Toward a Methodology for Assessing Electric Vehicle Exterior Sounds

Sneha Singh, Sarah R. Payne, and Paul A. Jennings

***Abstract*—Laws mandate that electric vehicles emit sounds to ensure pedestrians' safety by alerting pedestrians of the vehicles' approach. Additionally, manufacturers want these sounds to promote positive impressions of the vehicle brand. A reliable and valid methodology is needed to evaluate electric vehicles' exterior sounds. To help develop such a methodology, this paper examines automotive exterior sound evaluation methods in the context of experimental design and cognitive psychology. Currently, such evaluations are usually conducted on road or inside a laboratory; however, a virtual environment provides advantages of both these methods but none of their limitations. The stimuli selected for evaluations must satisfy legislative guidelines. Methods for presenting and measuring the stimuli can affect study outcomes. A methodology is proposed for conducting evaluations of an electric vehicle's exterior sounds, testing its detectability and emotional evaluation. An experiment tested the methodology. Thirty-one participants evaluated an electric car in a virtual environment of a town's T-junction with 15 exterior sounds as stimuli. The car's arrival time, direction of approach, and, thus, distance to pedestrian varied across conditions. Detection time of the sound and pleasantness and powerfulness evaluations of the car were recorded. The vehicle's arrival time and approach direction affected its detectability and emotional evaluation; thus, these are important elements to vary and control in studies. Overall, the proposed methodology increases the realistic context and experimental control than in existing listening evaluations. It benefits by combining two competing elements necessary for assessing electric vehicle exterior sounds, namely, pedestrians' safety and impressions of the vehicle brand.**

***Index Terms*—Electric vehicle sounds, emotional evaluation, vehicle detection, virtual environments.**

I. Introduction

ELECTRIC vehicles are quieter at low speeds compared with combustion engine vehicles. Research suggests that the sound pressure level of an electric vehicle can be 3–20 dB(A) lower than an internal combustion engine vehicle of a similar make and weight when operating below 6 ms^{-1} [1]. Concerns have been raised that this may pose a threat to the safe traveling of pedestrians and cyclists [1]–[3]. To resolve this issue, researchers propose environmental regulations such as reducing background sounds and vehicles' maximum noise level limits, infrastructure-based solutions such as auditory pedestrian signals and pedestrian detection systems, orientation and mobility training for blind pedestrians, pedestrian-held devices to generate audio/tactile signals upon a vehicle's approach, and vehicle-based devices to generate additional sounds during vehicle operation [2], [4]. The former measures are currently not feasible due to long implementation times, high costs, and opposition from blind community [2]. Therefore, emission of additional sounds from the electric vehicles is considered as the most feasible option.

Laws have been enacted worldwide for such electric vehicle sounds. Japan's Ministry of Land, Infrastructure, Transport and Tourism has mandated that electric and hybrid vehicles be fitted with a sound-generating device. This device is called an "Approaching Vehicle Audible System" (AVAS), which emits sounds to inform pedestrians and other road users of the vehicle's approach to avoid a potential collision [5]. The Pedestrian Safety Enhancement Act of 2010 in the U.S. has directed the U.S. Department of Transportation to establish a safety standard for electric and hybrid vehicles for alerting the pedestrians of the vehicles' operation [6]. Consequently, the U.S. government has issued Federal Motor Vehicle Safety Standards (FMVSS) that mandate these vehicles be fitted with devices that emit sounds to alert pedestrians, cyclists, and other road users of the vehicles' approach [7]. A similar standard, which is called Global Technical Regulation (GTR), has been formulated by the United Nations Economic Commission for Europe (UNECE) [8]. Like Japan, the UNECE also mandates an AVAS for electric and hybrid vehicles in Europe [8], [9]. GTR states the harmonized operational criteria and acoustic specifications of AVAS for Europe [8]. Research by these organizations show that electric vehicles' inherent sound increases with increasing speed as the tire–road sound becomes more dominant; therefore, additional sound is only required below a certain speed [1], [2], [5]–[8]. Therefore, to ensure pedestrians' safety, electric vehicles need to emit additional sounds at or below 5.6–11.4 ms^{-1} (20–41 km/h), depending on the vehicle make, and at idle and reverse [5], [7]–[9].

A pedestrian, upon hearing these sounds, could evaluate the electric vehicle as a potential consumer who may want to purchase or simply hear the vehicle pass by. Therefore, vehicle manufacturers will want these sounds to promote positive impressions of the vehicle brand [10]. At the same time, we do not want to lose the soundscape benefits of the current 'quietness' of these vehicles. The non-engine-based electric vehicle sounds must not add to the existing traffic noise related annoyance. Therefore, it is important to ensure that these sounds produce an

Manuscript received October 31, 2013; revised February 11, 2014 and May 10, 2014; accepted May 12, 2014. Date of publication June 18, 2014; date of current version August 1, 2014. The Associate Editor for this paper was C. Olaverri-Monreal.

S. Singh and P. A. Jennings are with WMG, University of Warwick, Coventry CV4 7AL, U.K. (e-mail: Sneha.Singh@warwick.ac.uk; Paul.Jennings@warwick.ac.uk).

S. R. Payne was with WMG, University of Warwick, Coventry CV4 7AL, U.K. She is now with the School of the Built Environment, Heriot-Watt University, Edinburgh EH14 4AS, U.K. (e-mail: S.R.Payne@hw.ac.uk).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TITS.2014.2327062

overall neutral or positive effect on soundscapes. Safety, brand, and soundscapes are the competing criteria for the evaluation of exterior sounds of electric vehicles.

Currently, these vehicles sounds are evaluated using basic detection tests. However, considering all these competing issues, a rigorous methodology is needed to evaluate potential electric vehicle sounds to ensure that they are detectable enough and promote positive impressions of the vehicle brand. Furthermore, the methodology should enable examining the effects these new sounds will have on soundscapes and community annoyance.

This paper examines the state-of-the-art automotive exterior sound evaluation methods to propose a methodology for conducting evaluations of an electric vehicle's exterior sounds. An evaluation experiment is performed, which uses the proposed methodology to assess the "detectability" of the sounds (how detectable the sound is) and emotional evaluations of an electric car based on listening to its sounds by pedestrians. The proposed methodology is then reviewed in light of the results of the experiments.

II. Listening Evaluations: State of the Art

This section examines the state-of-the-art evaluation methods of automotive exterior sounds in the context of experimental design and cognitive psychology. The aim is to propose a rigorous methodology for assessing electric vehicle's exterior sounds.

The major aspects of any listening evaluation are the following: the listening environment during the evaluation, participants used as evaluators, stimuli preparation and delivery, measurement scales for data collection, and analysis methods [11], [12]. These aspects are dependent on the purpose of evaluation [11], [12]. A review of these aspects in relation to evaluating electric vehicle sounds is presented below.

