Probability of Detection of Electric Vehicles with Added Warning Sounds

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Detection performance as a function of distance was measured for 16 subjects who pressed a button upon aurally detecting the approach of an electric vehicle. The vehicle was equipped with loudspeakers that broadcast one of four additive warning sounds. Other test conditions included two vehicle approach speeds (10 and 20 kph) and two background noise conditions (55 and 60 dBA). All of the test warning sounds were designed to be compliant with FMVSS-141 proposed regulations in regard to the overall sound pressure levels around the vehicle and in 1/3 octave-band levels. Previous work has provided detection results as average vehicle detection distance. This work provides the results as probability of detection as a function of distance. The curves provide insight into the false alarm rate when the vehicle is far away from the listeners as well and the probability of detection at the mean detection distance. Results suggest, although the test sounds provide an average detection distance that exceeds the NHTSA minimum at the two test speeds, detection probability is not always 100% at those distances particularly at the 10kph. At the higher speed of 20kph, the tire-road interaction noise becomes dominant, and the detection range is greatly extended.

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I. INTRODUCTION

The National Highway Traffic Safety Administration's (NHTSA) recently released Traffic Safety Facts (National Highway Traffic Safety Administration and others, 2020) revealed that "in 2018 there were 6,283 pedestrians killed in traffic crashes, a 3.4-percent increase from the 6,075 pedestrian fatalities in 2017". Although this increase can likely be attributed to a variety of causes, including distraction by both pedestrians and drivers alike, steadily increasing sales of quiet vehicles are altering how vehicles are perceived within traditional roadway environments due to their quiet operating noise relative to Internal Combustion Engine (ICE) counterparts. According to the Edison Electric Institute, "Global EV sales totaled about 2.1 million for 2018, an increase of 64% compared to the total sold in 2017. 2018 EV sales increased 79% in the U.S., 78% in China, and 34% in Europe compared to 2017. U.S. EV sales represented approximately 17% of global EV sales in 2018" (Edison Electric Institute, 2019). This trend shows no signs of slowing down, with automakers, such as General Motors, suggesting full shifts towards electric-only vehicles within the next decade (General Motors, 2019). In response to concerns raised regarding decreased detectability, many auto manufacturers are now producing non-ICE vehicles with an additive noise component aimed at signaling vehicle presence in the same way road users have learned to identify approaching vehicles through engine noise. The Virginia Tech Transportation Institute (VTTI) conducted an evaluation of quiet car detectability as part of a GM-funded project in 2015-2016 (Neurauter *et al.*, 2017; Roan *et al.*, 2017). This initial evaluation conducted vehicle warning signal testing based on methods outlined in the United Nations

Economic Commission of Europe (United Nations Economic Commission of Europe, 2015) and the developing NHTSA regulations available at the time. The primary focus involved a pedestrian detectability component, where vision-impaired participants were positioned on the side of the road as they evaluated four vehicle types (and related sound conditions) approaching at specific speeds. These vehicles included a 2011 Chevrolet Volt (EV, no additive sound), a 2014 Cadillac ELR (EV, production additive sound), a 2013 Toyota Prius (Hybrid Vehicle (HV), production additive sound under EV mode), and a 2013 Cadillac SRX (ICE benchmark). Despite each vehicle exceeding the UNECE minimum, this initial evaluation revealed that none of the vehicles, including the ICE benchmark, were immune to missed or late detections. Furthermore, the ICE benchmark significantly outperformed the other three vehicles under the 10kph steady approach, but these differences largely disappeared at 20kph due to increased tire and road noise. Trends of improved detectability offered by the additive noise signals were observed but did not demonstrate a significant advantage over the EV with no additional noise component. Since that original project, NHTSA has released their final version of the Federal Motor Vehicle Safety Standard (FMVSS) 141, outlining "Minimum Sound Requirements for Hybrid and Electric Vehicles (National Highway Traffic Safety Administration, 2018)". These regulations open the door for a new generation of additive sounds, and a follow-on project aimed to demonstrate differences in detectability by replicating the previous study but with newer, FMVSS 141, compliant sounds. This follow-on project produced all of the data used to generate results presented in the current work. Further details of the project can me found in (Neurauter *et al.*, 2020).

There has been other work in the detectability of approaching EVs by vision impaired pedestrians. (Altinsoy, 2013) used binaural recordings to show that pedestrians detect the sound of electric vehicles at an average of 14m, much closer than the sound of vehicles with internal combustion engines at a distance of roughly 36m. (Parizet *et al.*, 2014) provides results comparing sighted and non-sighted participants who listened to binaural dummy-head recordings of vehicle passbys. This work showed that there was no statistically significant difference in detection performance between the two groups. (Wall Emerson *et al.*, 2013) also studies detection of EVs by vision impaired pedestrians showing that detection performance dependencies included "average wind speed, amplitude modulation of the signal, hearing loss in the 500 Hz range, vehicle velocity, minimum ambient sound level, and overall vehicle sound level in units of A-weighted decibels". (Parizet *et al.*, 2013) evaluated the influence of various timbre parameters on sound detectability showing that an electric vehicle equipped with a particular low level sound was as detectable as a diesel vehicle. (Yamauchi, 2016) provides an in-depth perspective on the detectability of the EV additive warning sounds compared to the background noise levels and concluded that the additive sound approach could "solve problems only in limited scenarios". The environmental noise impact of additive sounds for EVs (Weinandy *et al.*, 2019) is also a topic of considerable discussion. (Steinbach *et al.*, 2017) used artificial neural network (ANN) detectors to model listener responses to show that the change of the speed-scaling of additive sounds greatly influences the detection time. The authors also conclude that the use of ANN provides a model which can predict the annoyance or the warning effectiveness of future electric vehicle sounds.

This work presents approaching-vehicle detection results from 16 listeners, plotted as probability of detection vs. distance (rather than average detection distance) for four regulatory-compliant additive sounds and the no-sound condition. This was done using a high-resolution differential GPS system placed on the test vehicle while subjects performed the task of vehicle detection. Detections were made in two background-noise level conditions of 55dBA and 60dBA and two approach speeds of 10kph and 20kph. Plots of probability of detection vs. distance show that although the sounds exceed the average detection regulatory criteria, at the 10kph speed condition, probability of detection does not reach 100% at the minimum detection distance. For higher vehicle speeds, tire noise greatly increases making the vehicle much more detectable at longer ranges consistent with previous work (Neurauter *et al.*, 2017). The results also include insights into false alarm rates for the test subjects for different background noise conditions.

The paper is organized as follows: Section II provides information on the test methods including the test set up, details on the transmitted additive warning sounds, participant demographics, measurement hardware and data analysis. Section III provides the detection results given as probability of detection vs. distance. Section Section IV provides points-of-discussion regarding the results and testing methodology as well as suggestions for future research studies.

II. METHODS

This section provides an overview of all tasks performed up to and including formal data collection during the listener evaluations.

