A Data Driven Approach to the Development and Evaluation of Acoustic Electric Vehicle Alerting Systems for Vision Impaired Pedestrians

February 2023 | Final Report

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Abstract

The number of electric vehicles on the road increases exponentially every year. Due to the quieter nature of these vehicles when operating at low speeds, there is significant concern that pedestrians and bicyclists will be at increased risk of vehicle collisions. This research explores the detectability of six electric vehicle acoustic additive sounds produced by two sound dispersion techniques: (1) using the factory approach versus (2) an exciter transducer-based system. Detectability was initially measured using on-road participant tests and was then replicated in a high-fidelity immersive reality lab. Results were analyzed through both mean detection distances and pedestrian probability of detection. This research aims to verify the lab environment in order to allow for a broader range of potential test scenarios, more repeatable tests, and faster test sessions. Along with pedestrian drive-by tests, supplemental experiments were conducted to evaluate stationary vehicle acoustics, 10 and 20 km/h drive by acoustics, and interior acoustics of each additive sound.

Acknowledgements

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Introduction

Motivation

Electric vehicles (EVs) are soaring in popularity all around the world [1]. Globally, EV sales are growing at rates three to eight times higher than internal combustion engine (ICE) vehicles in the light duty passenger car category, and the number of EVs on the road is increasing exponentially [2]. Growth rates are compounded with government initiatives aimed at requiring new passenger and midsized vehicles to be electric. The most notable of these initiatives is the International Zero Emission Vehicle Alliance, which requires new passenger vehicles to be zero emission by 2050 [3].

EVs generate significantly less external noise at speeds below 20 km/h than their ICE counterparts, causing safety concerns for pedestrians, particularly those who are vision impaired. A recent survey in Australia showed that a staggering 35% of visually impaired pedestrians have had a collision or near collision with an EV [4]. The main sources of vehicle noise include tire noise, exhaust, induction, and engine noise. Airflow and tire noise are similar between EVs and ICE vehicles, and above 20 km/h, EVs and ICE vehicles produce similar noise levels because airflow and tire noise are the dominant sound contributors [5]. At lower speeds that are typical of pedestrian heavy environments such as parking lots and city streets, EVs' drivetrain noise levels are significantly lower than those of ICE vehicles [6,7]. To address this, governments have begun instituting regulations concerning EV minimum sound levels.

Globally there are two main regulatory bodies that have set the pace for minimum sound level regulation: the National Highway and Traffic Safety Administration (NHTSA) in the United States and the United Nations Economic Commission for Europe (UNECE) in Europe. 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 [8]. The United States established 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]. These regulations have been used around the world by countries implementing EV noise requirements, with national regulations either based on one of these two regulations or a direct application of either [10].

Manufactures have addressed quiet vehicle regulations, in some cases prior to them becoming a requirement, by incorporating additive noise systems into their vehicles. These systems generate artificial sounds when the vehicle is moving within the regulatory speed region. Because there are open questions concerning the effectiveness of additive sounds, this research project aimed to investigate methods of evaluating sound types and dispersion techniques using controlled test track and lab test environments. Two acoustic transducer arrangements as well as several scientifically designed test sounds were examined to gain insight into the effects of transducer placement and signal frequency/modulation effects on sound detectability.

Past Research

Phase One Research

In 2015, the research team conducted a study to evaluate existing additive sounds against the UNECE regulations [11,12]. This was accomplished by recording the audio for four different vehicles—hybrid vehicle with additive sound while in electric mode, EV without an additive sound, EV with an additive sound, and a traditional ICE—at speeds of 10 and 20 km/h using methods described in UN R138. Acoustic measurements were used to assess vehicle regulatory compliance. These same vehicles were used in participant drive-by trials where visually impaired 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. These tests were completed with added background noise at overall A-weighted sound pressure levels (SPL) of 55 and 65 dBA. The research team measured mean distances at which participants detected an approaching vehicle.

Phase one testing demonstrated that all four vehicles had mean detection distances above the suggested detection thresholds provided by NHTSA for both 10 km/h and 20 km/h [13]. There was a statistically significant difference in pedestrian detection distances between the ICE test vehicle and the other three test vehicles at speeds of 10 km/h, with earlier (farther distance) mean detection for the ICE vehicle. Differences between the non-ICE vehicles at 10 km/h were minimal. As expected, detection distances were much larger for 20 km/h than 10 km/h. At 20 km/h, detection distances were similar for all vehicles, illustrating that wind and tire noise play a leading role in overall detectability at higher speeds. Increasing 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.

Phase Two Research

In 2018, the research team completed a second phase of EV additive sound research [14,15]. 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 developed by General Motors were evaluated. 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 FMVSS No. 141 regulations.

Phase two analysis involved looking at the probability that a pedestrian would be 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 results from both phases and regulations. Consistent with Phase 1, analysis revealed higher rates of detection when the vehicle was moving at the faster 20 km/h speed condition than at the 10 km/h speed. Furthermore, all additive sounds provided mean detection distances greater than detection thresholds suggested by NHTSA. Looking at mean detection distances revealed that while all sound conditions exceeded the detection thresholds, there was a large advantage to Additive Sound conditions when compared to the No Sound condition. Predicted pedestrian strikes "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" [14]. Like the Pd curve analysis described above, mean detection distances were higher at 20 km/h than 10 km/h, as tire noise became the leading causes of noise at the higher speed [15]. 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."

Phase 2 testing included one additive sound that had a significant amplitude modulation. This sound was detected at further ranges than the other sounds that were more consistent in their amplitudes. This led to the hypothesis that more "scientific" sounds, rather than those designed for aesthetic considerations, should be tested.

