ELECTRIC VEHICLE DETECTABILITY BY THE VISION IMPAIRED: QUANTIFYING IMPACT OF VEHICLE GENERATED ACOUSTIC SIGNATURES ON MINIMUM DETECTION DISTANCES

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Paper Number 17-0134

ABSTRACT

As the adoption of hybrid and electric vehicles (HVs and EVs) increases, concerns have emerged regarding their relative quietness with respect to pedestrian detectability. Although all pedestrians face a possible increase in risk due to lower operating noise associated with HVs and EVs, the visually impaired and blind community faces an even greater potential for risk due to their reliance on hearing as an assessment for when it is safe to cross a roadway.

Vehicle manufacturers have started implementing additive noise solutions designed to increase vehicle detectability while in electric mode and/or when traveling below certain speeds. This paper presents a single effort undertaken to evaluate the United Nations Economic Commission of Europe's (UNECE's) proposed evaluation method for quiet road vehicles, as well as to assess performance between two additive noise approaches. This effort also evaluated detectability of an EV with no additive noise versus a traditional internal combustion engine (ICE) vehicle.

Twenty-four legally blind individuals participated in a daylong session evaluating detectability of approaching vehicles within a controlled environment. Vehicle approach scenarios consisted of two levels of steady-state speed, and a scenario where vehicles came to a complete stop. Participants, seated within one lane of a closed-test track, declared auditory detection of an oncoming vehicle by pushing a hand-held button.

Findings suggest that although mean detection distances trend higher for vehicles with an additive noise component, they aren't significantly different from traditional EVs at speeds of 10 kph. Moreover, all EV/HVs were detected at significantly shorter distances relative to the ICE vehicle. At an approach speed of 20 kph, however, these differences become indistinguishable, likely due to the additional road noise produced by tires at higher travel speeds.

The findings from this study provide justification for the usefulness of examining additional vehicle types, approach maneuvers, road surfaces, and noise levels within the same general context. Furthermore, the findings from this study provide guidance regarding the impact of EV additive noise on detectability, particularly as it relates to the vision-impaired population.

INTRODUCTION

As the adoption of hybrid and electric vehicles (HVs and EVs) increases, concerns have emerged regarding their relative quietness with respect to pedestrian detectability. Although all pedestrians face a possible increase in risk due to lower operating noise associated with HVs and EVs, the visually impaired and blind community faces an even greater potential for risk due to their reliance on hearing as an assessment for when it is safe to cross a roadway.

In order to address these concerns, vehicle manufacturers have begun implementing additive noise solutions designed to enhance vehicle detectability while in electric mode and/or when traveling below a certain speed. Regulations regarding additive sound characteristics (e.g., loudness, tone, etc.) were not available as the study discussed herein was under development. As a result, there has been, and continues to be, a great deal of variability among available implementations.

In terms of assessing performance, however, the United Nations Economic Commission of Europe (UNECE) has developed a method for evaluating additive vehicle noise solutions in quiet road vehicles [1]. The research outlined in this paper encompasses a single effort undertaken to evaluate the UNECE's proposed method, as outlined. This research was also guided by interest in assessing General Motors' current EV additive noise approach relative to 1) a competitor application, 2) an EV with no additive noise feature, and 3) a traditional internal combustion engine (ICE) vehicle.

Proposed Regulations & Past Research

In 2011, The National Highway Traffic Safety Administration (NHTSA) proposed minimum sound requirements for HVs and EVs to ensure that these quiet vehicles emit an artificial sound in an effort to ensure that they are "…recognizable as motor vehicles in operation…"[2-3]. The current study sought to add to the existing body of knowledge regarding detectability of non-ICE vehicles.

Over the course of three phases of research beginning in 2013, NHTSA determined that adding synthetic sounds of combustion noise to EVs and HVs was relatively ineffective and that the ability to detect approaching vehicles was not significantly impacted by visual impairment. Moreover, NHTSA's research ultimately recommended minimum additive sound requirements designed to improve detection and recognition of EVs and HVs as motor vehicles [3]. NHTSA stated that international guidelines addressing the issue (namely UNECE guidelines [1]) fell short of the level of detail typically found in a Federal Motor Vehicle Safety Standard (FMVSS). Notably, NHTSA clarified that some test standards had failed to account for psychoacoustic factors, while others were still under development [2].

The research team conducted a review of relevant research during the course of this project in order to summarize previous findings in the area of additive sound for EVs and HVs, recognizing that further research was needed. The studies reviewed considered scenario environments (e.g., types of intersections and procedures used) [4-12], sounds (i.e., ambient/environmental and vehicle-based) [4-7], vehicle speed and characteristics [5, 7-8], and properties relative to participants (i.e., positioning of participants during experiments and individual hearing loss) [4-7, 9-12].

Research regarding sound factors revealed that when the ambient noise surrounding the roadway environment was lower, pedestrians made fewer risky decisions to cross the road. Often, pedestrians who are visually impaired rely on surges in vehicle traffic when making crossing decisions. A number of studies noted that more research was needed in higher ambient sound-level scenarios within a controlled environment, particularly where noise level conditions would remain constant across the study test scenarios. In addition, research suggests that the interaction of artificially-added sound coupled with an ambient background noise impacted visually-impaired pedestrian performance of orientation and mobility tasks along roadways. One study found that, specifically, sound energy in the 500–1,000 Hz range hindered detection of vehicle noise [5].

Studies considering vehicle factors, including vehicle speed and characterization, investigated vehicle speeds up to approximately 32 kph. These studies noted that previous research by NHTSA determined that most crashes involving HVs occur within the 10–20 kph range and that tire noise makes up the majority of the sound for approaching vehicles at higher speeds. NHTSA's proposed minimum sound requirements for EVs and HVs addressed speeds from idle up to 30 kph. In addition, one study noted that future research should take into consideration vehicle characteristics, such as tire tread wear, vehicle engine and exhaust system state of repair, whether fans or radios were on in passing vehicles, and battery charge state [7].

The research reviewed also examined factors related to study participants. In particular, participant alignment during the experiments was carefully considered, with many studies staggering participants along roadways in order to minimize sound "shadowing," which, if not accounted for, may hinder auditory detection of vehicle traffic. Participant hearing loss was also considered, with some studies using self-reported hearing loss information, verified by an audiometer, categorizing hearing loss in bins for analysis. In addition, studies reviewed may not have taken into account directional hearing loss (differences in hearing loss out of the right and/or left ear, depending on vehicle approach direction).