A. Experimental Task

For each of the four sessions, four subjects were seated on a flat, isolated section of the Virginia Tech Transportation Institute (VTTI) Smart Road (Fig. 1). All testing occured within the area at the bottom of the Smart Road. The Smart Road is a closed test bed adjacent to VTTI in Blacksburg, VA, and was selected because it provides: a safe (controlled) environment conducive to testing with listeners seated on or near the roadway, low ambient noise levels, a level roadway, a road surface representative of typical roadways, and a site with length appropriate for dynamic maneuvers. Four subjects per each day of trials were seated adjacent to the Smart Road test lane. The seating arrangement for the participants is shown in Fig. 2. An electric vehicle (2019 Chevy Bolt) drove along a trajectory perpendicular to

FIG. 1. Section of the VTTI Smart Road used for the listener tests.

the forward facing orientation of the listeners (Fig. 3). The EV was equipped with a pair of loudspeakers (Fig. 5) that broadcast one of the four test sounds and also made passes with no additive sound. Surrounding the subjects were six JBL LSR308 loudspeakers and a

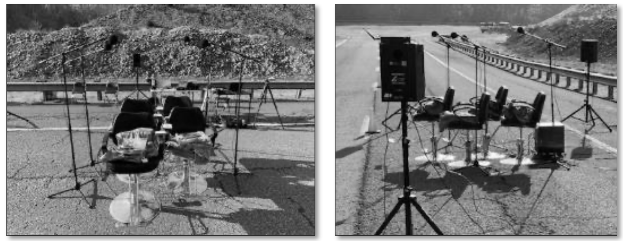


FIG. 2. Seating arrangement for the four subjects.

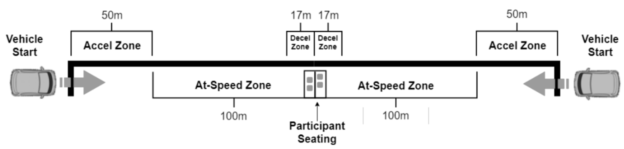


FIG. 3. Vehicle Trajectories Relative to the participants.

subwoofer directly adjacent the participants. These speakers broadcast a noise signal with the spectrum shown in Fig. 4. This spectrum is identical to that in (National Highway Traffic Safety Administration, 2011) and represents an “average urban background noise spectrum”. This noise signal was broadcast at either 55 or 60 dBA as measured by microphones placed just above the heads of the four participants. The 55dBA level was the prescribed level and the 60dBA level was added to study the impact of a higher background noise level. Between the vehicle speeds, test sound number, and background noise level, the listeners were presented with one of twenty constant-velocity scenarios. There were additional scenarios completed in which the vehicle slowed from 20kph to a stop in front of the participants. These were not included in this study because the goal was to study the probability of detection with a steady approach velocity. The scenarios used in this study are provided in Table I .

TABLE I. Driving scenarios presented to the listeners.

	Vehicle Speed (kph)	Background Noise (dBA)
Sound 1	10 or 20	55 or 60
Sound 2	10 or 20	55 or 60
Sound 3	10 or 20	55 or 60
Sound 4	10 or 20	55 or 60
No Sound	10 or 20	55 or 60

Each of these scenarios was repeated four times for the purpose of averaging the results. Subjects, who were wearing a sleep mask to block vision, were instructed to press a hand-held button when they detected the presence of an approaching vehicle and to release the button when they felt that the vehicle had passed. The demographics of the subjects are summarized below.

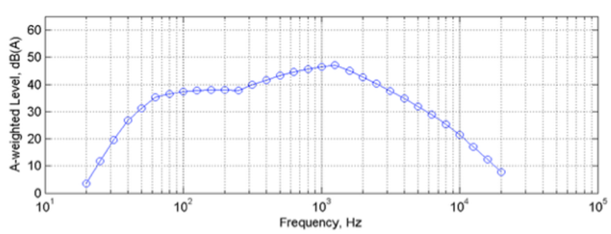


FIG. 4. 1/3 Octave band levels of the background noise.

B. Subjects

Sixteen individuals from the New River Valley and surrounding localities (e.g., Salem, Roanoke, etc.) signed up for participation in this study. Consistent with the previous study, specific age groups were not targeted (Neurauter *et al.*, 2017). Table II provides further detail pertaining to participant sample, both by gender and age. Vision-impairment was not required for eligibility, as it was not expected to impact vehicle detectability measurements (Parizet *et al.*, 2014). All participants were recruited in accordance with the Virginia Tech Institutional Review Board IRB # 15-729 "Electric Vehicle Detectability: Impact of Artificial Noise on Ability of Pedestrians to Safely Detect Approaching Electric Vehicles".

TABLE II. Participant age distribution.

		Age			
Gender	N=	Mean	Std Dev	Min	Max
Female	7	47.6	16.9	24	79
Male	9	42.9	21.4	21	80
Total	16	44.9	19.1	21	80

C. Data Collection

Three types of acoustical measurements were recorded: acoustic pressure, overall A-weighted SPL and 1/3 octave band SPLs (also A-weighted). The major components of the noise measurement data acquisition system (DAS) were as follows:

- Four G.R.A.S. 46AQ TEDS microphones
- One National Instruments cDAQ USB data acquisition rack
- One National Instruments NI 9234 analog to digital converter module
- A Dell Inspiron desktop PC (8GB RAM 1 TB HD) running MATLAB
- National Instruments Labview software
- The National Instruments Labview Acoustics and Vibrations Measurement Suite

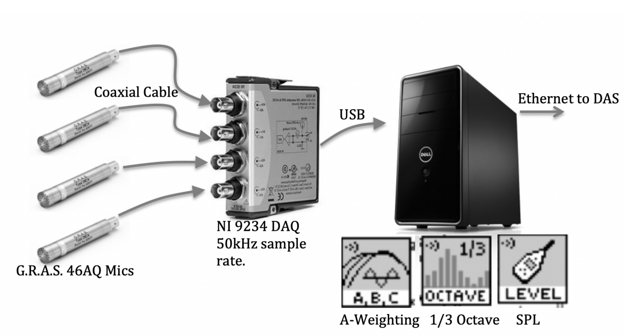


FIG. 5. Data acquisition system for acoustic measurements.

This hardware and software combination provides a Class 1 system that meets or exceeds the following standards: IEC 61260: 1995, Class 1, IEC 61672: 2002, Class 1, JIS C 1509-1: 2005, JIS C 1514: 2002, ANSI S1: 11 - 2004, Class 1, ANSI S1.4: 1983, ANSI S1.42: 1986,

ISO 8041: 2005(E), ISO 532: 1975, DIN 45631: 1991 , DIN 45631/A: 2008. This acquisition package was configured as shown in Fig. 5. Microphone output voltage was sampled at 50 kHz, and saved so that all raw pressure measurements were logged for all tests. Microphone pressure measurements were passed through an A-weighting filter and passed to a sound level meter in order to calculate overall SPL (.125s exponential averaging) and 1/3 octave band sound pressure levels. Overall SPL and 1/3 octave band calculations were logged on the PC and transmitted over Ethernet to the VTTI DAS at a rate of 10 Hz.