Background

This current phase of research extended the first two phases by exploring the effectiveness of the factory-installed sound dispersion method and an exciter transducer-based system mounted under the hood of the car. Four new additive sounds were developed to explore low and high frequency content sounds as well as two amplitude modulation rates. Additive sounds and systems were tuned to comply with FMVSS No. 141 and then were tested on both the Virginia Tech Transportation Institute (VTTI) Smart Roads and in a virtual lab environment at the Virginia Tech Acoustic Signal Processing and Immersive Reality Lab (ASPIRE Lab).

First, a prototype setup of the new exciter transducer-based additive sound system was constructed and tested for uniform sound level broadcasting around the front of the car. The research team wired into the factory system in order to play the range of additive sounds under evaluation. Stationary testing was conducted for each speaker configuration to evaluate how the two systems compared once the sounds were adjusted to meet FMVSS No. 141 regulations. Leveraging previous methods, participant drive-by tests were conducted to evaluate on-road participant detection distances and enable comparisons between the different sound dispersion approaches and additive sounds. A separate set of drive by tests were conducted without participants to evaluate FMVSS No. 141 compliance to drive-by tests and to gather recordings to be played in a virtual reality setting. Finally, lab tests were conducted using the drive-by recordings to compare the immersive reality environment to the on-road participant tests.

Method

Test Vehicle and Test Locations

A 2018 Chevy Bolt (EV) was provided by GM and used for the experiments presented in this project. This was the same vehicle used in the second study detailed above. 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 Roads. Drive-by measurements, drive-by participant measurements, and interior vehicle measurements were conducted on the VTTI Smart Roads. Finally, virtual environment lab tests were conducted in the Virginia Tech ASPIRE Lab.

The Smart Roads are closed test track facilities located in Blacksburg, Virginia. For consistency, testing was conducted on the same section of the Smart Roads used in prior studies. This section of test road was free from excessive background noise, was flat, straight, and had a surface consistent with typical roadways. A Google Maps image of the test site is provided in Figure 1.

Figure 1. VTTI Smart Roads test site.

The ASPIRE lab (see Figure 2) is a spatial acoustic immersive reality facility. The immersive reality lab consists of a semi anechoic chamber with 58 loudspeakers mounted around the lab at ear level when seated. A spatial recording, taken with a sound field microphone, 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. Theoretically, this allows for the listener to experience the audio as if they were at the site of the recording.

Figure 2. ASPIRE Lab.

Additive Sound Systems

One significant issue with Phase Two testing was that the additive sounds were much louder in the front of the vehicle than on the sides. Per the regulations, sound levels required adjustment until the lowest position (front, driver, passenger) met regulatory requirements. In Phase Two, this resulted in a louder sound in front of the vehicle in order to meet the requirements on either side. In this phase of testing, a new sound generation system was proposed and tested to see if it would produce a more uniform sound field. For comparison, the factory speaker system was modified in order to directly play the additive sounds, as opposed to using secondary speakers. As such, this allowed for the comparison of not only different additive sounds, but also for the two different sound generation systems.

Factory System Modification

The Chevy Bolt is factory equipped with a single speaker mounted in the front driver-side wheel well, which is used to emit the factory additive sound (see Figure 3). Modifications called for the factory speaker to be unplugged from the car's computer and instead connected directly to the experimenter laptop. The wires were fed from the speaker to the interior of the vehicle and the plastic shielding was replaced in the factory configuration.

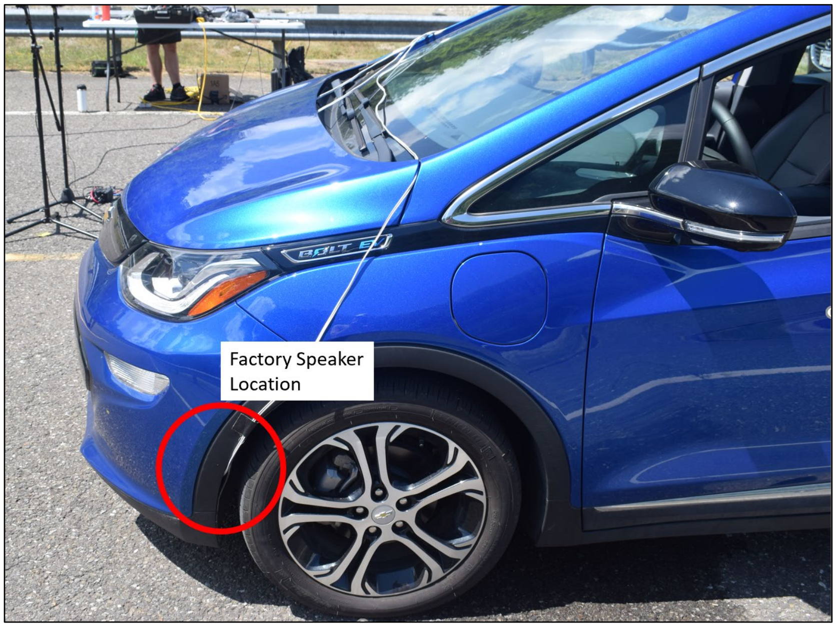

Figure 3. Factory speaker location.

An 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 50 W per channel. This allowed experimental sounds to be played from the factory speaker via a Lenovo S540 IdeaPad laptop computer. A diagram of this solution can be found in Figure 4.

Figure 4. Factory modified system diagram.

Exciter Transducer Based 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 vehicle's body panels would allow additive sounds to propagate uniformly around the vehicle. A simplified schematic showing this concept is shown below in Figure 5. These exciters would allow the sound to propagate from the surface of the body panel rather than from behind it, while still remaining inconspicuous.