Through this literature review, it was determined that further research should consider both ambient and vehicle-based sound, vehicle speed while controlling for vehicle characteristics (to the extent possible), and participant alignment along roadways.

METHODS

Test Site

Based on the given objectives, vehicle detection within a noise-controlled environment was the primary focus for these evaluations. As such, selection of an appropriate site location to support both benchmark vehicle noise testing, as well as the subsequent "listener" (participant) evaluations, was critical. Under ideal circumstances, this location would provide a safe environment conducive to testing with "pedestrians" seated on or near the roadway. Additionally, this site should offer low ambient noise levels, a level roadway, a road surface representative of typical roadways, and an appropriate distance to accommodate the selected dynamic maneuvers.

The research team identified multiple sites, conducting benchmark vehicle noise testing at each location before selecting a segment near the lower turnaround of the Virginia Smart Road (Figure 1), a closed test track adjacent to the Virginia Tech Transportation Institute (VTTI) in Blacksburg, VA. This location came closest to meeting the ideal requirements identified above.

Figure 1. Smart Road location and road surface.

As Smart Road access is controlled, testing within this location guaranteed that no other vehicles would enter the defined evaluation area. Noise levels at the selected location were the lowest of any site measured, primarily due to the absence of any direct impact by surrounding primary roadways. The roadway was relatively level, with an approximate 1% grade, while also providing sufficient distance to support dynamic maneuvers. Finally, the roadway surface closely resembled that of a typical asphalt-paved roadway throughout Virginia, but notably, was not representative of new pavement.

Vehicles

Four vehicles were selected for the benchmark vehicle noise tests and the listener testing component. These vehicles included a 2011 Chevrolet Volt (EV, no additive sound), a 2014 Cadillac ELR (EV, GM production additive sound), a 2013 Toyota Prius (HV, competitor additive sound under electric mode), and a 2013 Cadillac SRX (ICE).

It is critical to note that the Prius, as it is an HV rather than a pure EV, was only driven in electric mode (ICE off) during the approach maneuvers. Radios, heating, ventilation, and air conditioning also remained off throughout testing across all vehicles. The Volt and ELR were fully charged prior to testing.

UNECE Vehicle Noise Testing

Benchmark vehicle noise testing was conducted at multiple test locations during the test site search, measuring the overall sound pressure level (SPL) and 1/3 octave band levels of the vehicles at 10 kph and 20 kph. Testing followed the procedure outlined in the UNECE document [1], which provides guidelines on microphone spacing, vehicle speeds, number of trials, and background noise levels. Results included within this document are specific to testing conducted at the selected test location at the bottom of the Smart Road.

The UNECE testing procedure consisted of measuring the overall A-Weighted SPL and 1/3 octave band SPLs as the vehicle moved through a well-defined test area. The test area and microphone locations are illustrated in Figure 2.

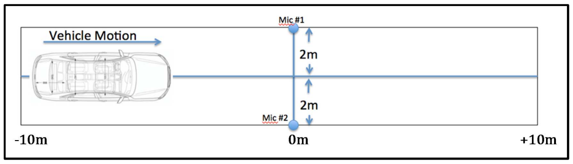

Figure 2. Dynamic vehicle noise testing.

Recording of acoustical measurements began when the vehicle's front bumper entered the test area (at -10 m) and stopped when the rear bumper exited the test area (+10 m). For each vehicle and speed, four runs were completed and the overall SPLs were then averaged as a function of distance. Background noise level measurements were also made throughout the testing procedure.

Valid tests were completed for each of the four vehicles across two speed conditions. Background noise, consisting of four 10-second measurements, provided an average background noise measurement across the two microphones at 41.6 (±.1) dBA.

Results for the 10 kph and 20 kph vehicle drive-by tests are provided below (Figure 3 and Figure 4). These plots represent the overall average across four trials for each vehicle and approach speed, with averages provided for both driver and passenger sides. The curves at 20 kph are heavily influenced by road/tire noise, and are therefore less variable. Because the average background noise value was 10 dBA below the peaks of all drive-by measurements, no correction for the background noise was necessary [1].

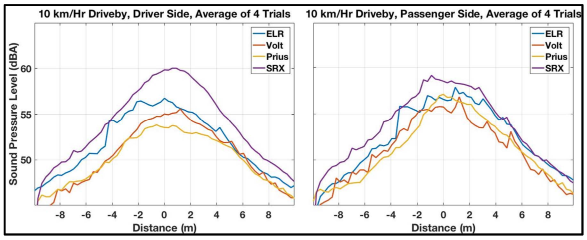

Figure 3. Drive-by noise testing at 10 kph (Left: Driver Side; Right: Passenger Side)

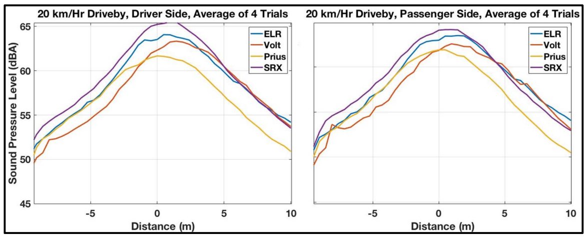

Figure 4. Drive-by noise testing at 20 kph (Left: Driver Side; Right: Passenger Side)

The octave band results corresponding to the plots above are provided below (Table 1 and Table 2). The yellow highlighted values illustrate 1/3 octave bands that fall below the UNECE proposed minimum (far right column within each table). In order to meet the standard, a vehicle must meet or exceed the prescribed minimum for at least two of the 1/3 octave bands, with one of those below 630Hz. Based on this criteria, all vehicles met the UNECE standard for both approach speeds.