Before and during all testing, each microphone was calibrated using a G.R.A.S. 42AA pistonphone calibrator. The 42AA (114 dB at 250 Hz) complies with all the requirements of International Electrotechnical Commission (IEC) Standard 942 (1988) Sound Calibrators Class 1, and was corrected with G.R.A.S. ZC0002K barometer. The data acquisition and analysis system described above was used for both the vehicle-noise tests and for the listener testing. Ambient background measurements were made periodically throughout all testing. Table III provides the daily averages of the ambient levels. The very low level on December 13, 2018 is due to the roughly 10 inches of snowfall at the site. All of the overall levels are at least 10 dB below the 52 dBA overall target level for the additive sounds so no correction due to elevated background noise was necessary.

A modified VTTI NextGen DAS shown in Fig. 6 logged distance and speed simultaneously with the acoustical measurments. The DAS was configured to communicate with a Differential Global Positioning System (DGPS) unit installed in the test vehicle. This DGPS unit consisted of a Novatel antenna on the vehicle roof and an AvaLAN transmitter placed on the passenger side dashboard.

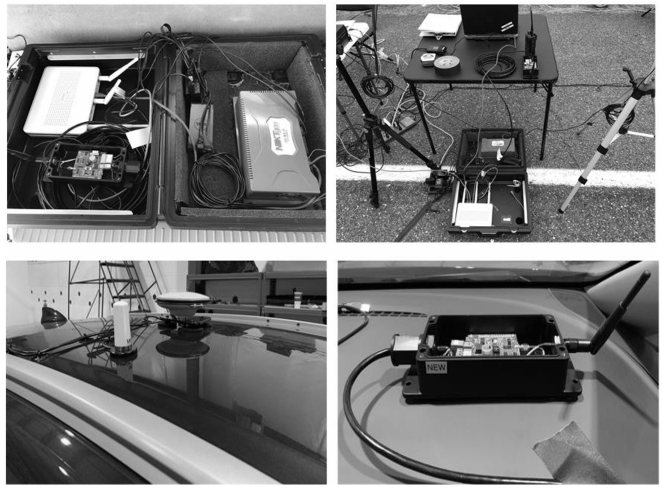


FIG. 6. Data acquisition system for acoustic measurements.

This instrumentation approach provided continuous recording of base-to-vehicle distance and speed. An experimenter calibrated the transmitter and receiver at the beginning of each test session, ensuring accuracy of the recorded output. Based on known positions of each participant's seated location with respect to vehicle path and location of antenna relative to the front bumper, accurate distances were calculated. The NextGen unit, paired with a laptop, allowed the experimenter to both monitor variables of interest in real time and add task codes for each trial to simplify review and analysis. Participants were given a hand-held buttons to record their detections. Participants were instructed to press the button upon detection of an approaching vehicle, and continue pressing until they felt it was safe to cross, at which point they would release the button. These interactions were recorded by the DAS, specific to each participant and trial.

TABLE III. Average daily background levels.

Date	Average Daily Level
November 11, 2018	39.6 dBA
November 18, 2018	40.1 dBA
November 19, 2018	41.3 dBA
November 29, 2018	40.4 dBA
December 13, 2018	35.4 dBA (Heavy Snowfall)

D. Stimuli - Additive warning sounds

Subjects were presented with one of four additive alert sounds and a no-sound condition. This section provides details of the additive sounds in terms of overall, A-weighted, sound pressure level and 1/3 octave band measurements. All sounds were designed to satisfy the proposed NHTSA regulations pertaining to FMVSS 141 (National Highway Traffic Safety Administration, 2018). These are, in short, "Vehicles complying with the 2-band option must meet minimum sound pressure levels in two non-adjacent one- third octave bands between 315 Hz and 3150 Hz, with one band below 1000 Hz and the other band at or above 1000 Hz. The two bands used to meet the 2-band option also must meet a minimum band sum level". Both stationary and drive-by measurements were made. These are provided in the following subsections.

1. *Stationary Measurements*

Using the geometry in Fig. 7, 20-second-long measurements were taken and recorded by the data acquisition system. The loudspeaker arrangement shown in Fig. 5 was used for all tests reported in this paper. Fig. 8 through Fig. 11 provide the results for both overall A-weighted SPL (left) and 1/3 octave bands (right). The overall SPL plots on the left provide a short time history of the overall A-weighted SPL at each of the microphones (driver, passenger, and front). At the bottom of the overall SPL plots, the peak level is given for each microphone position. The 1/3 octave band plots on the right of each figure are presented for the time that matches the peak of the overall SPL for the microphone position with the lowest overall SPL. For example, in Fig. 8, the microphone with the lowest overall level is the Passenger position. The peak overall level (50.6 dBA) for this microphone occurs at 11.6 seconds (marked by a circle marker). The plot on the right of Fig. 8 gives the 1/3 octave band levels at the time of the max overall SPL (i.e. 11.6 seconds). Additionally, the 1/3 octave plot provides the sum of the upper and lower range non-adjacent bands that exceed the NHTSA-prescribed octave band levels (in this case 48.2 dBA). Sound #1's

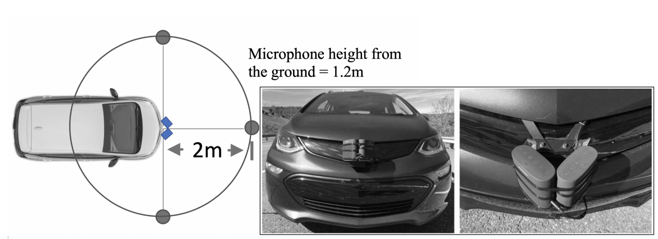
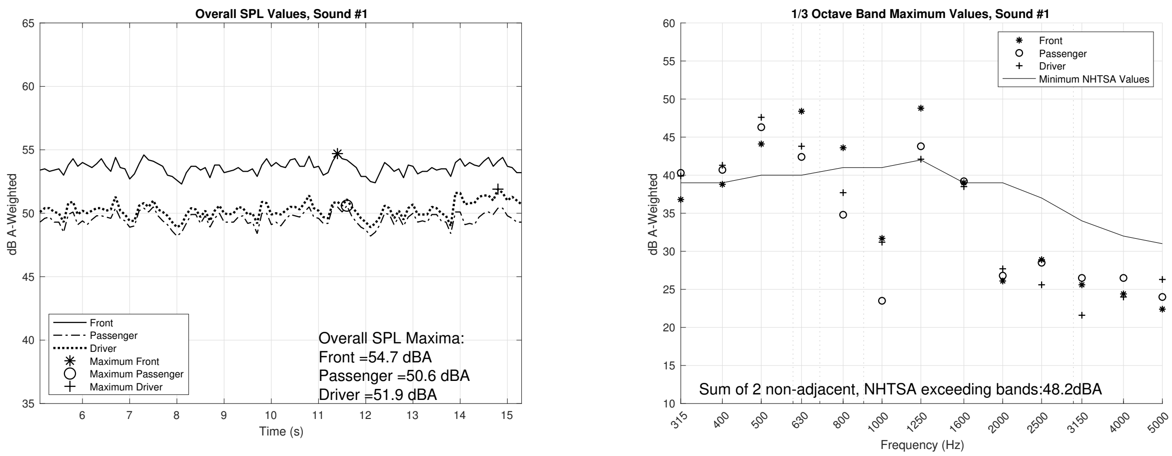