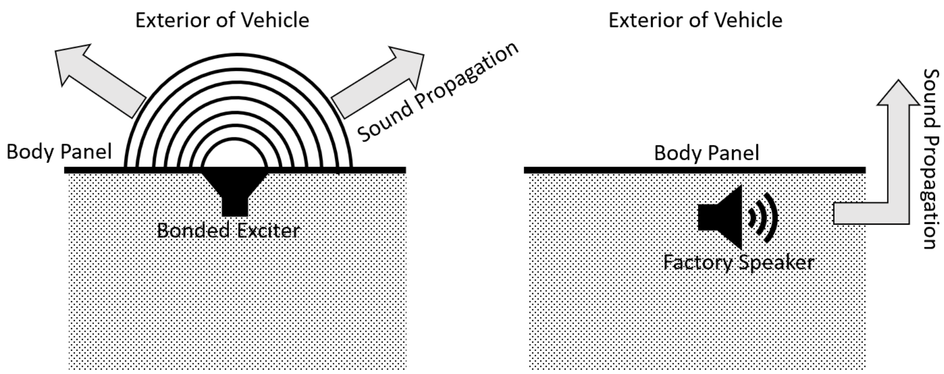

Figure 5. Exciter transducer concept.

To construct this system, two Dayton Audio daex32QMB-4 40W 4-ohm exciters were driven with the FX Audio FX-502A HiFi audio amplifier. This setup can be seen in Figure 6. The following three test vehicles were used to preliminarily test the system: a 2010 Honda Fit (short hood), a 2018 Chevy Bolt (medium hood), and a 2014 Mazda 3 (longer hood). Three microphones were set up around the test vehicle using FMVSS methods, and the exciter was placed on the outside hood of the test vehicle. For this testing, one and two exciter solutions were considered and only the relative sound levels around the vehicle were of interest. For each vehicle, overall A-weighted SPLs within approximately 1–2 dBA of each other at each microphone location were obtained when tested in the VTTI garage bay.

Figure 6. Exciter system diagram.

Further testing was then conducted to determine the optimal mounting location for 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 provided a large panel that is easily accessed, was located close to the front of the vehicle, and provided good results in preliminary testing. The final bonded configuration of the exciters is shown in Figure 7.

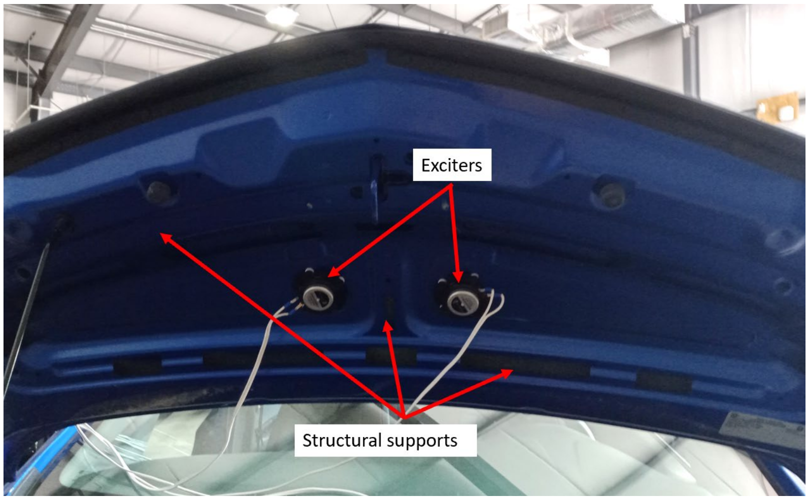

Figure 7. Exciter placement.

Finally, an audio switching box was installed on the Bolt's dashboard that allowed the experimenter to easily switch between the two systems during testing.

Additive Sounds

Four new additive sounds, one sound carried over from the second phase of testing, and a recording of the Bolt's factory additive sound, were included in this round of testing. As with before, the No Sound condition was included as a baseline.

Guided by the past phases of testing and reviewed literature, these four new additive sounds accounted for two different frequency contents and two modulation levels. For the first two additive sounds, a low frequency emphasis base sound was used. This base sound was then modulated at a frequency of 1 Hz and 2 Hz to create additive sounds LF 1 Hz and LF 2 Hz. Similarly, the other two additive sounds were created using a high frequency emphasis base sound and also modulated at a frequency of 1 Hz and 2 Hz to create additive sounds HF 1Hz and HF 2 Hz. These sounds were included specifically 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 well performing warning sound from Phase Two was included. This sound is hereafter 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 is hereafter referred to as Factory and had a mid-frequency emphasis and a low amplitude modulation.

Experimental Methods

Stationary Tests

Stationary tests were conducted to set the levels for the additive sounds and to verify they satisfied FMVSS No. 141 for both speaker configurations. A combination of the laptop volume adjustment and the volume knob of the FX Audio FX-502A HiFi audio amplifier were used to set the overall level.

Stationary testing was conducted at the aforementioned VTTI Smart Roads location, 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. Overall A-weighted SPL and 1/3 octave band data was collected using a Lenovo Ideapad 320 laptop, National Instruments LabVIEW Acoustics and Vibrations Measurement Suite, a National Instruments cDAQ USB Data Acquisition Rack, and a National Instruments NI 9234 analog-to-digital converter module sampling at 50 kHz. The microphones were set up at a height of 1.2 m and 2 m from the center of the vehicle's front bumper; this geometry is shown in Figure 8. For each additive sound and speaker configuration, the 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.

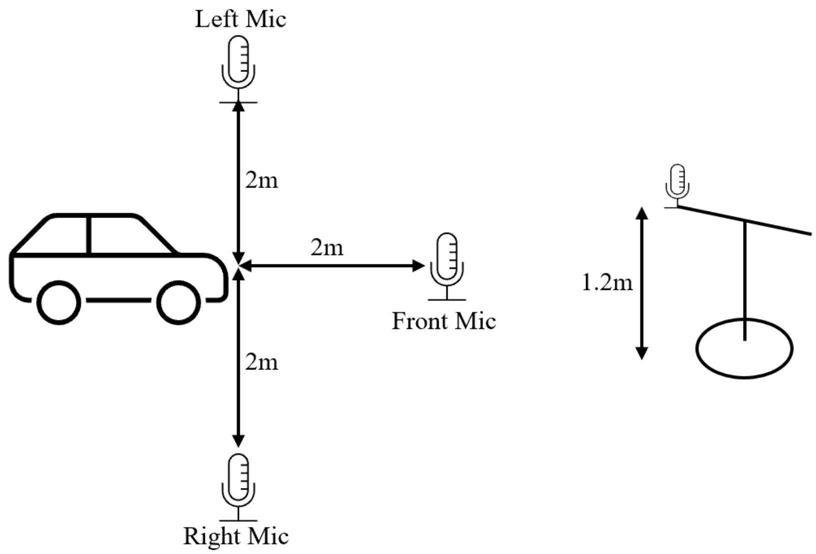

Figure 8. Stationary test geometry.