Table 1.
1/3 Octave Band Results for UNECE Tests at 10 kph. Frequency in Hz, Levels in dBA

Driver						Passenger					
Frequency	*ELR*	*Volt*	*Prius*	*SRX*	*ECE Min.*	*Frequency*	*ELR*	*Volt*	*Prius*	*SRX*	*ECE Min.*
160	35	37	34	35	45	160	35	37	33	35	45
200	40	39	39	39	44	200	40	38	38	38	44
250	43	41	44	42	43	250	42	40	43	42	43
315	41	42	42	40	44	315	42	43	41	40	44
400	46	44	41	43	45	400	46	41	38	42	45
500	46	46	42	47	45	500	45	43	41	47	45
630	49	47	45	48	46	630	50	46	45	49	46
800	51	49	45	48	46	800	52	49	46	50	46
1000	49	48	43	49	46	1000	49	49	45	49	46
1250	48	47	45	50	46	1250	51	51	47	52	46
1600	47	45	43	51	44	1600	49	49	45	51	44
2000	49	44	48	51	42	2000	50	48	52	50	42
2500	47	43	46	51	39	2500	52	46	52	51	39
3150	44	45	38	51	36	3150	49	46	42	49	36
4000	41	42	35	49	34	4000	46	44	38	48	34
5000	39	39	39	48	31	5000	42	41	47	47	31

Table 2.
1/3 Octave Band Results for UNECE Tests at 20 kph. Frequency in Hz, Levels in dBA

Driver						Passenger					
Frequency	*ELR*	*Volt*	*Prius*	*SRX*	*ECE Min.*	*Frequency*	*ELR*	*Volt*	*Prius*	*SRX*	*ECE Min.*
160	41	42	40	42	50	160	42	44	41	45	50
200	44	46	43	45	49	200	47	45	43	46	49
250	48	45	47	46	48	250	50	47	47	47	48
315	50	49	47	45	49	315	49	49	48	46	49
400	51	49	47	49	50	400	54	50	49	50	50
500	52	49	51	51	50	500	53	52	51	53	50
630	55	53	53	56	51	630	56	55	54	56	51
800	58	56	54	56	51	800	59	58	54	56	51
1000	56	56	54	55	51	1000	57	57	54	56	51
1250	54	54	55	56	51	1250	54	55	55	56	51
1600	53	54	53	55	49	1600	53	54	53	56	49
2000	52	52	51	53	47	2000	51	50	49	55	47
2500	53	49	51	53	44	2500	50	46	47	55	44
3150	49	47	49	52	41	3150	47	45	45	55	41
4000	47	45	43	51	39	4000	44	44	40	53	39
5000	45	43	45	49	36	5000	42	40	40	52	36

The overall sound pressure levels for each vehicle and speed are provided in Table 3, further illustrating that the 20 kph measurements are dominated by road noise as the vehicles become less separable (range of only 3 dBA for 20 kph, compared to 6 dBA for 10 kph). Notably, all vehicles exceeded the UNECE minimum by at least 4 dBA for 10 kph, and by at least 5 dBA for 20 kph approach speeds.

Table 3.
Overall peak SPL- A Weighted

Vehicle	**Test @ 10 kph**	**UNECE @ 10 kph**	**Test @ 20 kph**	**UNECE @ 20 kph**
VOLT	55±0.1 dBA	50	62±0.1 dBA	56
ELR	56±0.1 dBA	50	63±0.1 dBA	56
Prius	54±0.1 dBA	50	61±0.1 dBA	56
SRX	60±0.1 dBA	50	64±0.1 dBA	56

Listener Testing

Legally blind individuals were recruited to participate in a daylong session, evaluating detectability of the aforementioned vehicles within the controlled test environment.

Study Design The final study design accommodated three within-subject factors, as illustrated below (Table 4). These factors included vehicle-type (4 levels), approach speed (3 levels), and background noise level (2 levels). This 4x3x2 design provided 24 unique configurations, each repeated across three separate trials, for a total presentation of 72 scenarios per data collection session.

Table 4.
Independent variables

	Vehicle-Type	Approach Speed	Background Noise
1	EV, No Additive Sound	Steady (10 kph)	Proposed Standard (55 dBA)
2	EV, GM Production Additive Sound	Steady (20 kph)	Alternative Level (60 dBA)
3	EV, Competitor Production Additive Sound	Slowing to a Stop (20 kph–0 kph)	---
4	ICE Benchmark	---	---

As noted previously, these vehicles included EVs with and without an additive noise component, an HV with an additive noise component when operating in electric mode, and an ICE benchmark vehicle. The dynamic approaching scenarios incorporated two levels of steady-state speeds, along with one where vehicles came to a stop in front of the participants. As such, participants were asked to not only identify when they detected the approaching vehicle, but also the point at which it was safe to cross. The prescribed artificial noise was examined at the proposed dBA level (55 dBA), as well as at a second, higher level. The higher level was included in an effort to measure expected detection reduction within a noisier intersection environment.

The National Federation of the Blind (NFB) was involved during the study's design stage. Their input helped finalize the eligibility criteria, the consent process, and approach scenarios. The NFB also assisted during the recruitment phase by distributing materials to applicable organizations and individuals.

Dependent Measures The calculated distance between the approaching vehicle and static listener at the point of detection was the primary measure of interest. Detection distances presented within the upcoming results section take into account the lateral offset of each participant's seated location relative to the vehicle path; in other words, distances are representative of a true straight-line distance as opposed to perpendicular only.

Participants Twenty-four legally-blind individuals from the New River Valley and surrounding localities were recruited for participation in this study. Although specific age groups were not targeted, the sample was balanced by gender.

It is important to note that the designation of "legally blind" does not imply complete lack of sight. Approximately two-thirds of the participants (67%, 16/24) had near total vision loss, while the remaining participants demonstrated limited reliance on their remaining vision.

Test Procedure Individuals were screened over the phone to determine eligibility, in this case primarily defined as being legally blind. Eligible participants attended a single daylong session at VTTI, scheduled in groups of four per day (six data collection sessions). A daylong participation session was required due to the number of scenarios and repetitions participants experienced (72 total trials). To combat fatigue, data collection was divided into a morning and an afternoon session, with lunch provided in between. Breaks were offered approximately every hour, in addition to whenever requested by any participant.

Upon arrival, VTTI experimenters guided each participant through the necessary paperwork, including the Informed Consent Form. Afterwards, experimenters administered a pre-drive questionnaire, assessing how long participants had been legally blind, as well as how often they crossed streets independently (both overall and separated by rural and urban environments).

A hearing test was administered to account for each participant's hearing state across frequency bands, for each ear independently. A Smart Tone testing device, manufactured by Smart Diagnostic Devices, presented a series of three tones across targeted dBA levels for each frequency examined. Participants were asked to press a handheld button each time they identified a tone, with assessments completed for both right and left ears. Results from the hearing tests were not considered for basis of exclusion from participating, although it should be noted that the initial phone screening required normal or corrected-to-normal hearing in order to meet eligibility. Results of these hearing assessments are not believed to have had any impact on the findings, based on comparisons of mean detection distances relative to hearing test results (post hoc).