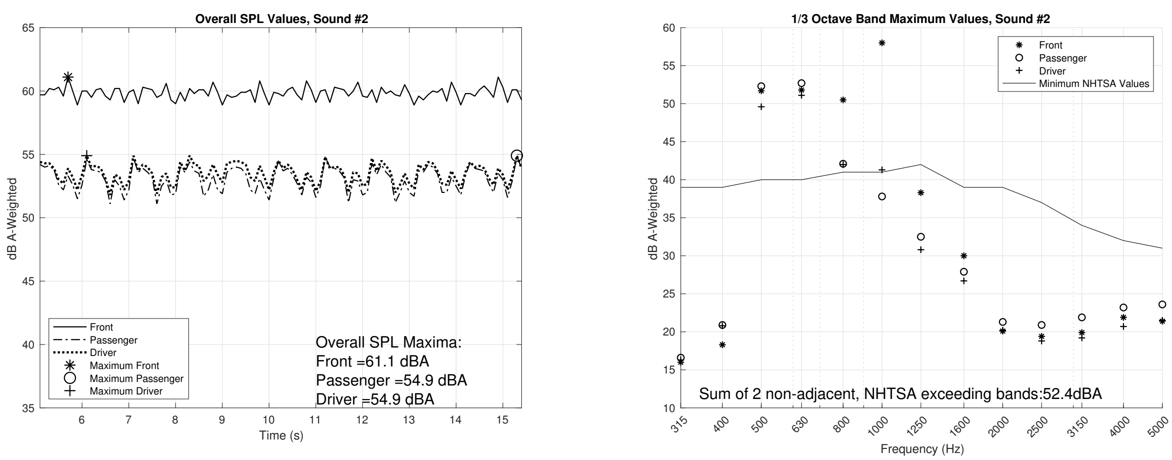
FIG. 7. Geometry for stationary sound measurements.

lowest overall level was from the passenger-side microphone. The 1/3 octave band results



(a) (b)

FIG. 8. Overall and 1/3 octave band levels of sound #1.

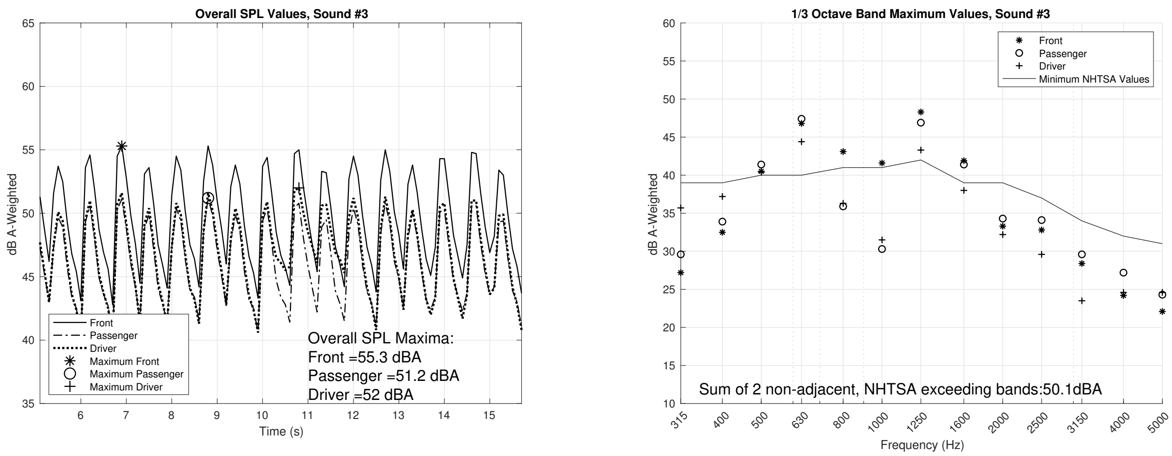


(a) (b)

FIG. 9. Overall and 1/3 octave band levels of sound #2.

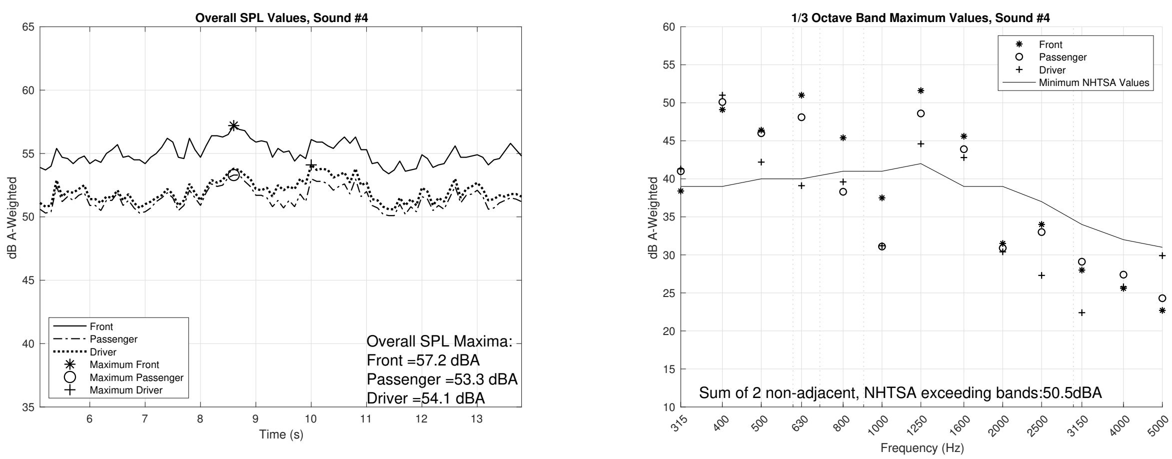
in Fig. 8 show that several bands in both the upper and lower ranges exceeded the NHTSA minima, and that the 2-band sum met the 48dB requirement. The passenger side overall peak level was 1dBA below the 52dBA requirement.

Sound #2 had the highest overall SPL in front of the vehicle. The driver-side microphone had the lowest overall level. The 1/3 octave band results in Fig. 9 show that several bands in



(a) (b)

FIG. 10. Overall and 1/3 octave band levels of sound #3.