A. Evaluation Environments

Listening evaluations of automotive exterior sounds are usually conducted on road or inside a laboratory. On-road evaluations involve driving the "target vehicle"—the vehicle being evaluated—emitting a sound, in urban town scenarios such as parking lots, crossroads, and junctions [1], [13]–[16], usually by reserving the test site to get no nearby traffic and very low background sound [13], [16], [17]. The participant usually sits on the pavement [1], [13], [14], [17] or occasionally stands as a pedestrian [15] and evaluates the sounds of the passing vehicle in real time while receiving visual and auditory stimuli of the urban ambience [1], [13]–[16], sometimes with additional vehicles, and other sound sources [13], [15]. This resembles the real-life pedestrian–vehicle interactions, where also a pedestrian experiences the electric vehicle's sounds in the presence of the mentioned stimuli. Here, due to the limited capacity of attention and human cognition, the pedestrian undergoes "divided attention," where his/her attention resources are divided among the various stimuli [18], [19]. Hence, on-road evaluations provide the correct context for evaluating vehicle sounds. However, they do not provide control on external factors, such as changes in the background sounds, visuals, traffic, and weather [13], [15]. Therefore, it is difficult to maintain consistency and repeatability in the results. On-road evaluations also require long testing durations as it is difficult to maintain various driving conditions of the target vehicle while maintaining a similar ambience [13], [15].

Laboratory evaluations follow a similar process but inside a controlled environment. Here, a recorded vehicle sound is played in an anechoic room, usually using headphones or an array of speakers and participants' response collected based on their listening [1], [2], [14], [20]–[22]. This environment provides better experimental control [2], [14], [20]–[22]. Therefore, consistency and repeatability are improved, and back-to-back comparative tests can be performed, thereby reducing the experimental duration. However, conventional laboratory listening tests/evaluations use a single stimulus (target vehicle's sound); therefore, they lack the appropriate context. Here, the listener undergoes a "focused auditory attention," where his/her attention is focused on the target vehicle sound, and information from other stimuli (if any) is ignored [18]. Evaluation of the sounds is influenced by the mode of processing information received from various stimuli during decision making, which, in turn, is affected by a listener's state of attention [18], [19]. Thus, correct context is important for a listening evaluation to obtain results representative of real-life situations.

Using a more immersive virtual environment created by a simulator may provide advantages of both conventional on-road and laboratory listening methods but none of the limitations. It can provide an appropriate context by simulating a realistic environment for pedestrian–vehicle interactions using sounds and visuals. Simultaneously, the researcher can fully control the experimental conditions.

Currently, most automotive noise, vibration and harshness ("NVH") applications of simulators create a virtual environment from a driver's perspective [23]–[26]. The vehicle NVH simulators have been successfully used for evaluating vehicle interior sounds to assess impressions of the vehicle brand by both experts (vehicle manufacturers and NVH engineers) and nonexperts (general public as potential customers) [12], [23]–[25].

The use of virtual environment simulators is very new for evaluating vehicles' exterior sounds. Brüel and Kjær have developed a new and one-of-a-kind software tool, namely, Exterior Sound Simulator (ESS), that simulates a virtual environment from a pedestrian's perspective [27]. It has an inbuilt U.K. town model, which includes various places where a pedestrian–vehicle interaction is likely, such as car parks, crossroads, and junctions with and without traffic lights, bus stops, streets, and market areas [2], [28] (see Fig. 1).

ESS uses "source decomposition technique" that facilitates the researcher to decompose a vehicle's total sound into source-based component sounds (e.g., engine harmonics, tire sound, wind sound, and alerting sounds from sound-emitting devices). These are stored as a vehicle's sound model. ESS also allows a researcher to create trajectories of a pedestrian's and a vehicle's maneuver in any chosen location of the virtual town. The simulator software takes the sound model and the maneuver data as input and uses vector-based amplitude panning for 3-D sound rendering to accurately synthesize the visual and the

(a) (b)

Fig. 1. Examples of visual scenarios available in ESS. (a) Car park. (b) Traffic junction.

sounds that the pedestrian will experience in the corresponding scenario. Detailed explanations of simulation algorithms are mentioned by its developers [26], [27].

The visuals when projected on screens and the sounds when played through speakers in a listening room can help create a virtual environment where a person can experience vehicles like a pedestrian in real life. This simulated environment provides a more realistic context for exterior sound evaluations.

B. Stimuli

1) Stimuli Selection: In the past decade, the potential danger to pedestrians due to the quietness of electric and hybrid vehicles have gained worldwide recognition leading to research activities, such as accident data analysis, interviews, and cognitive walkthroughs with pedestrians, including the visually impaired and orientation and mobility specialists [2], [28]. This has helped identify the most common scenarios for pedestrian–electric vehicle interactions that are critical to a pedestrian's safety [2]. The scenarios primarily include vehicle maneuvers at low speeds (below 15 ms^{-1}) in locations such as roads, crossroads, T-junctions, and parking lots [2], [28]. These scenarios are used in most on-road detection tests [1], [13]–[17] as they provide appropriate context for evaluations.

The new sounds for the electric and hybrid vehicles must satisfy the legislative guidelines. FMVSS recommends broadband low-frequency sounds in the range 160–5000 Hz to enhance audibility [7]. GTR also recommends that these sounds include at least two 1/3 octave bands within the frequency range 50 Hz to 5 kHz [8]. FMVSS in the U.S. has fixed their minimum sound level as 49 dB(A) at idle; 52 dB(A) at reverse; and 55, 62, and 66 dB(A) at 2.78, 5.56, and 8.33 ms^{-1} (10, 20, and 30 km/h), respectively [7]. Japanese guidelines recommend limiting the sound level to that of a similar vehicle of the same category equipped with an internal combustion engine and operating at 5.6 ms^{-1} (20 km/h) [5]. For the latest Japanese and European vehicles, this level is 62–66 dB(A) [1], [20].

The UNECE and Japanese guidelines prohibit using siren, horn, chime, bell, and emergency vehicle sounds; alarm sounds, e.g., fire, theft and smoke alarms; intermittent sound; melodious sounds; animal and insect sounds; and sounds that confuse the identification of a vehicle and/or its operation [5], [8].

The choice of sounds is also governed by the purpose of evaluation [11]. Evaluations of a set of candidate electric vehicle sounds involve comparing the sounds against one another on some evaluation criteria [2], [13], [16], [17]. The audibility and, hence, the detection rate of the sounds depend on psychoacoustic metrics such as A-weighted sound pressure level, "dB(A)," and frequency spectrum [7], [8]. Similarly, dB(A), loudness, sharpness, and roughness metrics closely relate to emotional evaluations of automotive sounds [10]. Therefore, using sounds with sufficient variation in these metrics ensures that these sounds will show enough variation in the evaluation scores for a relative comparison.