Once each participant completed these pre-study tasks, a brief overview of the day's schedule and activities was provided to the group. Following any questions, the participants were then transported to the Smart Road test site.

Upon arrival at the test site, researchers provided a second overview prior to exiting the transport vehicle. Participants were instructed that they would remain seated during the evaluation, but would mimic pedestrians waiting to cross an intersection while vehicles approached. Participants were also asked to wear sleep shades throughout, eliminating any advantages provided by those with limited sight. Participants were asked to both identify when they detected an approaching vehicle by pressing and holding down a 'cigar' button, as well as when it was safe to cross by releasing said button. The latter component varied by maneuver. For cases where vehicles approached and passed at a constant speed, participants were asked to identify the safe to cross point when they recognized the vehicle had passed their seated location. Alternatively, for cases where the vehicle stopped directly in front of their location, participants were asked to indicate the safe to cross point at the moment they recognized the vehicle had stopped, under the assumption that the driver of the vehicle was yielding and allowing them to cross.

Once participants understood the protocol and their responsibilities, the group completed six practice trials before continuing with the defined test configurations. It is important at this point to note that participants were instructed to detect vehicles approaching from both their left and right, although the test scenarios of interest always came from the participant's left. As such, for each targeted test scenario, there was a second approach that was never included in the subsequent analysis. This approach ensured participants were continuously monitoring the environment, but more importantly, avoided any cueing prior to each trial of interest.

Researchers monitored each participant's detection and safe to cross identification points across the practice trials, and any indications of misunderstanding were further clarified prior to conducting the actual tests. Formal testing commenced once researchers ensured participants were comfortable with the protocol. Presentation order of the unique scenarios and multiple trials was randomized for half of the participant sample, with mirrored orders for the remaining half in an effort to combat order effects.

Upon completion of the morning and afternoon sessions, participants were debriefed, paid $250 for participating, and thanked for their time.

Instrumentation Participants were closely grouped, but in a staggered formation so as to minimize any sound interference. The approaching vehicles had approximately 96 m available to them, with a targeted 'at speed' cone positioned approximately 55 m from where the participants were seated. Importantly, vehicle approach speed was almost always achieved well ahead of this marked point. Drivers were instructed to maintain as close to the prescribed speed as possible once achieved, and any trials outside of ±2 kph were repeated. A cone marking the deceleration point provided a reference for when to begin slowing as part of the 20 kph to 0 kph scenario, maintaining consistency across that maneuver as well.

Figure 5 and Figure 6 show the test site from both sides in order to provide perspective of the location and terrain. Trials of interest were conducted in the southeast direction (from the participant's left), but, as mentioned previously, the site configuration required that vehicles travel in both directions for staging purposes. In order to avoid any opportunities for confusion or misclassification, only one vehicle drove through the course at any given time. Figure 7 illustrates the close positioning of participant seating.

Figure 5. Test site location during "listener" testing – participant and instrumentation layout.

Figure 6. Test site location from view of approaching vehicle scenarios.

Figure 7. Participant and microphone positioning.

Vehicle-Based Instrumentation A modified NextGen data acquisition system (DAS) provided the means for formal data collection. Instead of instrumenting each of the four vehicles independently, a suitcase-based DAS was positioned adjacent to the participants, communicating with a transportable Differential Global Positioning System (DGPS) rotated through the vehicle fleet during testing. The DGPS configuration consisted of a Novatel antennae, AvaLAN transmitter, stand-alone battery, and vehicle power adapter. As it transitioned from one vehicle to the next based on the prescribed scenario order, the antenna was placed on the vehicle's roof near the front passenger side corner (point marked by a magnet). Drivers positioned the suitcase in the vehicle's passenger seat, placing the AvaLAN transmitter on the dashboard and plugging it into an appropriate receptacle in order to extend battery life. Battery life was a critical component as it allowed the unit to remain on, significantly reducing delays that would have occurred due to the typical initiation period upon start-up.

This approach allowed for continuous recording of base-to-vehicle distance (location accuracy within 10cm) and speed. Calibration of the transmitter and receiver occurred 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 detection distances were calculated post-hoc.

Direct distance output was received as a perpendicular measurement based on the relative positioning of the vehicle-mounted antenna and the assigned #1 seat location. This perpendicular measurement was first adjusted to account for each vehicle's front bumper, providing a distance measurement relative to the first point of "contact." Corrections were thereafter applied to incorporate both the longitudinal and lateral position of each individual seat relative to the approaching vehicle, providing a true straight-line distance specific to each participant's individual location.

The NextGen DAS was further linked to a laptop, which allowed an experimenter to both monitor variables of interest in real time and add task codes per trial for simplified review and analysis. Video from two cameras was recorded for the duration of each test session for verification purposes.

As a reminder, each participant had a hand-held button they were instructed to use when identifying their detection and safe to cross points. These interactions were recorded by the DAS, specific to each participant and trial.

Acoustic Noise and Measurement Equipment In order to provide a constant, steady background noise for the listener testing, artificial background noise was generated at two levels: 55 dBA and 60 dBA. The noise spectrum as determined by NHTSA [2; page 69] is illustrated in Figure 8.

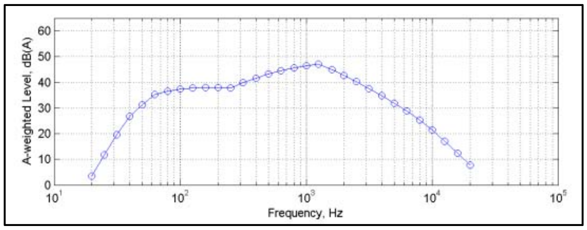

Figure 8. NHTSA background noise spectrum.

The noise was generated in Reaper, a commercially available digital audio workstation. The first step was to use a standard Reaper plugin — white noise to generate white, Gaussian noise. The noise was then filtered using a standard Reaper equalizer plugin. The low frequencies required a significant boost so that when this signal was A-weighted, the spectrum would match the NHTSA profile.

The noise signal was broadcast over five JBL LSR308 loudspeakers and one JBL LSR 310S subwoofer. As discussed previously, these speakers were positioned around the sides and to the rear of participants, creating a sound envelope within which the noise was evenly dispersed. All speaker output was routed through a Focusrite Scarlett 18i20 USB Audio Interface, as shown in Figure 9 (refer back to Figure 5 for the actual on-road arrangement).