Drive by Verification and Sound Field Data Collection

To verify compliance with FMVSS No. 141 drive-by tests, two G.R.A.S. 46AQ microphones were calibrated and positioned on either side of the test road, at 2 m from the center of the road and at a height of 1.2 m, as shown in Figure 9. The ambient 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 toward the microphones, maintaining a constant test speed from the 100 m 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 were recorded using VTTI's NextGen data acquisition system (DAS) and the National Instruments audio recording setup detailed above.

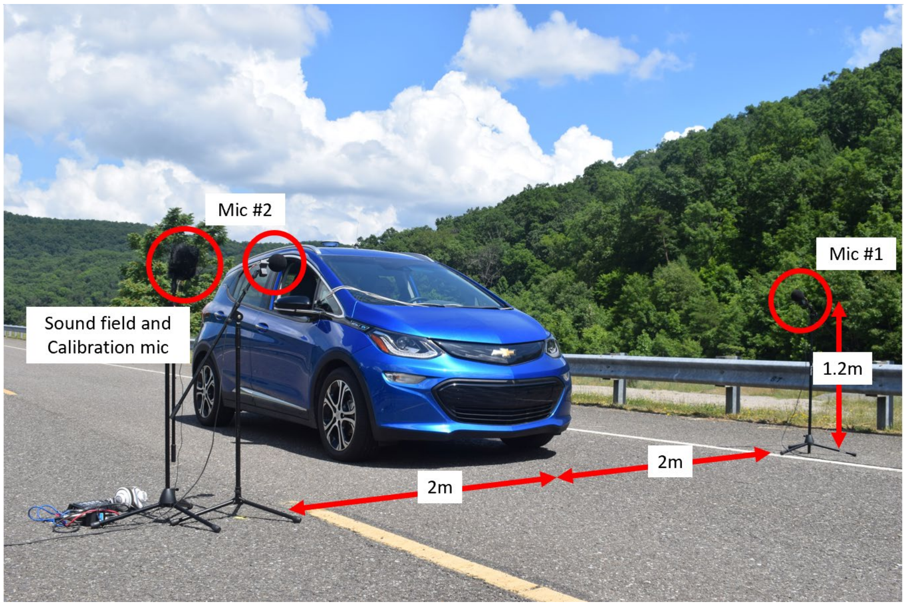

Figure 9. Drive-by test geometry.

During this testing session, sound field recordings and calibration audio were captured for use during participant testing in the ASPIRE Lab using a Core Sound Tetramic. The sound field microphone was positioned on the test track at the location and height of where participants would be seated during on-road participant testing (see Figure 9). 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. Data from the calibrated reference was collected with the NextGen DAS and was thereby aligned with vehicle distance. For each trial, data recording was first initiated on the sound field audio recorder and then with the DAS. 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 research vehicle was 100 m away from the sound field microphone and end the recording once it 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, the distance recorded by the DAS was used to isolate the recordings within the test envelope. A .wav file was created both for the sound field recording and corresponding vehicle distance during each test. These .wav files were then used to create Reaper projects for each test scenario to be played through an Ambisonic [15] immersive audio system in the ASPIRE Lab.

On-Road Participant Testing

Participants were recruited by VTTIs recruitment team for both on-road and lab drive-by testing. Twenty Virginia Tech students were recruited and split into five groups of four students each. The first group served as pilots to validate the experimental procedures. Students were compensated $60 for the first on-road session and $90 for the second in-lab session (approximately 5 hours of total participation time). Prior to on-road tests, participants were required to fill out informed consent documents and take a hearing test. Participants were briefed on their duties before each testing session and asked to complete a questionnaire at the end of their second session (lab environment). The order of on-road testing, followed by lab testing, was fixed for all participants. All participant activities were approved by Virginia Tech's Institutional Review Board.

On-road participant testing was conducted on the Smart Roads using methods consistent with both prior phases. These sessions were used to determine the distance at which participants detected the approaching vehicle when surrounded by background noise simulating a typical urban environment. 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 them at floor level. This setup is shown in Figure 10

One pilot session and four test sessions were conducted; each session lasted approximately 2 hours. For each session, four participants sat in barber chairs adjacent to the lane of travel, with four G.R.A.S. 46AQ TEDS microphones calibrated and positioned directly above each participant's head. These microphones served to monitor the background noise to ensure it maintained a 55 dBA level at each participant's location, and to record the A-weighted overall SPL and 1/3 octave band measurements from the participant's vantage point. This setup is seen in Figure 10.

Figure 10. On-road participant testing.

Participants were blindfolded to eliminate visual cuing. Participants were instructed to mimic a pedestrian waiting to cross the road and told that they were positioned on the corner of an intersection. Participants were given a handheld button and asked to press it when they heard a vehicle approaching, and to 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, were observed. The following data were collected for each test using the DAS: overall A-weighted SPL and 1/3 octave bands above each participant's head, vehicle distance, and vehicle speed. Test sessions were ordered and balanced to minimize order effects.

Lab Participant Tests

Participant tests were repeated in the ASPIRE Lab using the sound field recordings taken on the Smart Roads. Data collection involved the same set of participants. All equipment in the APSIRE

Lab that was not needed for testing was turned off to minimize background noise. The background noise was measured in the lab, both with all equipment turned off as well as with all the necessary equipment turned on, and was found to have an overall A-weighted SPL of 32.9 dBA and 33.6 dBA respectively.