2) Stimuli Presentation: During conventional laboratory detection tests of vehicle exterior sounds, a target vehicle sound is played as soon as a new experimental condition begins. Therefore, the vehicle could be heard arriving at the listener's position always after a fixed length of time and usually from a fixed direction [1], [2], [14], [20], [21]. This may result in a bias due to practice effects where the participants start expecting the arrival of the target vehicle at a fixed time. This problem increases during detection tests using visual simulations, whereby a participant may associate the arrival of the vehicle with certain visual cues such as arrival at a crossroad. Therefore, s/he may pay more attention to detecting a vehicle's sound upon receiving those visual cues and may even falsely respond that s/he has heard a vehicle approaching because s/he expects the vehicle to arrive. This form of bias is specific to all listening studies involving vehicle detection and may result in incorrect detection times of exterior sounds. In real life, a target vehicle can approach a crossroad from any direction and at any time. These variations should be reflected in experimental designs, by altering the direction of approach and the arrival times of the electric vehicle to reduce expectation biases and make the scenarios more realistic. This also allows their effect on participant evaluations to be examined.

C. Measures

Pedestrians' safety and impressions of the vehicle brand are among the major criteria for evaluating electric vehicle's exterior sounds (see Section I). Therefore, the methodology should assess these criteria simultaneously.

Most researchers use measures such as the "time-to-vehicle arrival" (the time from the first detection of the vehicle to the instance when the vehicle actually passes the pedestrian's location) [2] and "detection distance" (distance between the vehicle and the pedestrian location at the moment the pedestrian indicates detection) [1], [13], [16], [17], [21], [29] to assess the sounds for their safety risk to pedestrians.

Several verbal descriptors are used to convey impressions of the vehicle brand from listening to its sound [10]. These verbal descriptors can be mapped into two or three dimensions of emotional evaluations that discriminate between the different types of car sounds [10], [30], [31]. The emotional dimensions have been found and used to distinguish sounds of different characters such as "luxury" and "sporty," and sounds from different manufacturers [10], [30], [31]. Therefore, emotional evaluation of a vehicle upon listening to its sounds influences the assessment of the vehicle's brand overall and is an important consideration for manufacturers during the vehicle design and production. Most sound quality researchers use two underlying dimensions of emotional evaluation—where one dimension describes the strength or the power aspect of the vehicle, and the other describes the aspects related to comfort and pleasantness of the vehicle [10]. The dimensions "powerful" and "pleasant" were developed after factor analysis of a large number of verbal descriptors for car sounds, and together they explained 70% of the variance in emotionally evaluating numerous car sounds [30]. These dimensions are widely used for emotionally evaluating a vehicle based on its sounds [10], [30]–[32].

D. Measurement Scales

To measure detection time/distance, participants usually raise hands when they hear the target vehicle, and a video recording of the experiment gives an approximate distance of the vehicle [1], [14], [16]. Some researchers record the detection time more accurately using a push button, but use an array of photo sensors or road markers to approximate the vehicle's position when detected [13], [17]. A more accurate measurement method along with the facility to record multiple detection times is required.

The dimensions used for emotional evaluation of vehicle sounds, such as powerful and pleasant, are usually independent dimensions [30]. Therefore, the measurement scale for emotional evaluation should provide an independent measure of each attribute. The measurement scale must also provide a relative rating of the set of sounds used during a particular evaluation experiment. This is because there are numerous vehicle brands, and a person without an automotive background is unlikely to know all automotive sounds in existence, thus making comparisons, on an absolute scale, difficult. Therefore, automotive sound quality evaluations are essentially relative ratings of the candidate vehicle sounds [11]. The measurement scale must provide interval level data so that inferential statistics can be performed. If a measurement scale satisfies these necessary criteria, then a suitable method can be chosen considering further optional criteria: the shortest duration of evaluation, the ease of performing task, and the options to measure participants' repeatability.

Five measurement scales, namely, paired comparison, rank order, magnitude estimation, response scales, and semantic differential, are most widely used during subjective evaluations of automotive sounds. Otto *et al.* discussed the advantages and disadvantages of each method [11]. Based on the information provided by [11], Table I summarizes how these methods rate on the discussed criteria.

TABLE I
RANKING OF MEASUREMENT SCALES BASED ON THE SELECTION CRITERIA

	PC	RO	ME	NRS	SD
Independent measure per attribute	Yes	Yes	Yes	Yes	Yes
Relative rating	Yes	Yes	No	May be	May be
Interval level Data	No	No	Yes	Yes	Yes
Duration of evaluation	5th (longest)	1st (shortest)	2nd	3rd	3rd
Ease of participant task	1st (easiest)	2nd	5th (most difficult)	3rd	3rd
Measures of repeatability	Yes	No	No	No	No

Out of these methods, numbered response scales and semantic differential are deemed appropriate as only these scales satisfy all the necessary criteria for sound quality evaluations. That is, they provide an independent measure per attribute and interval level data and have a potential to provide relative rating of sounds. These scales can be improved to provide a relative rating, if the participants are familiarized beforehand with the target vehicle sounds to give them an idea of the variety of sounds used. Then, they should be instructed to make a relative assessment of the sounds based on their exposure to the sound variety.

If a numbered response scale is used for measuring an attribute, the meaning of the left end of the scale is unclear. Participants may perceive the extreme left end to mean either "neutral," i.e., not having the attribute being measured, or "negative," i.e., having the opposite attribute. Semantic differential scales are like numbered response scales but with bipolar adjectives at the opposing ends of the scale. This makes the scale bidirectional, where it is clear that the middle point stands for neutrality, and the left and right ends are opposing attributes. The interparticipant variability is also less in semantic differential scales [11]. These scales avoid the "pseudoneglect" effect, which is the bias due to attention to the left- or right-hand side of the scale [33]. They also help reduce the "acquiescence bias," which is the tendency to agree with statements [33].

Scale order and format may also influence responses if they are altered between experimental conditions, as they may potentially confuse participants [33]. The scale format has changed if negative semantics are placed on the left end of the scale and then on the right end of the scale. By fixing the scale order and format of the semantics for all experimental conditions for a participant, any acquiescence or pseudoneglect bias can be monitored, which may, otherwise, remain unobserved.

Semantic differential scales, however, do not directly give a measure of participants' repeatability, which is the participants' degree to produce the same results if the experimental conditions are repeated. By repeating an experimental condition and then comparing the two data sets, participants' repeatability can be estimated.

E. Proposed Methodology

The methodology proposes a way to holistically evaluate electric vehicle exterior sounds by suggesting an experimental approach that assesses detectability of these sounds and emotional evaluation of the vehicle based on listening to its sounds. For this purpose, the methodology proposes an experimental setup that includes the following:

1) immersive virtual environment(s) to provide the context of a real-life pedestrian–vehicle interaction(s);
2) traffic scenario(s) that are critical to pedestrians' safety (e.g., electric car moving at low speeds in parking lots, T-junctions, and crossroads);
3) ambient sounds that represent real-life urban environments;
4) target vehicle's sounds that satisfy legislative guidelines;
5) detection time measurement method that has options for recording many instances of detections.