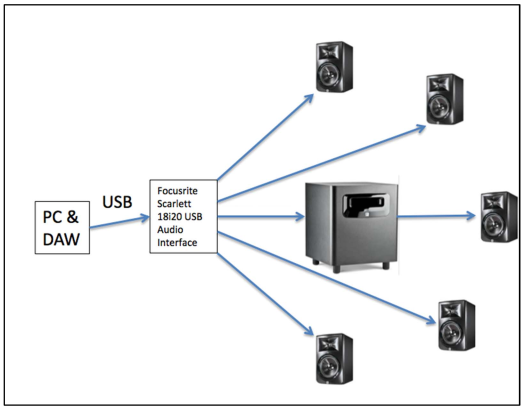

Figure 9. Noise signal instrumentation and setup.

For recording measurements, four microphones were placed directly above each participant's seated position (refer back to Figure 7). Four G.R.A.S. 46AQ ½" TEDS Microphones (Omnidirectional) were used, with a sensitivity of 50 mV/Pa, a frequency range from 3.15 Hz to 12.5 KHz, and a dynamic range of 17 dBA to 138 dBA. This configuration provided accurate sound pressure levels and 1/3 octave band measurements throughout the experiment. All of this equipment was connected through a National Instruments cDAQ USB Data Acquisition Rack and a National Instruments 9234 Analog to digital converter module connected to a PC running customized LabView software, which recorded all relevant acoustic measures for each task. Output was also directly routed to the DAS for collection in parallel with the time-stamped Differential Global Positioning System (DGPS) measurements.

Noise verification was conducted throughout listener testing as well. During periods where vehicles were parked and not running, measurements were recorded and the 1/3 octave band spectra were averaged over all trials to determine the actual signal spectrum received at the microphones.

Weather Instrumentation Due to the potential impact on noise and sound travel, wind was measured and monitored throughout testing, with max wind speed and direction recorded for each trial. An AcuRite 8-inch professional digital weather center was installed adjacent to the test location, providing accurate wind speed, wind direction, and temperature output, among other measurements. Prior to testing, a criterion of 7 mph was established as the maximum allowable wind speed. Potential session dates were frequently cancelled due to higher predicted wind speeds; therefore, wind speed was rarely an issue on days where testing occurred. However, there were times when testing was paused, or trials were repeated, due to a brief increase in wind speed.

RESULTS

Results presented herein focus primarily on comparisons across vehicle type within the targeted noise levels and approach maneuvers. Detection distances as a whole are compared directly to the "desired detection distances" per NHTSA's *Minimum Sound Requirements for Hybrid and Electric Vehicles* [1; page 109]. These distances, specified as 5.6 m for the 10 kph approach and 11.1 m for the 20 kph approach, are included as reference points within forthcoming charts, where applicable. Importantly, these desired detection distances are indicative of a response achieved by a driver who is attentive and ready to respond with the required urgency.

Each sample-based measurement within this section is accompanied by categorical assessments across individual responses, beyond simply examining mean detection distances. Specifically, these figures provide critical insight into cases of missed or late detections, a detail easily overlooked when considering only the distance-based averages. Realistically, cases where participants missed a detection, or detected at a close distance, indicate a higher potential for collision were they making a characteristically representative assessment within a real-world environment.

Furthermore, under conditions where a detection was missed, in the sense that participants never indicated their detection of an approaching vehicle, a value of 0 m is included within the calculated means. This "penalty" ultimately had little bearing on the relationship across the vehicle types, but arguably provides a more accurate numeric value when comparing means against the desired detection thresholds.

It is also important to note that, although rare, there were a selected number of cases that were thrown out due to unmet circumstances. These include, for example, cases where a detection was made before the approaching vehicle reached the targeted speed. Although efforts were made to incorporate a sufficient amount of run-up space for vehicles to achieve their targeted speed, future studies of this kind would benefit from adjusting the test site to provide for a longer approach. In general, however, with three repetitions of each trial, the number of cases impacted was relatively few.

Detection by Vehicle & Approach Speed with 55 dBA Background Noise

Mean detection distances within the 55 dBA background noise level by vehicle for both of the steady-speed approach maneuvers are illustrated below (Figure 10). Further examination into differences within each individual maneuver are offered in the text that follows, but this figure provides a direct comparison of how the change in approach speed directly impacts detection. Across the sample, increasing the speed from 10 kph to 20 kph nets an increase of detection distances by nearly twofold, on average, particularly with the non-ICE vehicles. Importantly, mean detection distance within both approach speeds exceeds the NHTSA criteria proposed for each travel speed (5.6 m at 10 kph, and 11.1 m at 20 kph).

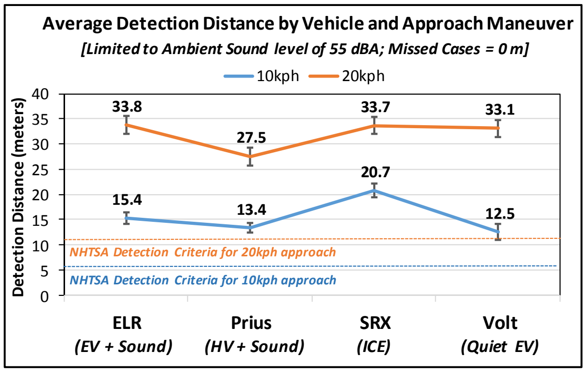

Figure 10. Average detection distance for 10 kph and 20 kph at 55 dBA.

When focusing solely on the 10 kph approach speed, significance is observed across the sample (repeated measures ANOVA), as a clear separation emerges with respect to the detectability advantage provided by the traditional ICE vehicle (SRX) relative to its EV and HV counterparts (Figure 11). As indicated by the post hoc analysis, the SRX elicits a significantly greater detection advantage compared to the other three vehicles, none of which are significantly different from each other (indicated by no overlap across the post hoc letter values; e.g., A vs. B is significant, whereas A vs. A is not). That said, even though the ELR, with an additive noise component, provides a trending advantage over the Volt, with no noise, the differences are not significant. Again, all vehicles ellicited mean detection distances well above the NHTSA threshold.