(a) (b)

FIG. 11. Overall and 1/3 octave band levels of sound #4.

the lower range and one band in the upper range exceeded the NHTSA minima, and that the two-band sum met the 48dB requirement. The passenger side overall peak level exceeded the 52dBA requirement by 3dBA, a very high measurement due to the two-band requirement. In order for the single upper-range octave band (1000 Hz) to exceed the NHTSA requirement

(41dBA), the overall level had to be increased. This created a very loud sound at the front of the vehicle.

Sound #3 had a tempo that was almost impulsive as evidenced by the time series plot of the overall SPL. The passenger-side microphone had the lowest overall level. The 1/3 octave band results in Fig. 10 show that one band in both the upper and lower ranges exceeded the NHTSA minimum, and that the two-band sum met the 48dB requirement. The passenger side overall peak level was 1dBA below the 52dBA requirement.

Sound #4 spectrum contained much more lower-frequency energy than the other sounds. The passenger side microphone had the lowest overall level. The 1/3 octave band results in Fig. 11 show that several bands in both the upper and lower ranges exceeded the NHTSA minimum, and that the two-band sum met the 48dB requirement. The passenger side overall peak level exceeded the 52dBA requirement by 1dBA.

In all of the cases above the overall A-weighted SPL in front of the vehicle was 3-6 dBA above the lowest overall SPL for that sound. Sound #2 was the extreme at 6dB above the level on the sides of the vehicle. These differences can be attributed to the loudspeaker arrangement used to transmit the test sounds. First, the speakers are not omni-directional. Using two speakers increased coverage to the sides of the vehicle, but also increased the overall level in front of the vehicle. In order to fully understand the directionality issues of the loudspeaker arrangement, measurements in an anechoic chamber on a turntable would be required.

2. *Drive-by Measurements*

The dynamic testing procedure consisted of measuring the overall A-Weighted SPL as the vehicle moved through the test area at either 10 or 20 kph. These tests were designed to match the measurement criteria provided in the FMVSS141 test measurement procedure document (National Highway Traffic Safety Administration, 2018). The test area and microphone locations are illustrated in Fig. 12. Background noise-level measurements were also made throughout the testing procedure (See Table III: Average daily ambient background noise levels). Figs 13 - Fig. 17 provide the drive-by results with the vehicle moving from left to right. The right to left measurements are consistent with the left to right and have been omitted for brevity. All of the drive-by measurements illustrate the directionality

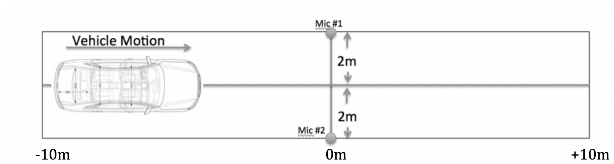


FIG. 12. Geometry for drive-by measurements.

of the loudspeaker source where the sound had a higher SPL in front of the vehicle. This is evidenced by the peak occurring roughly 10m before the car reaches the microphones. The higher speed of 20kph causes an increase in overall SPL of roughly 10dB seen in all of the plots. This is also seen in the no sound condition plot in Fig. 15 particularly as the car's noise emerges from the background noise at a distance of roughy 20m. The no sound condition peaks at 9m from the two microphones at 52dBA for the 10kph case and 62dB for the 20kph case. Sound #2 had the highest SPL in front of the vehicle as shown in the

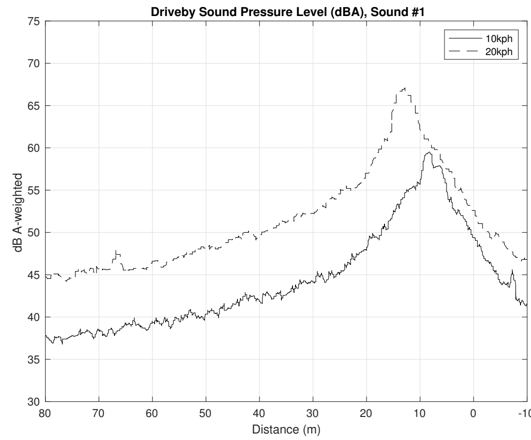


FIG. 13. Sound #1 Drive-by SPL measurements.

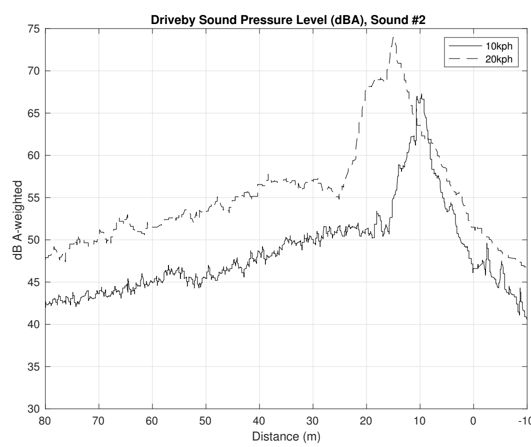


FIG. 14. Sound #2 Drive-by SPL measurements.

stationary measurements above Fig. 7. The driveby plot in Fig. 12 shows that the effect of this is a peak SPL occurring ever further away from the 0m mark at roughly 15m.

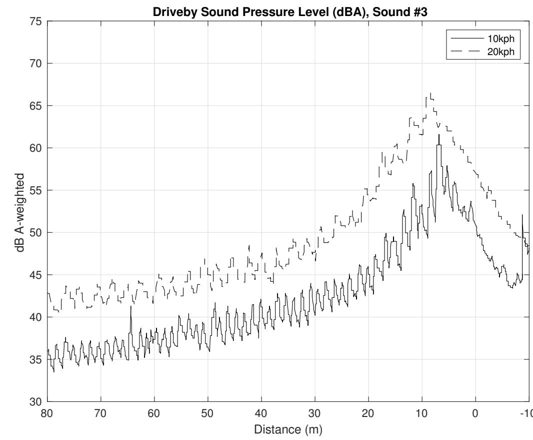


FIG. 15. Sound #3 Drive-by SPL measurements.

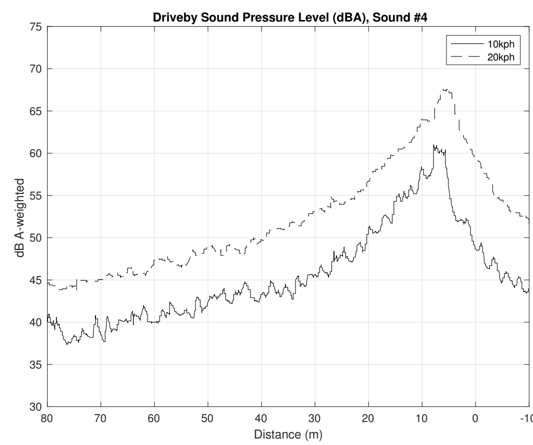


FIG. 16. Sound #4 Drive-by SPL measurements.