The methodology further proposes randomized variations in the target vehicle's maneuver such as the vehicle's approach direction and time of arrival during the experiment. It also recommends familiarizing participants with target vehicle sounds prior to the experiment and using valid and reliable scales for emotional evaluations such as semantic differentials.

III. Experiment

A. Aim

The aim of the experiment was to test the proposed methodology in a virtual environment of a town's T-junction, using an ESS.

B. Participants

People were recruited as participants if they were 18 years or older and if they reported no known hearing problems or uncorrected visual impairment. Data were obtained from 31 participants, i.e., 19 males and 12 females, with the modal age group of 26–35 years, consisting of the staff and students from the University of Warwick.

The study was designed for repeated measures one-way analysis of variance (ANOVA). Software G$*$Power 3.1.4 [34] gave 24 as the minimum number of participants required for this analysis, to achieve a minimum statistical power of 0.8 [35] at α-error probability of 0.05 with a medium effect size, i.e., $f = 0.25$ [35]. However, use of "balanced Latin square" (Section III-F) required 31 participants for complete counterbalancing of presentation order of sounds.

C. Evaluation Environment

Experiments were conducted using simulations of the virtual town created by ESS inside a sound room located at WMG, at the University of Warwick. The sound room is a closed room

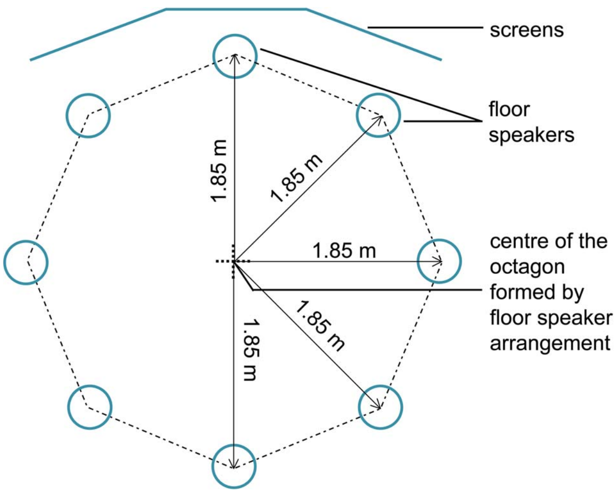

Fig. 2. Schematic of the sound room.

with three screens and eight floor speakers arranged in a regular octagon (see Fig. 2).

A participant was seated on a chair at the center of this octagon. The visuals synthesized by ESS were projected on screens, and the sounds were played through the speakers. Before the experiment, the sound room speakers were calibrated. For this, the same chair, as used during experiments, was placed at the center of the floor speaker octagon. A team member connected the ESS audio output to each speaker one at a time and played an 80-dB sine wave from the simulator's pure tone generator. Another team member sat on the chair and recorded the sounds produced at his ears using binaural headphone microphones. The speaker volume gain was adjusted to match the sound level produced at the ear's position. Later, the ESS audio output was set to all speakers, and the total sound level produced at the ear's position was checked. The eye height for ESS visuals was entered as 1.6 m. Thus, every participant saw the visuals as seen by an upright pedestrian with an eye height of 1.6 m.

D. Stimuli

Thirty experimental conditions were designed using every combination of 15 audio and 2 visual stimuli.

1) Visual Stimuli: The visual stimuli are described below as a combination of a virtual town location (T-junction), the pedestrian's maneuver, and the target vehicle's maneuver.

Virtual town location: The participant was exposed to a straight road ending in a T-junction with no traffic lights and no visible traffic (see Fig. 3).

Pedestrian's maneuver: The participant was the pedestrian, and s/he experienced himself/herself as walking along the pavement at a constant speed of 1.34 ms^{-1} (3 mph). After 10 s of walking, s/he arrived at the junction and waited there until the target vehicle passed by (see Fig. 3). Everything that a participant saw corresponds to the things that the pedestrian would see when carrying out this maneuver. For example, when walking along the pavement, the participant saw the objects of the virtual town move opposite to his/her direction of motion. Similarly, when the pedestrian paused at the junction, the participant saw the visuals pause at the junction as would

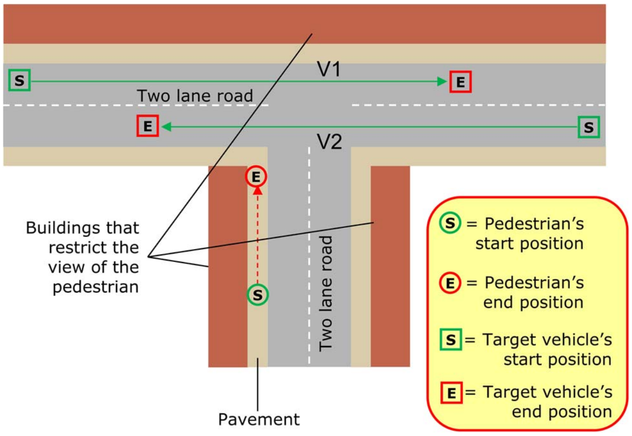

Fig. 3. Schematic of the visual scenario. Red dotted lines indicate a pedestrian's path as experienced by a participant. Green solid lines indicate a target vehicle's path for visual stimulus 1 ("V1") and visual stimulus 2 ("V2").

Fig. 4. Sound room setup during the experiments.

be seen by the pedestrian. The view the participant saw was restricted by buildings on either side of the road (see Fig. 4).

Target vehicle's maneuver: An electric car started from a distant offscreen position on the road perpendicular to the pedestrian's pavement, which they were currently walking up. It moved at a constant speed of 4.47 ms^{-1} (10 mph). The target car arrived at the junction appearing on screen at one of three arrival times from the start of the visuals: 21.4, 29.7, or 36.6 s. In visual stimulus 1, the car approached the junction from the pedestrian's left-hand side along the lane farther away from the pedestrian's standing position. The lane was situated at a perpendicular distance of 5.5 m from the pedestrian's standing position. In visual stimulus 2, the car approached from the pedestrian's right-hand side along the nearer lane situated at a distance of 3 m from the pedestrian. Fig. 3 shows the layout for both visual stimuli together.

2) Audio Stimuli: The focus of this study was to test the proposed methodology and not to validate or create new sounds. Therefore, 15 sounds synthesized from engine recordings, pure tones signals, and tire sounds were used as the target car's exterior sounds (Sound 1 to Sound 15; see Table II).