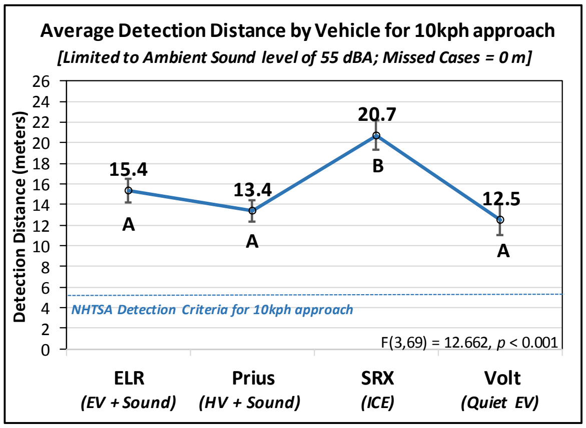

Figure 11. Average detection distance for 10 kph at 55 dBA.

Valid cases were binned within one of the following three categories: No detection (miss), Above NHTSA criteria (5.6 m), or Below NHTSA criteria (5.6 m). Breakouts by vehicles are illustrated in Figure 12. Combining the frequency of misses and detections that occurred below the 5.6 m detection criteria provides a metric indicative of a possible strike had the pedestrian crossed the road under the presented circumstances. Each vehicle, including the ICE benchmark, had at least one miss and one below-criteria detection, respectively. The Volt drew the highest allocation of these qualifying cases, with just over 14% of all valid trials falling within this calculated dilemma zone, approaching nearly double what was observed for both the ELR and Prius. Although the mean detection distances failed to demonstrate any significant differences, these potential strike cases do suggest an advantage provided by the additive noise component.

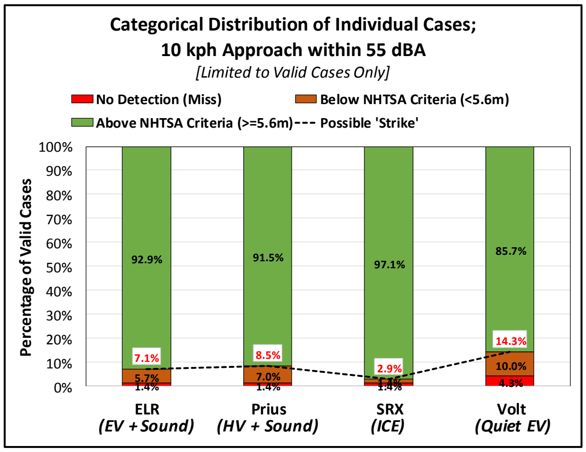

Figure 12. Distribution of detection distances for 10 kph at 55 dBA.

Mean detection distances by vehicle for the 20 kph steady approach are provided in Figure 13. As noted previously, detection distances increase dramatically relative to those observed for 10 kph, which is indicative of the additional road noise provided by tires at higher speeds. The advantage held earlier by the ICE vehicle relative to the quieter vehicles disappears except for the Prius. Statistically, the Prius elicited significantly shorter mean detection distances relative to each of the other three vehicles. Notably, the Prius was equipped with the narrowest tires of the group, likely influencing these results. Regardless, mean detection distances for each vehicle are, again, well above the NHTSA minimum criteria.

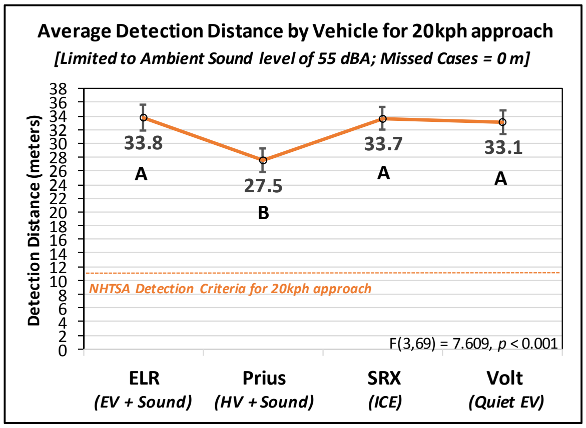

Figure 13. Average detection distance for 20 kph at 55 dBA.

Not surprisingly, the advantage of road/tire noise at the higher travel speed dramatically reduces the likelihood of a possible strike, as calculated based on the combined missed and below criteria cases shown below (Figure 14). None of the valid cases included a missed detection for any of the four vehicles, and the number of detections below NHTSA's 11.1 m desired criteria ranged from a low of one for the Volt to a high of four for the Prius.

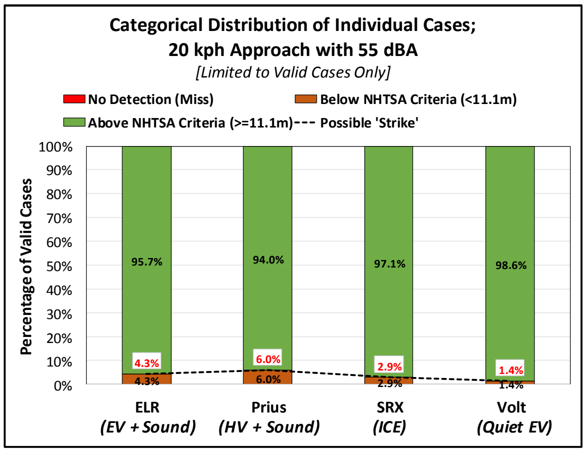

Figure 14. Distribution of detection distances for 20 kph at 55 dBA.

Detection by Vehicle & Approach Speed with 60 dBA Background Noise

As expected, an increase in background noise negatively impacted detection distances. However, Figure 15 illustrates how trends observed across both the 10 kph and 20 kph steady approach scenarios under the 55 dBA background noise remain relatively stable, albeit reduced proportionally, with the increase to 60 dBA. Across the sample, detection distances fell approximately 33% for the 10 kph approach, with vehicle-specific reductions 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.

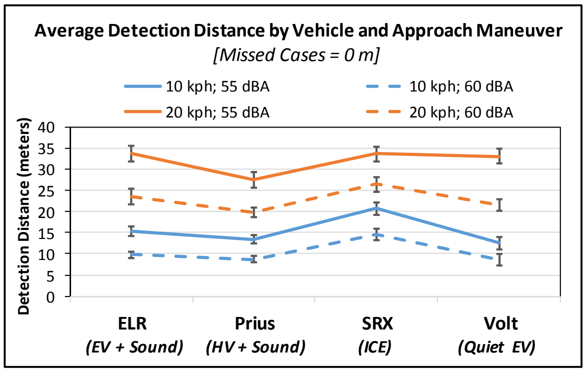

Figure 15. Average detection distance between 55 dBA and 60 dBA.