E. Data Analysis

Previous results for the data collected in this work were expressed as mean detection distances (Neurauter *et al.*, 2020; Roan *et al.*, 2017). Hhuman detection performance in this work presented as probability of detection vs. distance and is based on passive sonar signal processing as discussed in (Van Trees, 2004). The process is illustrated in Fig. 18. The

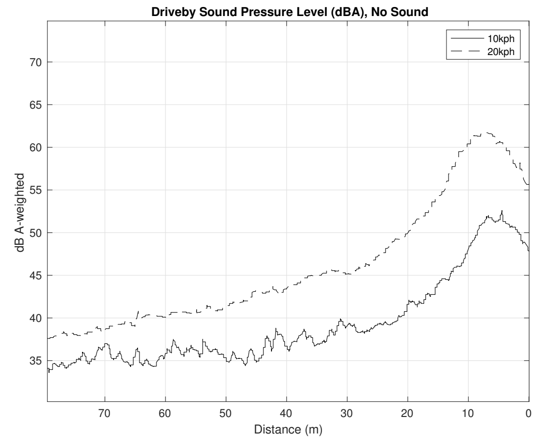


FIG. 17. No sound drive-by SPL measurements.

data from a 4m window that corresponds to the length of the vehicle is used to calculate probability of detection and probability of missed detection directly. During the time when 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 probability of detection 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.

III. RESULTS

The process shown in Fig. 18 was completed for all of the twenty test conditions. This section provides the results in Figs. 19 through Fig. 23. Each plot consists of two subplots.

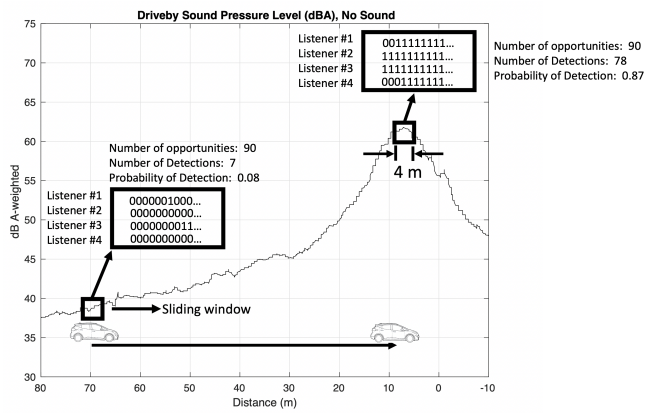
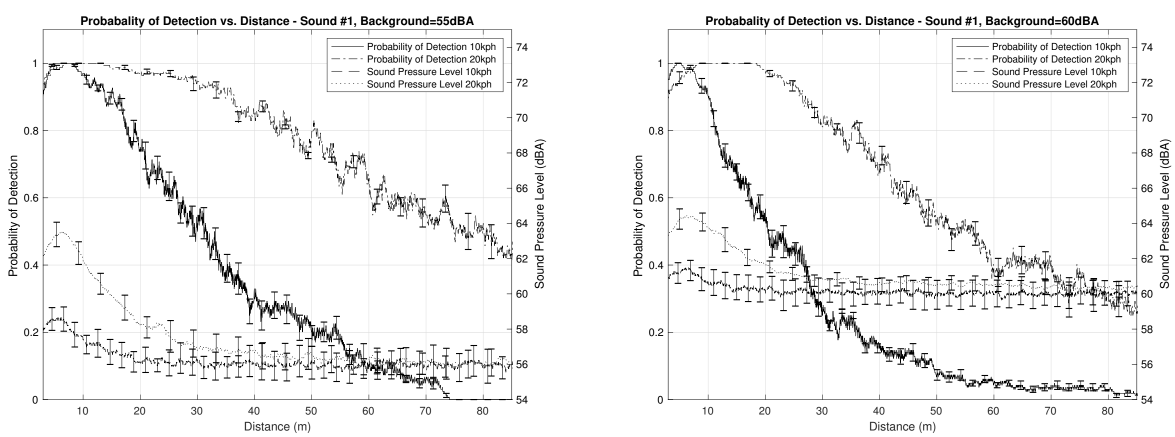


FIG. 18. Illustration of the data processing to calculate probability of detection vs. distance.

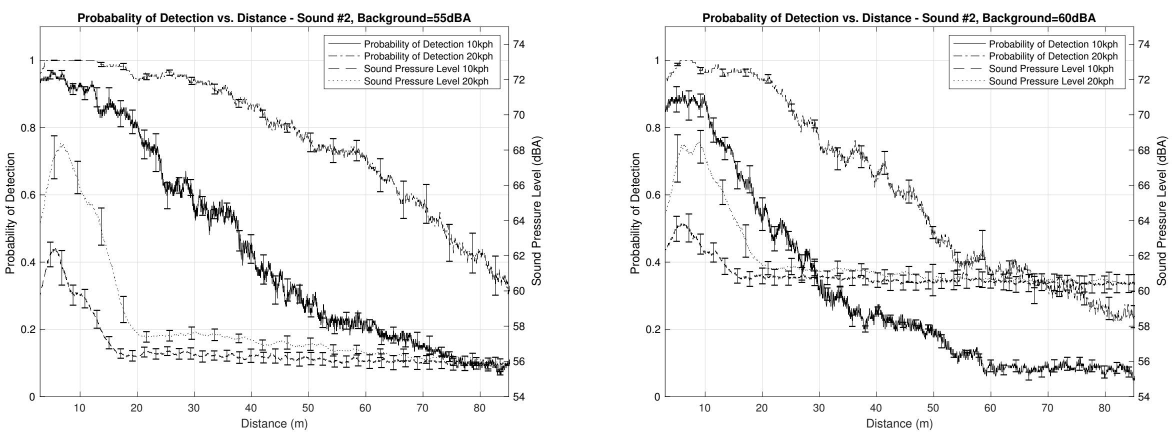
The plot on the left, labeled as (a), is for the 55dBA background noise condition for vehicle speeds of 10 and 20 kph. The plot on the right, labeled as (b) is for the 60dBA background noise condition for vehicle speeds of 10 and 20 kph. For both (a) and (b) plots, the left hand axis is probability of detection. The right-hand axis is A-weighted sound pressure level from the microphones above the listeners' heads. Error bars indicate standard error.



(a) (b)

FIG. 19. Probability of detection vs. distance for sound #1.