Their equivalent sound pressure level was in the range of 51–61 dB(A), which complies with the combined dB(A) range

TABLE II
PSYCHOACOUSTIC METRICS OF THE SOUNDS USED IN EXPERIMENTS

Sound	SPL (dB(A))	Loudness (sones)	Sharpness (acum)	Roughness (asper)
Sound 1	55	5.8	1.46	0.46
Sound 2	54	4.8	0.41	0.09
Sound 3	55	5.8	0.36	0.04
Sound 4	48	7.7	0.75	0.31
Sound 5	61	9.9	0.52	0.01
Sound 6	52	5.5	0.52	0.06
Sound 7	55	7.2	1.08	1.72
Sound 8	53	6.2	0.43	0.00
Sound 9	51	6.1	0.59	0.41
Sound 10	51	6.2	0.81	0.50
Sound 11	52	6	0.52	0.38
Sound 12	60	8.8	1.19	0.50
Sound 13	57	9.8	0.98	1.84
Sound 14	58	9.3	0.52	0.22
Sound 15	52	7.9	0.79	0.14
Ambience	42	4.4	0.99	0.15

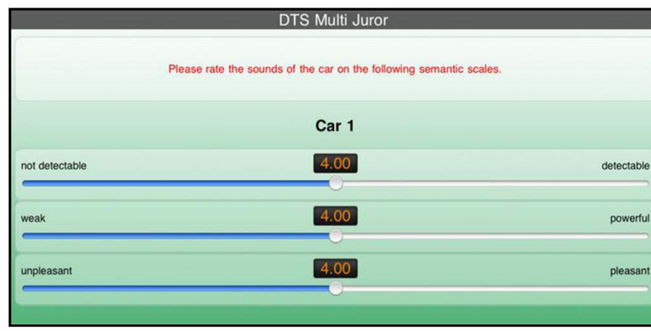

Fig. 5. Evaluation interface.

specified by the FMVSS and AVAS guidelines. All sounds were broadband with at least one signal in the range 160–5000 Hz so that they complied with the standards of FMVSS and GTR. In accordance with vehicle standards, none of these sounds resembled siren, horn, chime, bell, alarm, animal, and insect sounds. However, two sounds (Sound 5 and Sound 6) were melodious sounds. An 18-s 42-dB(A) binaural recording made in a parking space was played in a loop as ambience soundscape for every stimulus. To match the visual scenario, this ambience soundscape included sounds of regular bird chirping and light winds, as well as some occasional distant traffic. No moving vehicle was visible during the actual sound recording; thus, there were no noticeable sound of nearby vehicles.

E. Measures

1) Detectability: Participants were asked to indicate as soon as they detected a car, visually or aurally, by pressing a scale on an interface (first scale; see Fig. 5). Detectability was evaluated using time-to-vehicle arrival, which is defined here as the time in seconds taken by the target car to appear on screen from the instant it was detected by the participant. It was calculated by subtracting the time when the participant pressed the scale from the time the car appeared on screen. In order to eliminate negative values, the time-to-vehicle arrival was given a value of zero whenever a participant did not press the detection scale or pressed the scale after the car appeared on screen.

2) Emotional Evaluations: Participants were asked to emotionally evaluate impressions of the electric car from listening to its sounds using seven-point semantic differential scales of "weak–powerful" and "unpleasant–pleasant" [30] (see Fig. 5).

3) Feedback: After the experiment, participants were asked to "provide feedback on their experience of the experiment and suggestions, if any, to improve the experiment."

4) Method of Data Collection: Participants were given an electronic touch screen tablet with the evaluation interface developed within ESS (see Fig. 5). The current ESS facility supports interfaces with scales but not touch buttons. Therefore, a detection scale was used to record the time of vehicle detection. Participants were instructed to first slide the detection scale (first scale in the interface) to any value by moving the center button of the slider as soon as they heard or saw a vehicle approaching. If they later thought they had incorrectly perceived hearing the car or moved the scale mistakenly, they were instructed to slide the detection scale again when they thought they started hearing the car.[1] The interface recorded the time of every instance a participant pressed or moved the scale with a least count of 0.01 s. The time-to-vehicle arrival was calculated using the recorded time when the participant last pressed the detection scale. After detection, they were instructed to rate the impressions of the car from listening to its sounds by sliding the powerful and pleasant scales to a value of 1 to 7.

F. Experimental Design

A repeated measures design was selected for this study because it is the most convenient for perception research. This is because such research requires extensive laboratory setup and preparation of the different stimuli and much less time to expose participants to different stimuli one after another [36]. This design also eliminated the requirement of having equivalent groups [36].

The first experimental condition, i.e., the target car emitting Sound 1 and approaching from the pedestrian's left-hand side, was repeated for every participant to measure participants' repeatability. Therefore, each participant was exposed to 31 experimental conditions.

Exposure to a fixed sequence of experimental conditions may bias the results due to practice effects (participants become more experienced and better at the task as the experiment proceeds) and fatigue effects (participants get tired as the experiment proceeds). The presentation order of the experimental conditions was randomized using the balanced Latin square method to control such effects [36].

Randomizing the direction of approach and arrival time of the car increased the validity of the experiment to represent real-life scenarios of pedestrian–vehicle interaction. The arrival time (time from the start of the visual stimulus to when the car appeared on screen) was counterbalanced for each car sound across participants, but not within the participants. This is because presenting each car sound at every arrival time for every participant would have increased the experimental conditions to 90, thereby increasing the experimental duration.

The presentation format of scale items was fixed by keeping positive adjectives—powerful and pleasant—on the right and negative adjectives—weak and unpleasant—on the left for the first 16 participants. The scales were reversed for the rest.

G. Procedure

The experiment was performed on each participant one at a time in the following manner. The whole study lasted about 40 min.

1) Participant sat at the center of the sound room's floor speaker arrangement (see Fig. 2). A written informed consent was obtained from the participant.
2) S/he reported his/her demographics. Pilot studies done on ESS showed that a participant may occasionally experience moderate "simulator sickness" [37]. Therefore, if and only if the participant self-reported as feeling "well" was s/he was allowed to proceed.
3) S/he was briefed about the experiment.
4) Seven-second clips of the 15 target car sounds were played in the absence of the ambient soundscape, followed by the clip of ambient soundscape separately played to familiarize the participant to the variety of sounds used in this experiment.
5) Since the participant had heard the type of sounds used for the target car, s/he was instructed to detect these sounds without considering if these sounds could be recognized as emanating from a car.
6) S/he was instructed to detect the car aurally or visually and then make a relative rating on the two semantic scales of the emotional evaluation of the target car based on its sound.
7) S/he was exposed to a trial car for practice followed by the exposure to the experimental conditions, and s/he completed the task.
8) S/he was thanked and debriefed, and feedback was collected.

IV. Results

A. Error in Detection

Data recorded by interface show that 68% participants (21 out of 31) pressed the detection scale more than once. This indicates that there is a high probability that listeners may detect a target car sound incorrectly.

B. Participants' repeatability

Paired t-tests found no significant difference between the powerfulness ratings $t(30) = -0.97,\ p > 0.05$; pleasantness ratings $t(30) = 0.53$, $p > 0.05$; and the time-to-vehicle arrival $t(30) = -0.77,\ p > 0.05$ of the target car upon participants' repetition of the same experimental condition. Thus, the participants were repeatable.