As with the lower noise level, the overall separation between the ICE and the other three vehicles remains significant for 10 kph at 60 dBA (Figure 16). Again, the averages are still above NHTSA's desired detection distance, albeit reduced relative to that observed under 55 dBA.

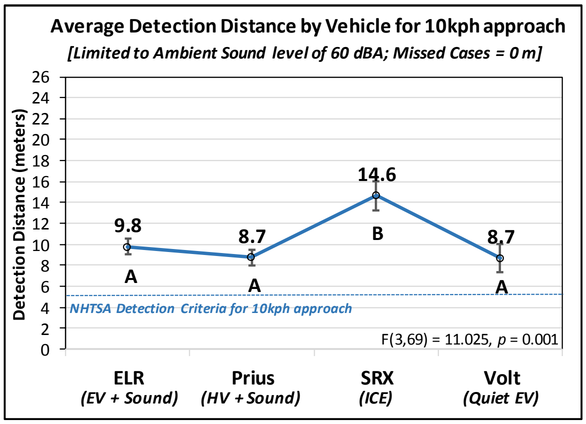

Figure 16. Average detection distance for 10 kph and at 60 dBA.

The differences between the two ambient noise levels become even more apparent when examining the frequency of missed detections and those that fell below the desired criteria (Figure 17). The percentage of cases that fall within the possible strike zone increases dramatically with increased 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. Nearly 42% of all cases for the Volt under this scenario fell below NHTSA's desired detection point.

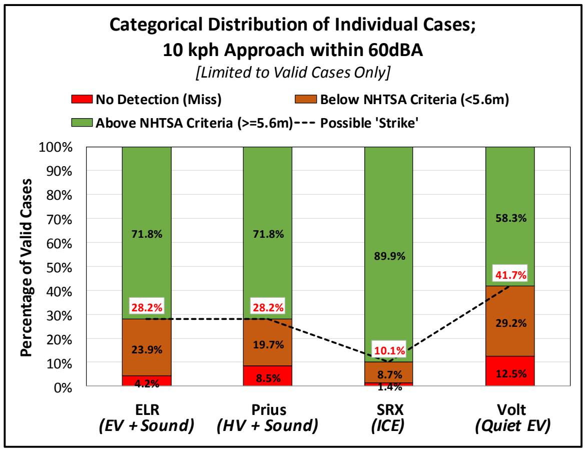

Figure 17. Distribution of detection distances for 10 kph at 60 dBA.

The trend continues for 20 kph under 60 dBA, with similar differences across vehicle type as observed under 55 dBA (Figure 18). Statistically, the SRX provides significantly larger detection distances relative to the Prius and Volt, but no other differences are present. Again, all mean distances remain well above NHTSA's desired detection distance.

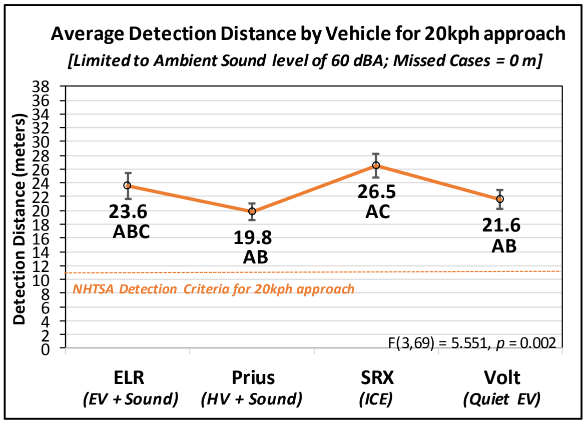

Figure 18. Average detection distance for 20 kph at 60 dBA.

Although the number of missed cases remained low for the 20 kph approach, there was another dramatic increase in the number of detections that occurred below the 11.1 m criteria (Figure 19). The ELR, Prius, and SRX each saw increases in the number of possible strike cases of two to three times that observed under the 55 dBA configuration, but the number of cases for the Volt increased by nearly 13 (1.4% vs. 18.1%).

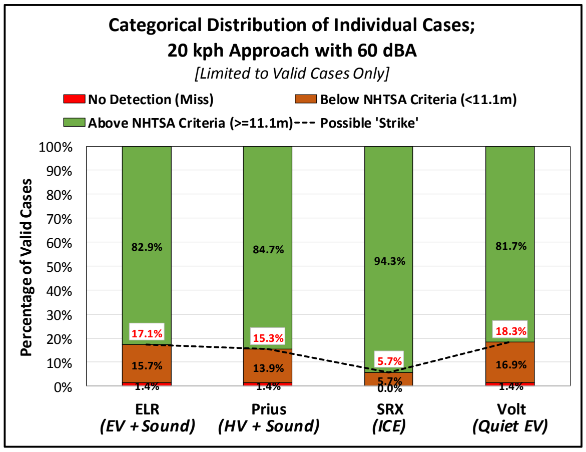

Figure 19. Distribution of detection distances for 20 kph at 60 dBA.

Clearly, detection distances and possible strike cases are negatively impacted by an increase in ambient noise. Not surprisingly, the louder the intersection environment, the greater the likelihood for conflict cases during crossing by visually impaired pedestrians.

Safe to Cross (Recognition of Stopped Vehicle)

As a reminder, participants indicated their perceived safe to cross point following detection of the approaching vehicle by releasing the hand-held button. Interest laid primarily in their ability to identify that a vehicle had stopped directly in front of them. As such, discussion regarding this metric is herein limited to the scenario in which vehicles approached at 20 kph before gradually decelerating down to 0 kph, then remaining stationary for 5 seconds before continuing.

Based on timing relative to when the vehicle truly stopped, responses were categorized as follows: 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).

The timing of these button releases revealed that a large number of safe to cross identification points actually occurred before the vehicle came to a complete stop (Figure 20). Notably, the Prius demonstrated the fewest number of cases where this occurred, at only 11.1%, versus 33.3%, 27.8%, and 38.9% for the ELR, SRX, and Volt, respectively. As in the possible strike metric discussed relative to the identified detection points, this early release is also an indicator of a potential safety concern across all vehicle types, not just EVs and HVs. Notably, the additive noise provided by the Prius is only generated when the vehicle is in motion. As such, when the vehicle came to a stop, the additive noise ceased, providing a valuable tool aiding in recognition of a vehicle stop that the other vehicles did not provide. This logic likely explains the advantage demonstrated by the Prius.