As discussed above, Reaper projects for each testing scenario were constructed. These contained tracks for the sound field recordings, corresponding vehicle distance, participant button 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' button 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.

It was necessary to match the volume of these recordings in the lab to the volume of the approaching vehicle on the Smart Roads in order 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 Roads. The volume of each sound field track was adjusted until it matched the peak seen on the Smart Roads.

Once the peaks matched the overall A-weighted SPL throughout, the playback was recorded and plotted against the measurements taken on the Smart Roads. Two characteristic plots are shown below in Figure 11, illustrating alignment between both environments. The peaks in the ASPIRE lab were purposely set slightly higher than recorded on the Smart Road. This was due to the additive sounds being played at a slightly lower level during the recording sessions than during on-road participant tests. The peaks in the ASPIRE lab are designed to match the peak overall SPL heard by participants during on-road participant testing.

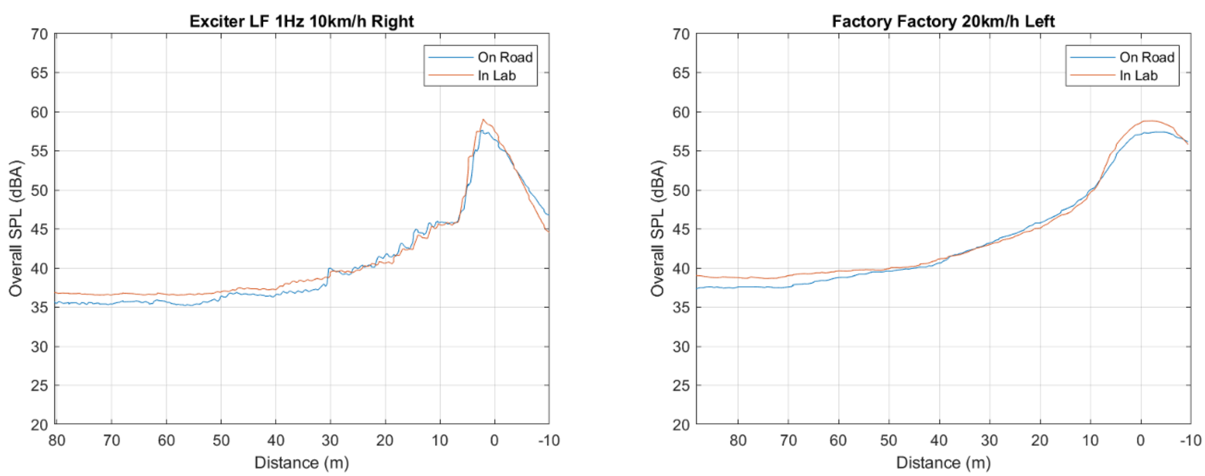

Figure 11. In-lab and on-road A-weighted overall SPL comparison.

Results

Stationary Test

To meet FMVSS 2-band requirements, two non-adjacent 1/3 octave band levels between 315 and 3150 Hz must meet or exceed 40 dBA. One selected band must be below 1000 Hz, and another must be at or above 1000 Hz. The two bands used to meet this requirement must have a band sum of at least 44 dBA. 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 additive 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 No. 141 compliant). All the additive sounds met the band sum requirement. While all additive sounds were designed with frequency content in the 1/3 octave bands needed to meet FMVSS No. 141 requirements, stationary tests showed that experimentally measured frequency content differed from the designed signal content, suggesting attenuation and content shifting caused by both additive sound systems. The average overall A-weighted SPLs at each microphone location are provided in Table 1 and Table 2

Table 1. Stationary Testing Overall A-weighted SPL Data (dBA) – Exciter Speaker

Driver	Front	Passenger	Additive Sound	SPL Range (dBA)
61.6	49.5	59.5	LF 1Hz	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

Table 2. Stationary Testing Overall A-weighted SPL Data (dBA) – Factory Speaker

Driver	Front	Passenger	Additive Sound	SPL Range (dBA)
55.9	49.8	51.1	LF 1Hz	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

Drive-by Tests

On-road drive-by tests were used to verify vehicle compliance to FMVSS No. 141 regulations. 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 0–10 km/h approach speeds for the 10 km/h drive by tests and regulatory limits for 10-20 km/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.

The minimum overall A-weighted SPL of the passenger- and driver-side microphone readings were used to determine which side met FMVSS regulations. A-weighted 1/3 octave band levels during the vehicle pass-bys were determined for the side with the lower overall A-weighted SPL. All additive sound solutions exceeded regulatory requirements for both the 10 and 20 km/h speed conditions. The No Sound conditions exceeded regulatory requirements for all 20 km/h cases, but only for the right approach direction at 10 km/h. Regulations were not met for the left approach direction at 10km/h.

Participant Tests

On-road participant tests were used to evaluate the performance of both the different additive sounds and sound distribution methods. Detection distances were examined by speed and environment, with an analysis of variance (ANOVA; $\alpha = .05$) completed using speaker, additive sound, direction, and participants as grouping variables. For 10 km/h trials, statistically significant differences were observed for the sound distribution method, additive sound, and participant, with respective p-values of $3.1 * 10^{-5}$, $1.9 * 10^{-53}$, and $4.1 * 10^{-33}$. No statistically significant differences were observed by approach direction. For 20 km/h trials, statistically significant differences were observed for the additive sound, direction, and participant with respective p-values of $3.2 * 10^{-9}$, 0.02 and $7.8 * 10^{-35}$. At 20 km/h, statistically significant differences for the sound distribution methods were not observed. This is due to the fact that broadband road/tire interaction noise dominates, so that, statistically speaking, the sound emanating from the vehicle had the same distribution regardless of the sound used.