The data collected from the repeated experimental conditions were combined, and their mean was used for further analysis. This new data satisfied all assumptions of the parametric tests.

[1]This was done because, during pilot testing, using two participants (1 male, 1 female), both of them commented that they thought they had heard the car, pressed the scale, and later realized that the sound was another sound in the ambient soundscape rather than the target car's sound.

C. Effect of Arrival Time

Since each car sound could not be presented at every arrival time for every participant, repeated measures ANOVA could not be directly performed on the original repeated measures data using arrival time as an independent variable. Therefore, in order to check the effect of arrival time, the repeated measures data were converted into an equivalent independent group design by treating every data as independent. ANCOVA was used for analysis to eliminate the effect of individual differences by using the participant ID as a covariate. The data satisfied all assumptions of ANCOVA.

Three independent group ANCOVAs were performed using arrival time as the independent variable; participant ID as the covariate; and powerfulness, pleasantness, and time-to-vehicle arrival as dependent variables.

The covariate participant ID was not significantly related to the powerfulness score $F(1, 926) = 3.31$, $p > 0.05$, $r = .06$. There was a significant effect of arrival time on powerfulness score after eliminating the effect of individual differences, $F(2, 926) = 3.74$, $p < 0.05$, partial $\eta^2 = 0.008$. Planned contrasts revealed that arrival time of 36.55 s significantly decreased powerfulness scores compared with arrival time of 21.43 s, $t(926) = 2.7$, $p < 0.05$, $r = 0.09$, but did not do so compared with arrival time of 29.69 s, $t(926) = 0.99$, $p > 0.05$, $r = 0.03$. Thus, the later the car arrived, the less powerful it was perceived to be.

The covariate participant ID was significantly related to the pleasantness score $F(1, 926) = 4.77$, $p < 0.05$, $r = 0.07$. There was no significant effect of arrival time on pleasantness score after eliminating the effect of individual differences, $F(2, 926) = 2.85$, $p > 0.05$, partial $\eta^2 = 0.006$.

The covariate participant ID was not significantly related to time-to-vehicle arrival, $F(1, 926) = 1.52$, $p > 0.05$, $r = 0.04$. There was a significant effect of arrival time on time-to-vehicle arrival after eliminating the effect of individual differences, $F(2, 926) = 28.25$, $p < 0.05$, partial $\eta^2 = 0.06$. Planned contrasts revealed that arrival time of 36.55 s significantly decreased the time-to-vehicle arrival compared with arrival time of 21.43 s, $t(926) = 7.51$, $p < 0.05$, $r = 0.24$ and compared with arrival time of 29.69 s, $t(926) = 3.42$, $p < 0.05$, $r = 0.11$. Thus, the later the car arrived, the slower it was detected (lower time-to-vehicle arrival).

D. Effect of Car's Sound and Car's Approach Direction

Arrival time had no significant effect on the pleasantness scores. Therefore, the data for the three arrival times were combined, and the effects of the car's sound and the direction of car's approach on pleasantness were calculated using repeated measures ANOVA with car's sound and car's approach direction as independent variables and pleasantness scores as dependent variable. Arrival time, however, did significantly decrease the powerfulness scores and time-to-vehicle arrival. Thus, the data were grouped into three sets for each arrival time, and separate independent group ANCOVAs were performed for each group using powerfulness scores and time-to-vehicle arrival as dependent variables, car's sound and car's approach direction as independent variables, and participant ID as covariate.

Mauchly's test indicated that the assumption of sphericity had been violated for the main effects of the target car's sound on pleasantness, $p < 0.001$. Thus, these results have been reported after applying Greenhouse–Geisser correction ($\varepsilon = 0.53$).

There was a significant effect of the target car's sound on the pleasantness score, $F(7.43, 222.78) = 21.69$, $p < 0.001$. However, there was no significant effect of the car's approach direction on the pleasantness score, $F(1, 30) = 1.87$, $p > 0.05$.

1) For Arrival Time 1: The covariate participant ID was not significantly related to the powerfulness score $F(1, 279) = 1.95$, $p > 0.05$ or to the time-to-vehicle arrival $F(1, 279) = 1.11$, $p > 0.05$. After eliminating the effect of individual differences, the powerfulness scores were significantly affected by the target car's sound, $F(14, 279) = 5.24$, $p < 0.05$ and the direction of car's approach, $F(1, 279) = 5.98$, $p < 0.05$. Paired comparisons revealed that the target car was perceived as more powerful when approaching from the right, i.e., when it passed by along the lane nearer to the pedestrian's position.

Similarly, the time-to-vehicle arrival was significantly affected by the target car's sound, $F(14, 279) = 50.43$, $p < 0.05$ and the direction of car's approach, $F(1, 279) = 7.12$, $p < 0.05$. Paired comparisons revealed that the target car was detected faster (higher time-to-vehicle arrival) when approaching from the right, i.e., when it passed by along the lane nearer to the pedestrian's position.

2) For Arrival Time 2: The covariate participant ID was not significantly related to the powerfulness score $F(1, 279) = 0.37$, $p > 0.05$ or to the time-to-vehicle arrival $F(1, 279) = 0.80$, $p > 0.05$. After eliminating the effect of individual differences, the powerfulness scores were significantly affected by the target car's sound, $F(14, 279) = 7.35$, $p < 0.05$ and the direction of car's approach, $F(1, 279) = 6.66$, $p < 0.05$. Paired comparisons revealed that the target car was perceived as more powerful when approaching from the right.

Similarly, the time-to-vehicle arrival was significantly affected by the target car's sound, $F(14, 279) = 29.93$, $p < 0.05$, but not by the direction of car's approach, $F(1, 279) = 0.35$, $p > 0.05$.

3) For Arrival Time 3: The covariate participant ID was not significantly related to the powerfulness score $F(1, 279) = 1.81$, $p > 0.05$ or to the time-to-vehicle arrival $F(1, 279) = 1.85$, $p > 0.05$. After eliminating the effect of individual differences, the powerfulness scores were significantly affected by the target car's sound, $F(14, 279) = 6.59$, $p < 0.05$ and the direction of car's approach, $F(1, 279) = 5.85$, $p < 0.05$. Paired comparisons revealed that the target car was perceived as more powerful when approaching from the right.

Similarly, the time-to-vehicle arrival was significantly affected by the target car's sound, $F(14, 279) = 24.87$, $p < 0.05$, but not by the direction of car's approach, $F(1, 279) = 0.92$, $p > 0.05$.

E. Feedback

All participants reported enjoying the experiments. No participant suggested improvement in the experimental design. However, before the experiment began, many participants were confused about the use of semantics powerful and pleasant. In particular, they found the semantic pleasant unusual and asked for an explanation on how it relates to an electric car that emits a sound that is supposed to warn pedestrians of the vehicle approach. Many participants reported finding the detection task difficult as they got confused with the background sound; hence, they pressed the scale multiple times. Some participants considered they would feel more confident about their results if they could evaluate the detectability of sounds subjectively on a seven-point scale in addition to recording the "exact" time when the car was detected. Participants commented that some sounds used in this experiment did not seem likely to be emanating from a vehicle. Therefore, although they detected these sounds during the experiment, they did not think they would recognize them as vehicle sounds in real life. They particularly emphasized including vehicle sound recognition as a key parameter for future vehicle sound evaluations.