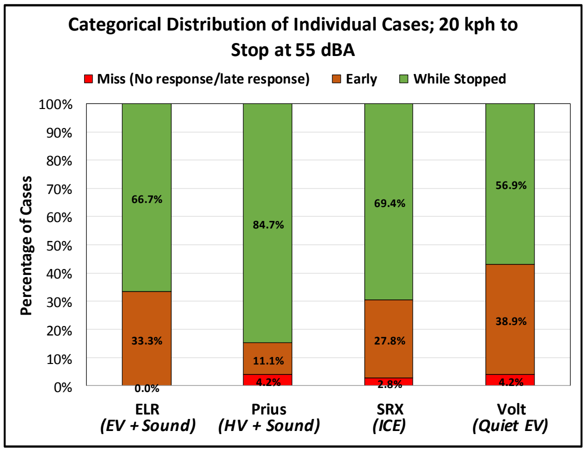

Figure 20. Distribution of safe to cross recognition at 55 dBA.

Not surprisingly, the number of missed responses increased for each vehicle under the higher noise level (Figure 21). Interestingly, the distribution of early button releases decreased for the SRX and Volt, while increasing slightly for the ELR and eliciting no change for the Prius.

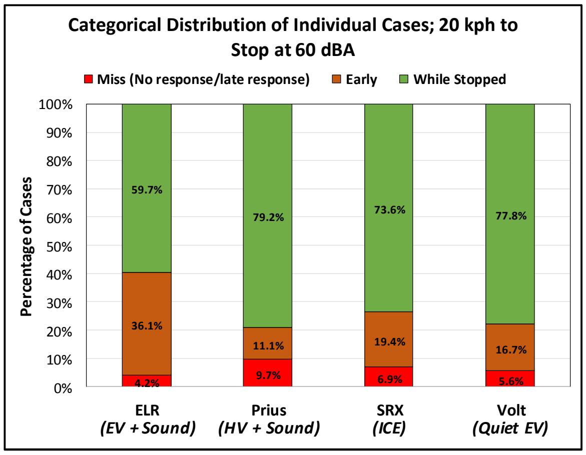

Figure 21. Distribution of safe to cross recognition at 60 dBA.

CONCLUSIONS

The primary objective of this research effort was to examine appropriateness of the proposed UNECE test methodology for evaluating detectability of quiet (non-ICE) vehicles. The vehicles evaluated during the listener testing collectively exceeded the UNECE minimum by at least 4 dBA for 10 kph, and by at least 5 dBA for 20 kph approach speeds. However, testing revealed that none of these candidate vehicle types, including the ICE benchmark, were immune to missed or late detections. This was particularly true for the 10 kph approach, yet not entirely absent at 20 kph, either. Increasing the ambient noise within the test environment only exacerbated these findings.

Notably, the observed degradation in overall detectability across all vehicle types dropped, by approximately 30%, on average, when increasing background noise from 55 dBA to 60 dBA. When evaluating mean detection distances across the sample, both background noise levels still elicited detection distances above NHTSA's desired detection threshold. It is important to reiterate that this desired detection distance is based on the assumption that the driver is attentive and ready to respond in an urgent manner. As such, the greater the perceived detection, the better chance both drivers and pedestrians have at avoiding any potential conflict. But, as discussed, the mean detection distances only tell part of the story.

Cases of missed detections, as well as those that occurred below the desired detection distance, as anticipated, increased directly with dBA. With these results in mind, characterization of background noise levels within typical intersection environments would greatly benefit the appropriateness of the selected evaluation criteria.

Demonstrated differences across the steady state approach speeds also met expectations, as tire-road noise increases directly with speed. Detection distances were vastly improved when increasing speeds from 10 kph to 20 kph, with reduced occurrences of missed or below-threshold detections. This increased road noise essentially eliminated differences in detection between the ELR and Volt relative to the ICE-benchmark SRX. The Prius' detection difference, although still greatly improved from 10 kph, was significantly lower relative to the other three vehicles. Riding on the narrowest tires within the group likely contributed to this finding. Ultimately, these trends held relatively stable across both noise levels. These findings provide more evidence that proposed testing standards can limit testing to speeds at or below 20 kph.

Results indicated difficulty in assessing when a vehicle comes to an absolute stop, as illustrated by the high percentage of early safe to cross points where participants believed the vehicle had stopped when it was, in fact, still in the act of stopping. Admittedly, the vast majority of these early classifications occurred when the vehicle was almost stopped, but still demonstrates a potential safety concern. The Prius outperformed the other three vehicle types, likely due to the logic behind presenting its additive noise feature only while the vehicle is in motion, as opposed to based on selected gear. As such, participants appeared to learn and benefit from an added cue specific to the Prius within this particular scenario.

Ultimately, even the SRX wasn't immune to possible strike cases as calculated based on missed and below-threshold detections. This finding is indicative of an issue that warrants reliance upon approaches beyond additive noise components when working towards eliminating vehicle-pedestrian conflicts. Active safety features, such as pedestrian recognition features coupled with in-vehicle warnings and auto-braking implementations, will contribute towards reducing these conflicts. Furthermore, as vehicles become more connected with each other and the environment, incorporating pedestrians within the mix will further aid in reducing conflicts by notifying both drivers and pedestrians of potential hazards.

Future Work

The findings from this study provide justification for the usefulness of examining additional vehicle types, approach maneuvers, and noise levels within the same general context. With such a large increase in detection distances from 10 kph to 20 kph, it would be beneficial to see where the ability to differentiate between the HV/EV and ICE benchmark begins to disappear. Furthermore, the recorded sound-based measurements provide an opportunity to continue developing and refining additive noise features, targeting max detectability within this controlled environment, while still under the assumption that performance translates into the real world.

As an alternative to the controlled ambient noise, testing within an environment that is modeled from an actual intersection environment may provide more realistic results. This approach would entail selection of a candidate intersection environment, capturing sound recordings, and interjecting this playback within the controlled environment instead of using an ambient noise profile.

Another avenue for future work that may provide long term benefit involves constructing a computational model that uses the results from this study and the development of several more automated detectors (e.g., spatial processing, filtering, matched filtering, spectral cues) to predict human detection performance given a vehicle drive-by signature (as measured in the UNECE portion of this study).

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