciter	HF_2Hz	10	Left
2522	Factory	FP	20	Right
2211	Factory	LF_2Hz	10	Left
1112	Exciter	LF_1Hz	10	Right
2511	Factory	FP	10	Left
2312	Factory	HF_1Hz	10	Right
1511	Exciter	FP	10	Left
2622	Factory	Factory	20	Right
2321	Factory	HF_1Hz	20	Left
1512	Exciter	FP	10	Right
1611	Exciter	Factory	10	Left
2412	Factory	HF_2Hz	10	Right
2611	Factory	Factory	10	Left
1322	Exciter	HF_1Hz	20	Right
2621	Factory	Factory	20	Left
2422	Factory	HF_2Hz	20	Right
1111	Exciter	LF_1Hz	10	Left
2212	Factory	LF_2Hz	10	Right
2411	Factory	HF_2Hz	10	Left
1422	Exciter	HF_2Hz	20	Right
2221	Factory	LF_2Hz	20	Left
2512	Factory	FP	10	Right
3711	None	None	10	Left
1522	Exciter	FP	20	Right
1221	Exciter	LF_2Hz	20	Left

2222	Factory	LF_2Hz	20	Right
2521	Factory	FP	20	Left
2322	Factory	HF_1Hz	20	Right

Session 2

Task Code	**Speaker**	**Sound**	**Speed**	**Direction**
1121	Exciter	LF_1Hz	20	Left
2112	Factory	LF_1Hz	10	Right
2511	Factory	FP	10	Left
2412	Factory	HF_2Hz	10	Right
1321	Exciter	HF_1Hz	20	Left
1122	Exciter	LF_1Hz	20	Right
2521	Factory	FP	20	Left
1522	Exciter	FP	20	Right
1621	Exciter	Factory	20	Left
1112	Exciter	LF_1Hz	10	Right
2411	Factory	HF_2Hz	10	Left
1622	Exciter	Factory	20	Right
1311	Exciter	HF_1Hz	10	Left
2512	Factory	FP	10	Right
1211	Exciter	LF_2Hz	10	Left
2622	Factory	Factory	20	Right
2421	Factory	HF_2Hz	20	Left
2122	Factory	LF_1Hz	20	Right
1411	Exciter	HF_2Hz	10	Left
2222	Factory	LF_2Hz	20	Right
1521	Exciter	FP	20	Left
1412	Exciter	HF_2Hz	10	Right
2221	Factory	LF_2Hz	20	Left
1612	Exciter	Factory	10	Right
2111	Factory	LF_1Hz	10	Left
1422	Exciter	HF_2Hz	20	Right
3721	None	None	20	Left
2612	Factory	Factory	10	Right
2311	Factory	HF_1Hz	10	Left
1512	Exciter	FP	10	Right
2611	Factory	Factory	10	Left
1212	Exciter	LF_2Hz	10	Right
2121	Factory	LF_1Hz	20	Left
1322	Exciter	HF_1Hz	20	Right
1111	Exciter	LF_1Hz	10	Left
2312	Factory	HF_1Hz	10	Right

1611	Exciter	Factory	10	Left
2422	Factory	HF_2Hz	20	Right
2211	Factory	LF_2Hz	10	Left
1312	Exciter	HF_1Hz	10	Right
1421	Exciter	HF_2Hz	20	Left
3722	None	None	20	Right
1511	Exciter	FP	10	Left
2322	Factory	HF_1Hz	20	Right
3711	None	None	10	Left
2212	Factory	LF_2Hz	10	Right
2321	Factory	HF_1Hz	20	Left
1222	Exciter	LF_2Hz	20	Right
2621	Factory	Factory	20	Left
3712	None	None	10	Right
1221	Exciter	LF_2Hz	20	Left
2522	Factory	FP	20	Right

Session 3

Task Code	**Speaker**	**Sound**	**Speed**	**Direction**
2322	Factory	HF_1Hz	20	Right
2521	Factory	FP	20	Left
2222	Factory	LF_2Hz	20	Right
1221	Exciter	LF_2Hz	20	Left
1522	Exciter	FP	20	Right
3711	None	None	10	Left
2512	Factory	FP	10	Right
2221	Factory	LF_2Hz	20	Left
1422	Exciter	HF_2Hz	20	Right
2411	Factory	HF_2Hz	10	Left
2212	Factory	LF_2Hz	10	Right
1111	Exciter	LF_1Hz	10	Left
2422	Factory	HF_2Hz	20	Right
2621	Factory	Factory	20	Left
1322	Exciter	HF_1Hz	20	Right
2611	Factory	Factory	10	Left
2412	Factory	HF_2Hz	10	Right
1611	Exciter	Factory	10	Left
1512	Exciter	FP	10	Right
2321	Factory	HF_1Hz	20	Left
2622	Factory	Factory	20	Right
1511	Exciter	FP	10	Left
2312	Factory	HF_1Hz	10	Right