V. Discussions

This study aimed at proposing and testing a methodology for evaluating electric vehicle exterior sounds, but did not aim to create or design new sounds. Hence, the target car sounds were chosen only as samples to demonstrate the implementation of the methodology. To account for the unrepresentative stimuli, this paper presents and discusses the results concerning the basic aspects of methodological design rather than the results of differences and comparisons among sounds. The latter results are available in the authors' previous paper [38].

A. Discussion of Experimental Results

Analyses showed that aspects of the methodological design of detection and emotional evaluations of electric vehicle exterior sounds are influential in the produced results. Therefore, care is needed in the design of these studies, by considering factors such as participant errors, arrival time and direction of approach of the target car, and the type of target car sound. This is important as they impact on the detectability and evaluation of the car's powerfulness and pleasantness.

Results showed that participants used the detection scale more than once, thus self-reporting that they made errors in detecting. This could be because of the 'unrecognizability' of these sounds as car sounds, resulting in false detections. Therefore, whenever there were spikes in the ambient soundscape, from another sound being introduced, participants assumed it was the start of the electric car sound, when in fact it was the sound of wind and leaves. Listening tests should include a facility for participants to reevaluate their detectability decisions, such as the option in this study for rerecording their car detection time. ESS helps in achieving this as participants can interact with the scales and record times of detection and the semantic scores continuously until they are satisfied with their evaluations. This is also supported by the fact that participants preferred a semantic scale evaluating the car's detectability in addition to recording the time they detected the car. The reason they gave for this was that they felt more confident about the results they provided on a subjective scale than the detection time.

The detection of a car was affected by the car's arrival time; the later the car arrived, the slower it was detected. This has implications from conventional listening test methods, where the car sound to be detected is present from the very beginning of the stimulus [1], [2], [14], [20], [21], and participants expect to hear the car from the very beginning. This expectancy bias is also indicated by the participants' false detections made toward the beginning of the presentation of each experimental condition. Reduced expectations and decreased attention caused the participants to detect the car slower as time increased in a particular experimental condition. Although powerfulness scores are affected in a similar way, the effect size is too small to comment on it.

Evaluation of pleasantness of the car is not affected by the arrival time or the direction of car's approach. However, no particular inferences can be drawn from it as many participants were confused about using pleasant as an attribute for evaluating an electric car based on a sound that is meant to warn pedestrians of its approach. This also explains the significant differences found among the participants while evaluating the pleasantness of the target car.

The semantic pleasant is traditionally used for assessing a combustion engine vehicle based on its sounds [10], [30]–[32]. The new sounds for electric vehicles are being developed to alert the pedestrians of the vehicle's approach. Therefore, participants could have evaluated the target car while associating its sounds as a warning sound, such as a horn or an alarm, rather than a sound that is intrinsic to the car as in a combustion engine vehicle. Thus, they were unable to relate the word pleasant to such a car. A reframing of the study to put an emphasis on safety or on the vehicle brand from a potential consumer perspective may avoid confusion with regard to the use of the semantic pleasant. Appropriate semantics need to be used for the context of electric vehicle sounds. More semantics may be necessary when trying to compare safety and brand in the same study.

The results found that a car was evaluated as more powerful when approaching from the right. Sound quality research shows strong correlations between the evaluation of powerfulness and the loudness level of the sound [10]. In this paper, the reported loudness level is an average of the sound played to the participant, when the car approached from the left and from the right. However, the actual sound heard was louder when the car approached from the right. This is because, in the experimental design, the distance between the target car and the pedestrian's position was shorter when the car approached from the pedestrian's right-hand side, as it was moving on a lane nearer to the pedestrian (see Fig. 3). Given the existing loudness–powerfulness relationships, this would explain why participants perceived the car sound approaching from the right as more powerful. In future, psychoacoustic metrics of the target car's sound for both direction of approach will be separately analyzed. This would enable examining the relationship between these metrics and emotional evaluation scores, to help explain this result.

These results further indicate that conventional listening tests that use fixed arrival and direction may bias results. A detection test could be made more realistic by varying these factors, but the results must be analyzed while accounting for the effect of these factors.

Overall, the experiment demonstrated a successful application of simulated environment for conducting simultaneous detection and evaluation tests.

B. Review of the Proposed Methodology

The proposed methodology constitutes using virtual environments for pedestrian–vehicle interactions and conducting listening experiments using the principles of experimental design and cognitive psychology. This methodology is applicable to all simulators that present virtual environments from a pedestrian's perspective. Conventional listening tests aim to measure the detection distance or time of the electric vehicle sounds to assess pedestrians' safety. The presented methodology aims for a more holistic evaluation where the electric vehicle sounds could be simultaneously tested for detectability to assess pedestrians' safety and emotional evaluations to assess the impressions of the vehicle brand. The proposed methodology is free from any expectancy biases that are present in conventional evaluation methods that use fixed arrival time and direction of the target vehicle. Moreover, the methodology makes the evaluations more representative of real life as the participants experience the vehicles in the presence of appropriate visual and audio stimuli. The methodology is reliable as the participants show repeatability.

However, the methodology could be further improved by using more appropriate and valid semantics for assessing the impressions of the vehicle brand. Furthermore, it needs testing using more representative sounds being developed by conventional electric and hybrid vehicle manufacturers. The present methodology could be enhanced by adding tests for recognizability of the target sounds as a vehicle and detectability assessments using subjective scales.

Currently, the motion of standing and walking is different, but without further equipment capabilities (e.g., a moving walkable on the spot floor), this correction is not possible, and it is not considered to have been detrimental to the results.

C. Future Studies

Future studies will use sounds developed by electric car manufacturers. The ESS provides options to create more visual scenarios and use different ambient sounds and additional vehicles as traffic. Future studies will explore these options to study how ambient sounds and additional vehicles affect the evaluation of an electric vehicle based on its sounds. The evaluations using simulation will also be compared with real-life evaluations to assess the external validity of the proposed methodology. Future studies will also test aspects such as recognition of the sounds as emanating from a vehicle and assessment of pedestrians' safety using both subjective evaluations and measuring the time or distance of vehicle detection.