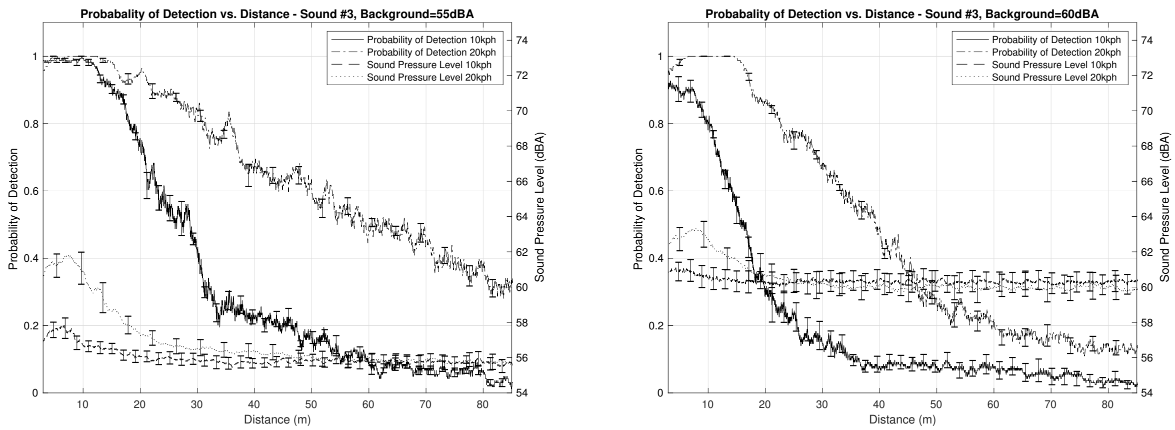
For sound #2, the results in Fig. 20 show increased detection distance due to the higher overall SPL of the additive sound in front of the vehicle. Additionally the slope of the detection curve is less negative than the other sounds indicating a higher overall Pd at further distances. However, the probability of detection of this sound is actually lower than Sound #1 in the close range (less than 10m). The Pd for this sound never reaches 1 for the 10kph case in either background condition, and the Pd for 20 kph reaches 1 at a shorter distance.



(a) (b)

FIG. 20. Probability of detection vs. distance for sound #2.

Sound #3 was different from the other sounds in that it was more of a periodic impulsive sound as shown in Fig. 8. This sound has the poorest overall performance of the four sounds at all distances. This is evidenced by the steepest negative slope of the Pd curve. However, at closer distances for the 10kph case, the performance was better than sounds 1 or 2 with a Pd of roughly 1 inside of 11m. This may indicate that a more pulsing sound is more detectable at closer ranges, but has a lower impact on the soundscape at further distances where detecting the vehicle is unnecessary.

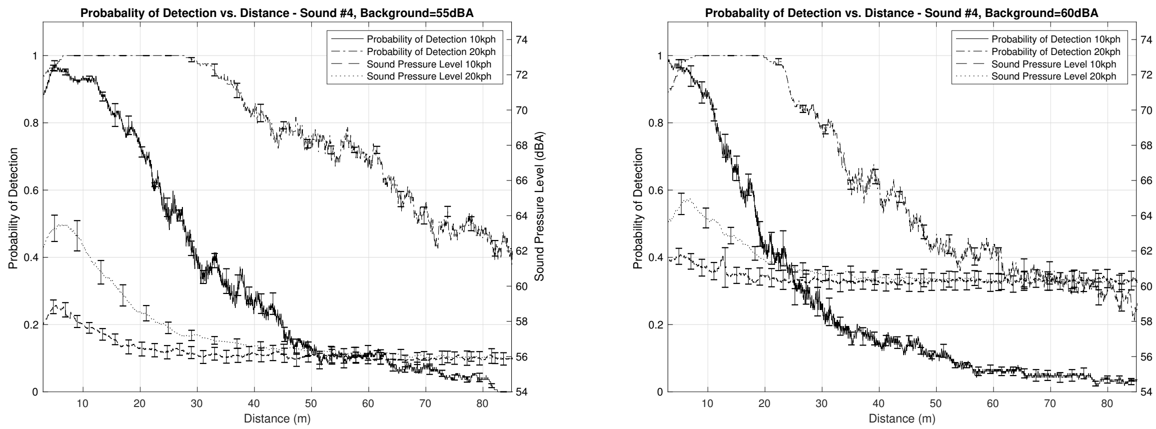


(a) (b)

FIG. 21. Probability of detection vs. distance for sound #3.

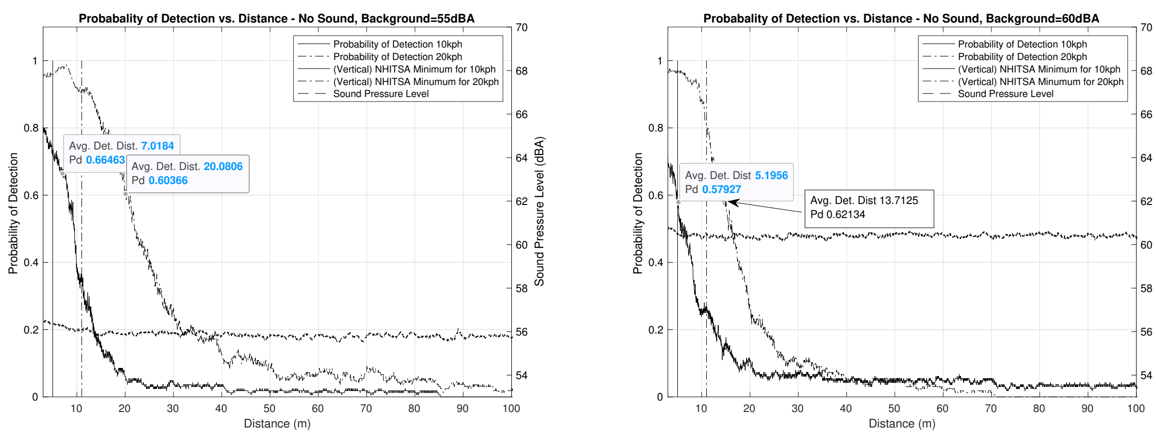
Sound #4 had similar detection performance to sounds 1 and 2 for the 10kph cases but had superior detection performance at 20kph. In the 55dBA background condition for 20kph approaches, sound #4 had a Pd of 1 out to a distance of 30m and to 20m for the 60dBA background. The 10kph curves never reach a Pd of 1 for either 55 or 60dBA background. Sound #4 was the only sound with significant energy in the 1600Hz octave band (followed by sound #3). The sound also had the highest number of bands that exceeded the NHTSA minimums giving the sound the highest level of frequency diversity.

The no sound condition provided the worst performance in terms of detectability. The Pd curves have the steepest negative slopes and never reach a Pd of one for any of the test conditions. Table IV and Table V provide several points of interest from the Pd vs. distance curves. The second column in the tables gives the Pd at the NHTSA minimum



(a) (b)

FIG. 22. Probability of detection vs. distance for sound #4.



(a) (b)

FIG. 23. Probability of detection vs. distance for No Sound.

detection distance of 5m (National Highway Traffic Safety Administration, 2011). In the 55dB background noise for 10kph vehicle speed, all of the sounds exceeded a detection probability of 90%, but only sound #1 reached 100% detection at the minimum prescribed distance. At 20kph, in 55dBA background, all sounds achieved 100% detection. At the mean detection distances, all sounds hovered in the 40-60% probability of detection range.