Additive sound performance was evaluated statistically using a multiple comparison test and quantitatively using mean detection distances. Results for all speaker and sound combinations for 10 km/h trials are found in Figure 12. At 10 km/h, LF 1Hz and LF 2Hz from both the exciter and factory speaker captured mean detection distances statistically further out compared to all other additive sound and speaker combinations. For these test sounds, mean detection distances ranged from a high of 70.4 m (Factory LF 1Hz) to 56.0 m (exciter LF 1Hz). This performance was 3.5 times further than the lowest performing additive sound (exciter HF 2Hz), which had a mean detection distance of 20.3 m. HF 1Hz, HF 2Hz, and the Factory additive sounds had statistically similar performance to the No Sound configuration. The No Sound configuration had the second lowest performance with a mean detection distance of 22.1 m. Despite the large variation of detection distances, all participants detected the vehicle at distances greater than the suggested 5-m NHTSA detection threshold. The average detection distance for all sound configurations was 39.8 m with a standard deviation between configurations of 17.6 m.

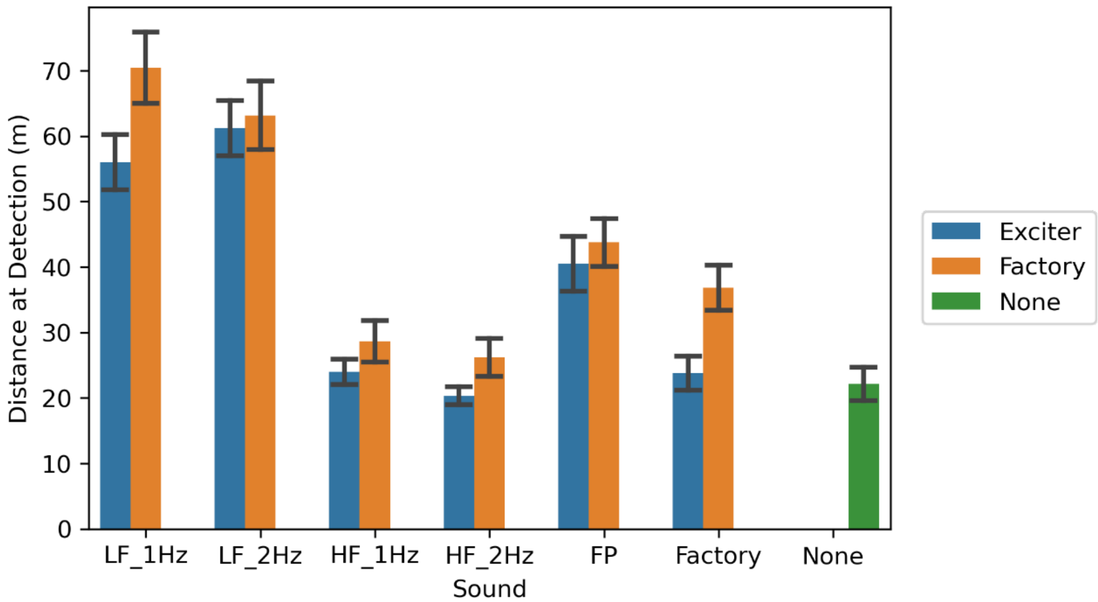

Figure 12. Mean detection distances for each additive sound by speaker configuration – 10 kph road trials.

At 20 km/h, low frequency sounds still outperformed the other conditions for mean detection distance. All results for sounds and speaker configurations can be found in Figure 13. LF 1 Hz from the factory speaker achieved the highest mean detection distance (72.6 m) and was the only configuration that was statistically different from all non-low frequency emphasis additive sounds. LF 2 Hz with the exciter captured a mean detection distance of 65.8 m and was only statistically different from HF 2 Hz with the exciter, FP with the exciter, and the Factory noise with the exciter. Detection distances ranging from 49.2 m to 56.0 m were observed for non-low frequency additive sounds. LF 1 Hz with the factory speaker was the only additive sound configuration to achieve statistical significance from the No Sound configuration. The average detection distance for all noise configurations was 58.0 m with a standard deviation between configurations of 7.7m. This variation was significantly less than what was observed at the 10 km/h speed condition.

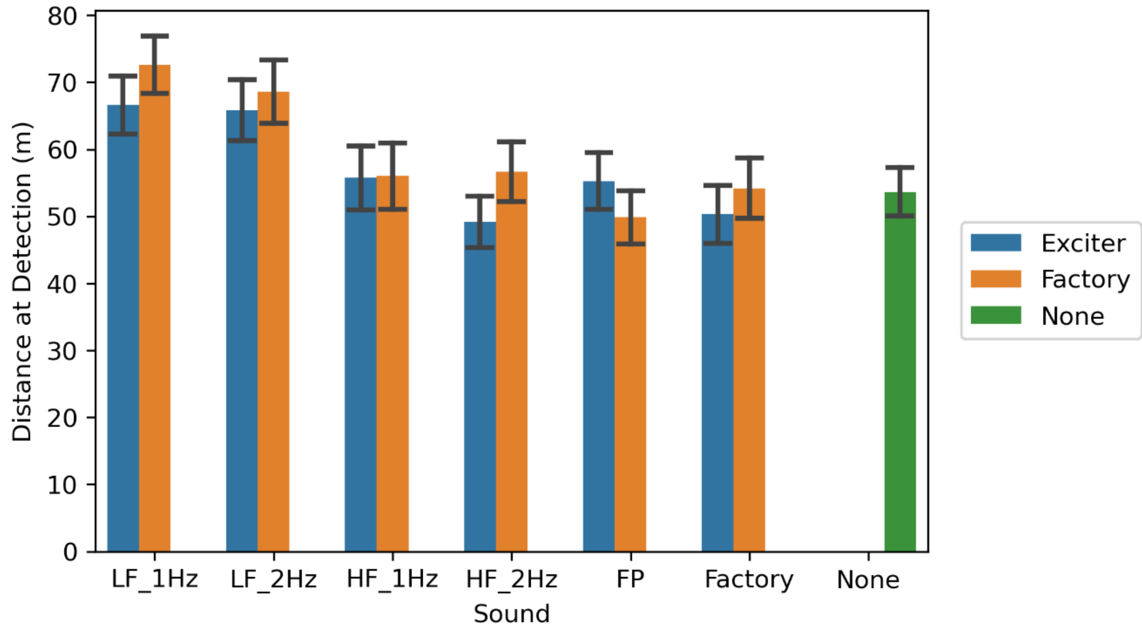

Figure 13. Mean detection distances for each additive sound by speaker configuration – 20 kph road trials.