2511	Factory	FP	10	Left
1112	Exciter	LF_1Hz	10	Right
2211	Factory	LF_2Hz	10	Left
2522	Factory	FP	20	Right
1411	Exciter	HF_2Hz	10	Left
1312	Exciter	HF_1Hz	10	Right
1621	Exciter	Factory	20	Left
2122	Factory	LF_1Hz	20	Right
1421	Exciter	HF_2Hz	20	Left
1222	Exciter	LF_2Hz	20	Right
2111	Factory	LF_1Hz	10	Left
1622	Exciter	Factory	20	Right
1521	Exciter	FP	20	Left
2112	Factory	LF_1Hz	10	Right
1121	Exciter	LF_1Hz	20	Left
1412	Exciter	HF_2Hz	10	Right
2121	Factory	LF_1Hz	20	Left
1122	Exciter	LF_1Hz	20	Right
3721	None	None	20	Left
2612	Factory	Factory	10	Right
2311	Factory	HF_1Hz	10	Left
1612	Exciter	Factory	10	Right
1211	Exciter	LF_2Hz	10	Left
3712	None	None	10	Right
1321	Exciter	HF_1Hz	20	Left
1212	Exciter	LF_2Hz	10	Right
2421	Factory	HF_2Hz	20	Left
3722	None	None	20	Right
1311	Exciter	HF_1Hz	10	Left

Session 4

Task Code	**Speaker**	**Sound**	**Speed**	**Direction**
2522	Factory	FP	20	Right
1221	Exciter	LF_2Hz	20	Left
3712	None	None	10	Right
2621	Factory	Factory	20	Left
1222	Exciter	LF_2Hz	20	Right
2321	Factory	HF_1Hz	20	Left
2212	Factory	LF_2Hz	10	Right
3711	None	None	10	Left
2322	Factory	HF_1Hz	20	Right
1511	Exciter	FP	10	Left

3722	None	None	20	Right
1421	Exciter	HF_2Hz	20	Left
1312	Exciter	HF_1Hz	10	Right
2211	Factory	LF_2Hz	10	Left
2422	Factory	HF_2Hz	20	Right
1611	Exciter	Factory	10	Left
2312	Factory	HF_1Hz	10	Right
1111	Exciter	LF_1Hz	10	Left
1322	Exciter	HF_1Hz	20	Right
2121	Factory	LF_1Hz	20	Left
1212	Exciter	LF_2Hz	10	Right
2611	Factory	Factory	10	Left
1512	Exciter	FP	10	Right
2311	Factory	HF_1Hz	10	Left
2612	Factory	Factory	10	Right
3721	None	None	20	Left
1422	Exciter	HF_2Hz	20	Right
2111	Factory	LF_1Hz	10	Left
1612	Exciter	Factory	10	Right
2221	Factory	LF_2Hz	20	Left
1412	Exciter	HF_2Hz	10	Right
1521	Exciter	FP	20	Left
2222	Factory	LF_2Hz	20	Right
1411	Exciter	HF_2Hz	10	Left
2122	Factory	LF_1Hz	20	Right
2421	Factory	HF_2Hz	20	Left
2622	Factory	Factory	20	Right
1211	Exciter	LF_2Hz	10	Left
2512	Factory	FP	10	Right
1311	Exciter	HF_1Hz	10	Left
1622	Exciter	Factory	20	Right
2411	Factory	HF_2Hz	10	Left
1112	Exciter	LF_1Hz	10	Right
1621	Exciter	Factory	20	Left
1522	Exciter	FP	20	Right
2521	Factory	FP	20	Left
1122	Exciter	LF_1Hz	20	Right
1321	Exciter	HF_1Hz	20	Left
2412	Factory	HF_2Hz	10	Right
2511	Factory	FP	10	Left
2112	Factory	LF_1Hz	10	Right
1121	Exciter	LF_1Hz	20	Left

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