As expected, the no-sound case performed poorly. In the 60dB background noise for 10kph vehicle speed, performance was reduced with no sounds achieving 100% detection. At 20kph and 60dBA background, all sounds achieved 100% detection. At the mean detection distances (all greatly reduced from the 55dBA background cases), all sounds again had 40-60% probability of detection ranges.

TABLE IV. Pd at NHTSA minimums and mean detection distances (55dBA Background)

Sound #	Pd at 5m (10kph)	Pd at 11m (20kph)	Pd at mean (10kph)	Pd at mean (20kph)
1	1	1	0.52 (29.7m)	0.52 (73.4m)
2	0.92	1	0.58 (32.1m)	0.51 (71.4m)
3	0.95	1	0.50 (24.1m)	0.48 (59.1m)
4	0.92	1	0.51 (27.3m)	0.61 (69.9m)
None	0.69	0.91	0.63 (7.0m)	0.60 (20.1m)

IV. DISCUSSION

Figs. 19 through 23 above provide detection probability as a function of distance to the vehicle for all 16 subjects with four trials per speed and background noise condition. In terms of general trends, the higher speed case of 20kph, as expected, produced higher overall detection probabilities due to increased tire noise. These curves had the lowest negative slope indicating higher detection probability at further distances. The NHTSA minimum dis-

TABLE V. Pd at NHITSA minimums and mean distances (60dBA Background)

Sound #	Pd at 5m (10kph)	Pd at 11m (20kph)	Pd at mean (10kph)	Pd at mean (20kph)
1	0.98	1	0.47 (20.4m)	0.51 (55.2m)
2	0.89	1	0.50 (21.7m)	0.47 (53.2m)
3	0.87	1	0.62 (13.8m)	0.55 (35.6m)
4	0.95	1	0.52 (18.3m)	0.42 (57.4m)
None	0.48	0.82	0.44 (5.2m)	0.75 (13.7m)

tances for detection for 10kph and 20kph approaches are 5m and 11m respectively (National Highway Traffic Safety Administration, 2011). The average detection distances (Tables IV and V) far exceed the minimum required distances. Observing the probability of detection at these distances provides a clearer picture of actual performance (i.e., Pd in the 0.4 to 0.6 range). The average detection distances were consistent with the authors' previous work (Roan *et al.*, 2017) and that in (Altinsoy, 2013) .

All of the sounds except Sound #2 in 60 dBA background noise reached 100% Pd at distances exceeding the NHTSA minimum of 11m. Sound #2 reached 95 % at 11m for the 60dBA background for the 20kph approach speed. Sound #2 had the highest overall SPL as shown by Fig. 7 and Fig. 12, but also had the lowest energy in the 1250 and 1600Hz 1/3 octave bands. Sound #3 presents an interesting case in that it's overall energy was quite low. This was the only sound that had significant dynamic amplitude shifts as shown in

Fig. 8a. This sound provided a Pd that reached 100% for all of the scenarios except for the 10kph approach in 60dBA background where it reached 0.87 at 5m. Sound #3 provided high Pd at close ranges, but had the steepest negative slope for all cases at distances further than 10m. This result is consistent with the work in (Wall Emerson *et al.*, 2013) regarding amplitude modulation of the signal. Additionally, this type of detection curve is what would be needed to begin to satisfy the balance between safety at close ranges and annoyance at further ranges. Sound #4 also provided interesting Pd results. In the 10kph case, it had performance similar to the other sounds, but had superior performance in the 20kph cases. As noted above, Sound #4 had the highest levels of low frequency content Fig. 9, but also had a peak SPL in the drive-by tests that was the latest to arrive at the listeners Fig. 14. Lastly, the no sound case did not in any case reach 100% detection. Pd for the no sound case at the NHTSA minimums for 10kph was 0.65 in 55dBA background and 0.47 in 60dBA background. This shows that all of the warning sounds did provide a high level of detection performance improvement over the no sound condition.

The no sound condition also provides insight into another performance parameter often discussed in the passive sonar literature (Van Trees, 2004) for analogous detection problems: false alarm rate. Fig. 23a shows a leveling of the Pd curve at distances greater than 50m for the 55dBA background condition at a Pd level of 2.4%. Fig. 23b shows a leveling of the Pd curve at distances greater than 70m for the 60dBA background condition at a higher Pd level of 5.0%. In classical detection and estimation theory, a false alarm rate is selected and the detection statistic (level, matched filter output, etc.) is thresholded. Values of the detection statistic above the threshold are declared detections and those below it are nondetections (Poor, 2013). The number of correct detections given a true hypothesis divided by the number of opportunities is the probability of detection. These types of detectors are referred to as constant false alarm rate or CFAR detectors. In analogous sonar problems, as the signal to noise ratio (SNR) goes down into the noise, the probability of detection asymptotically approaches the false alarm rate as the source moves away from the detector and Pd levels off as we see in Fig. 23a and Fig. 23b. These false alarm rates are relatively low and are consistent in that when the background noise level is almost doubled, the listeners become more likely to guess when the vehicle sound is extremely low.

There are several aspects of this work that point to future research topics. First, starting with the source, efforts should be taken to provide an acoustic source that provides a uniform SPL for the warning sounds around the front of the vehicle (and the back as well for the reverse problem). Given the tonal nature of the requirements, this may prove difficult as many factors will impact directionality. These will include acoustic bounces from the road surface creating multipath interference patterns as a function of angle around the vehicle and height of the listener. Speaker placement will play an important role in producing sound outside the perimeter of the vehicle. For example, will tires or other vehicle parts produce shadow zones for some octave band components? Because of increasing concern regarding noise annoyance, simply making louder sounds may not be the answer. A second area for future research is to perform a regression analysis relating the octave band levels to detection performance. This work is currently underway and will be a topic of future publication by the authors. Once a relationship is established relating required octave band content to detection performance, various approaches to sound design should be considered.

Sound aesthetics plays a very important role in the perception of vehicle quality (Genuit, 2004). Therefore, sounds are not likely to be designed with only regulatory requirements in mind and methods of incorporating aesthetics will be required. Lastly, immersive audio techniques could be employed to provide both test uniformity and diversity in terms of road surfaces, and other environmental considerations. The recruitment of test subjects for live in-person vehicle testing is very expensive and has many factors that make reproducibility difficult. The tests performed in this study were done on a closed section of roadway that was isolated from many environmental acoustic sources such as traffic and industrial noise, but still required stopping testing several times a day due to aircraft fly-overs, changes in wind, and locomotive pass-bys. These types of test sites are scarce, so immersive audio techniques would provide the ability to reproduce the experiments with a high degree of spatial diversity with, for example, realistic soundfield recordings of actual urban intersection noise. Lastly, in regard to background noise, it would be very beneficial to understand detection performance in realistic backgrounds rather than the broadband, uniform continuous noise tested to date. This background should include the presence of several slow moving EVs in the area around the pedestrian to determine the impact of many alert sounds possibly confusing the listener.

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