Significant differences were also observed between the on-road and in-lab environments. An ANOVA comparing the in-lab and on-road environments was conducted using the speaker, sound, speed, direction, participant, and environment as grouping variables. From this analysis, a p-value of $1.5 * 10^{-79}$ was obtained, demonstrating evidence that the lab environment varied significantly from the on-road environment with respect to mean detection distances. As illustrated in Figure 14, an average decrease in detection distance of 12.9 m and percent difference of 30.8% was observed in the lab environment for trials conducted at 10 km/h. For 20 km/h trials, a 25.8 m decrease in detection distance and a 46.1% difference was observed. Despite the significantly lower detection distances, similar performance ordering was seen in the lab environment. For both 10 km/h and 20 km/h approach speeds, the low frequency additive sounds again exhibited higher mean detection distances compared to the other sound conditions. At the 10 km/h approach speed, the FP and factory sound recorded the next largest mean detection distances, 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.

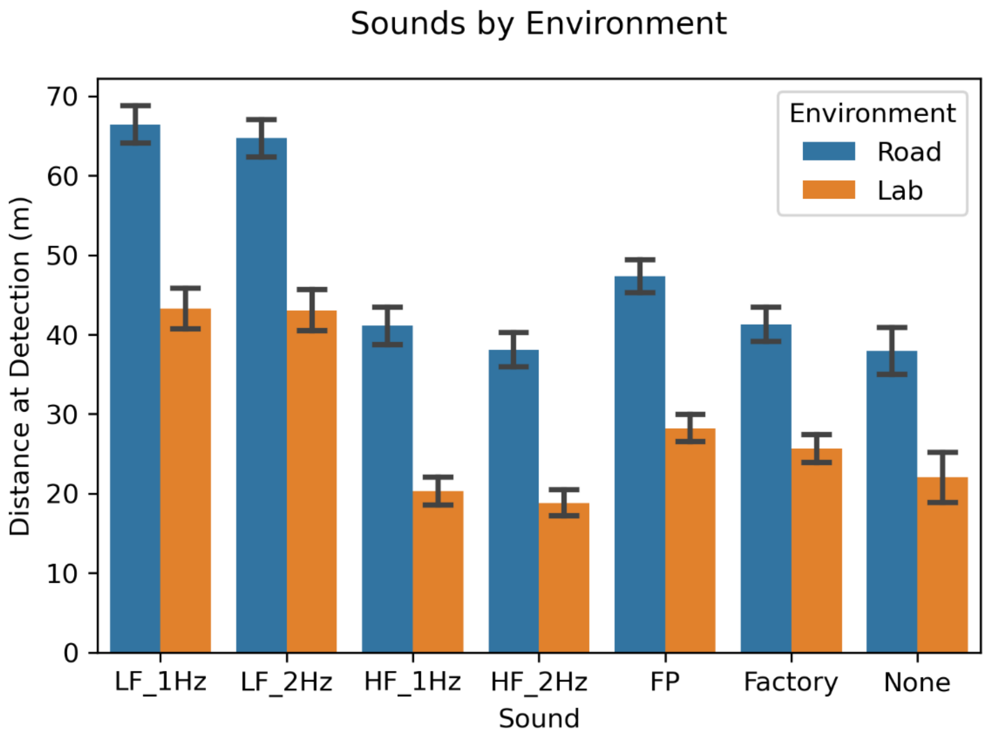

Figure 14. Mean detection distances for each additive sound and approach speed by environment.

To better understand the potential differences seen between the on-road and in-lab environments, 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. Two surface plots characteristic of the results obtained and corresponding to the overall SPL results provided earlier are shown below in Figure 15. As seen in the plots, the octave band levels from 20 to 315 Hz in the lab typically had higher levels than that observed on the Smart Roads. In the 1/3 octave bands from 400 to 1250 Hz, the band levels in the lab initially start outed very similar to those seen on the Smart Roads during approach, then the levels on the road exceeded those seen in the lab as the vehicle got closer to the microphone. This may illustrate that the more detectable frequencies (400–1250 Hz) were at a higher SPL on the Smart Roads and thus the vehicle was detectable at further distances. As such, in the future, matching between levels for on-road and in-lab testing must occur for overall SPL and 1/3-octave band levels, which is much more complicated and will require sophisticated equalization methods.

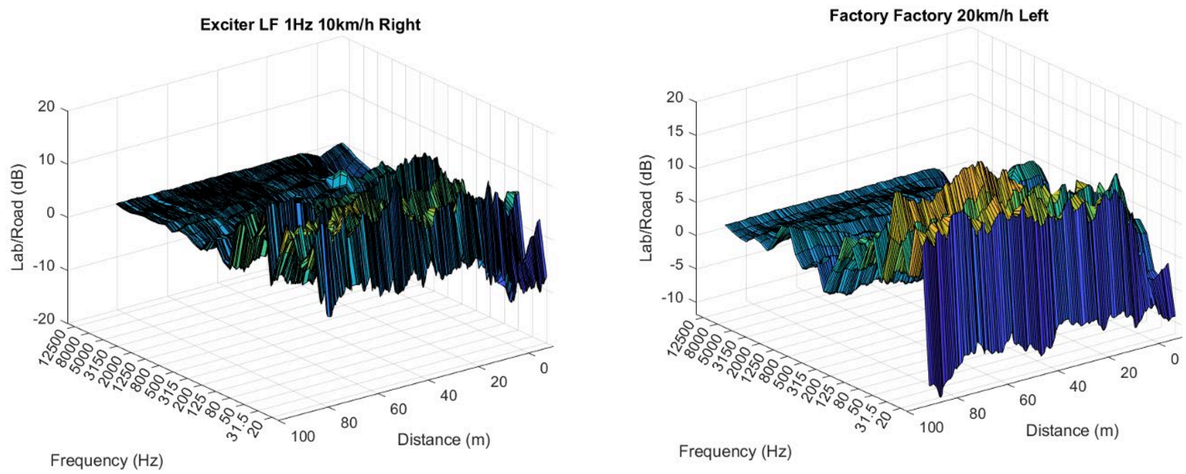

Figure 15. Lab to road ratio 1/3 octave bands.

Discussion

Stationary testing results were surprising, as all additive sounds were designed to have sufficient frequency content to meet the 2-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 sounds or by tuning each sound's 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 rather than to adjust each sound to meet regulations and have widely varying volumes. Except for the HF 1 Hz and HF 2Hz sounds, each sound had the lowest overall A-weighted SPL in the front of the vehicle. HF 1 Hz and HF 2 Hz had the lowest level on the passenger side of the vehicle followed by the front of the vehicle, which was approximately 2 dBA lower. Ideally, the overall A-weighted SPL coming toward the participants from the front of the vehicle should be approximately the same for each sound. The overall A-weighted SPL will start to vary more as the vehicle begins to pass the participants and the sound coming from the sides of the vehicle becomes a more dominant source of noise.

Stationary tests also showed that the bonded exciter did create a 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. 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, the results suggest 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 or, more preferably, an anechoic chamber would be an appropriate next step for future research.

Drive-by tests provided similar results to past phases of research. Additive sound solutions meeting FMVSS regulations were more easily detected than the No Sound condition. Additionally, at the higher approach speed of 20 km/h, all sound 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 0–10 km/h approach speeds for the 10 km/h drive by tests and regulatory limits for 10–20 km/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, yet similar configuration ordering as that seen on the Smart Roads was generally maintained. In general, good alignment between the overall A-weighted SPL in the lab and Smart Roads was observed, and 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 (i.e., sound field microphone sensitivity was too low). Since the sound field microphone has a self-noise floor of 19 dBA, which is well below the background noise and vehicle acoustics, this was deemed to be an unlikely cause of misalignment.

Frequency analysis provided interesting insights into what may have contributed to differences between the in-lab and on-road environments. It appears there is low/mid frequency resonation in the lab in the 20–315 Hz region, causing there to be more low frequency content in the artificial background noise 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 from 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, as shown by the ratio maintaining close to a 0 dB level. As the vehicle approaches, the ratio dips below zero, indicating that levels are higher on-road than represented in the lab environment. Higher levels of these higher (more detectable) frequencies could explain why participants detected on-road vehicles further away than virtual vehicles.

Conclusions and Recommendations

Based on the results seen in this study, the highest performing additive sounds were those with a low frequency emphasis (with modulations of LF 1 Hz and LF 2 Hz) followed by those with broader frequency content and no modulation (FP and Factory). The high frequency sounds had similar performance to the No Sound condition. Modulation rates did not seem to have a big influence, with both 1 Hz and 2 Hz rates performing similarly. Despite the large variation in detectability, all configurations met NHTSA's suggested minimum detection distance thresholds.

The exciter transducer configuration was able to create more uniform sound levels on the passenger and driver sides of the vehicle than the factory speaker, but consistently had lower sound levels at the front of the vehicle. These results suggest that the current exciter placement projects sound mostly to the sides of the vehicle as well as in the upward direction. This could potentially be tuned using an iterative approach of bonding the exciters in different locations and then performing stationary testing to confirm more uniform sound projection. The factory speaker marginally outperformed the exciter speaker in its current configuration.

Further investigation is needed to verify the cause(s) of 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. Based on these results, it may be necessary to take additional measures to reduce acoustic reflections and resonation in the lab environment. Iterative measures would likely be necessary until the frequency content measured on the road matches that measured in the lab. If these measures do not allow for alignment, it may be necessary to use a larger higher-fidelity lab environment to provide participants with more spatial resolution.

Additional Products

Applicable EWD, T2, and Data Products can be found at our Safe-D UTC project page, linked below.

https://safed.vtti.vt.edu/projects/a-data-driven-approach-to-the-development-and-evaluation-of-acoustic-electric-vehicle-alerting-systems-for-vision-impaired-pedestrians/

Education and Workforce Development Products

This project provided tuition and a stipend for a Virginia Tech masters student through a graduate research assistantship. Funding was provided for three semesters and two summers. The master's student conducted a master's thesis based on the research summarized in this report.

Dr. Roan intends on incorporating this research into future course materials, where appropriate.

Technology Transfer Products

As our industry champion, Douglas Moore (GM) was consulted on this project at various points throughout the period of performance. The research team has shared their findings with Doug, but it is unclear what impact that may have on future EV additive sounds.

The research team has presented the results of this project internally at VTTI, at SAE's Noise, Vibration, and Harshness conference, at the Acoustical Society of America Meeting, and at Penn State's Transportation Noise and Vibration Symposium. The research was mentioned by media outlets over 10 times following the presentation at the Acoustical Society of America Meeting. A paper discussing the team's findings is currently being prepared for submission to the *Journal of the Acoustical Society of America.*

Data Products

The research team has provided data that may prove useful to developers of EV additive sounds. This dataset includes timeseries recordings of the participants session, with data related to the vehicle's distance from participants along with the sound pressure level and octave band data recorded via the microphone above each participant's head. Button presses for when participants detected the approaching vehicle are also included, indicated detection distance.

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