VI. Conclusion

A methodology has been proposed for conducting evaluations of an electric vehicle's exterior sounds by enhancing state-of-the-art listening evaluation approaches using principles from experimental design and cognitive psychology. The methodology constitutes experiments to assess pedestrians' detectability and emotional evaluation of an electric vehicle upon listening to its sound in a simulated town environment representative of real-life pedestrian–vehicle interactions. The methodology's prime focus is to make the evaluations more realistic so that results could represent real-life experiences. This requires the context of the common scenarios of pedestrian–electric vehicle interactions that are critical to pedestrians' safety and random variations in the vehicle's arrival time, distance, and approach direction throughout the experiments. Moreover, ambient sounds should represent real-life urban environments, and the target vehicle sounds must satisfy the legislative guidelines.

The proposed methodology is an improvement over conventional methods of automotive sound evaluations. This is because simulators present a more realistic context of pedestrian–vehicle interactions than conventional laboratory listening methods. At the same time, researchers have much better experimental control than conventional on-road evaluations. Second, conventional listening tests only focus on measuring the detection distance or time of the electric vehicle sounds, whereas the proposed methodology achieves a more holistic evaluation by testing the electric vehicle sounds for both detectability to assess pedestrians' safety and emotional evaluations to assess the impressions of the vehicle brand. Moreover, the proposed methodology is reliable and free from any expectancy bias present in conventional evaluation methods that use fixed arrival time and direction of the target vehicle. However, the methodology could be improved, and more studies will be conducted to enhance the methodology.

Acknowledgment

This work is part of a doctoral project funded through WMG-Indian Institute of Technology Kharagpur collaboration. The authors would like to thank Brüel and Kjær for supporting the project.

References

[1] Japan Automobile Standards Internationalization Centre, "A study on approach warning systems for hybrid vehicle in motor mode," 49th UNECE/WP/GRB, Tokyo, Japan, Document number: GRB-49-10, Feb. 2009. [Online]. Available: http://www.unece.org/trans/main/wp29/wp29wgs/wp29grb/grbinf49.html

[2] L. Garay-Vega, A. Hastings, J. K. Pollard, M. Zuschlag, and M. D. Stearns, "Quieter cars and the safety of blind pedestrians: Phase I," National Highway Traffic Safety Administration, Washington, DC, USA, Document No.: DOT HS 811 304, Apr. 2010.

[3] Quiet Road Transport Vehicles (QRTV), "Terms of reference and rules of procedures for the GRB working group on Quiet Road Transport Vehicles (QRTV)," GRB Informal Group on Quiet Road Transport Vehicles (QRTV): Working Papers of the 1st Informal Meeting, Geneva, Switzerland, Feb. 2010. [Online]. Available: http://www.unece.org/trans/main/wp29/wp29wgs/wp29grb/qrtv_1.html

[4] U. Sandberg, "Adding noise to quiet electric and hybrid vehicles: An electric issue," *Acoust. Aust.*, vol. 40, no. 3, pp. 211–220, Dec. 2012.

[5] Ministry of Land, Infrastructure, Transport and Tourism and Japan Automobile Standards Internationalization Centre, "Guideline for measure against quietness problem of HV, etc.," GRB Informal Group on Quiet Road Transport Vehicles (QRTV): Working Papers of the 3rd Informal Meeting, Tokyo, Japan, Jul. 2010. [Online]. Available: http://www.unece.org/trans/main/wp29/wp29wgs/wp29grb/qrtv_3.html

[6] United States Congress, Public Law 111-373: Pedestrian Safety Enhancement Act of 2010.

[7] G. Dalrymple, "Minimum sound requirements for hybrid and electric vehicles: Draft environmental assessment," National Highway Traffic Safety Administration, Washington, DC, USA, Document No.: NHTSA-2011-0100, Jan. 2013.

[8] "Draft recommendations for a global technical regulation regarding audible vehicle alerting systems for quiet road transport vehicles," United Nations Economic Commission for Europe (UNECE), Geneva, Switzerland, Document No.: GRB-55-14, Feb. 2012.

[9] "Proposal for guidelines on measures ensuring the audibility of hybrid and electric vehicles," United Nations Economic Commission for Europe (UNECE), Geneva, Switzerland, Tech. Rep. GRB-53-09-Rev.1, Feb. 2011.

[10] P. Jennings, G. Dunne, R. Williams, and S. Giudice, "Tools and techniques for understanding the fundamentals of automotive sound quality," *Inst. Mech. Eng. Proc. Part D, J. Automob. Eng.*, vol. 224, no. 10, pp. 1263–1278, Oct. 2010.

[11] N. Otto, S. Amman, C. Eaton, and S. Lake, "Guidelines for jury evaluations of automotive sounds," SAE International, Warrendale, PA, USA, Tech. Rep. 1999-01-1822, 1999.

[12] P. Jennings *et al.*, "Developing best practice for sound evaluation using an interactive NVH simulator," *Trans. Jpn. Soc. Autom. Eng.*, vol. 38, no. 1, pp. 31–36, 2007.

[13] A. Hastings, J. K. Pollard, L. Garay-Vega, M. D. Stearns, and C. Guthy, "Quieter cars and the safety of blind pedestrians, phase 2: Development of potential specifications for vehicle countermeasure sounds-final report," National Highway Traffic Safety Administration (NHTSA), Washington, DC, USA, Document No.: DOT HS 811 496, Oct. 2011.

[14] H. Konet *et al.*, "Development of approaching Vehicle Sound for Pedestrians (VSP) for quiet electric vehicles," *SAE Int. J. Engines*, vol. 4, no. 1, pp. 1217–1224, Apr. 2011.

[15] R. W. Emerson, K. Naghshineh, J. Hapeman, and W. Wiener, "A pilot study of pedestrians with visual impairments detecting traffic gaps and surges containing hybrid vehicles," *Transp. Res. Part F. Traffic Psychol. Behav.*, vol. 14, no. 2, pp. 117–127, Mar. 2011.

[16] P. Goodes, Y. B. Bai, and E. Meyer, "Investigation into the detection of a quiet vehicle by the blind community and the application of an external noise emitting system," SAE International, Warrendale, PA, USA, Tech. Rep. 2009-01-2189, 2009.

[17] R. W. Emerson, D. S. Kim, K. Naghshineh, J. Pliskow, and K. Myers, "Detection of quiet vehicles by blind pedestrians," *J. Transp. Eng.*, vol. 139, no. 1, pp. 50–56, Jan. 2013.

[18] M. W. Eysenck and M. T. Keane, "Attention and performance," in *Cognitive Psychology: A Student's Handbook*., 6th ed. New York, NY, USA: Psychology Press, 2010, pp. 153–201.

[19] F. T. Durso, R. S. Nickerson, S. T. Dumais, S. Lewandowsky, and T. J. Perfect, "Attention," in *Handbook of Applied Cognition*., 2nd ed. Chichester, U.K.: Wiley, 2007, pp. 29–54.

[20] P. A. Morgan, L. Morris, M. Muirhead, L. K. Walter, and J. Martin, "Assessing the Perceived Safety Risk From Quiet Electric and Hybrid Vehicles to Vision-Impaired Pedestrians," Transport Research Laboratory Ltd., Berkshire, U.K., Published Project Rep. PPR525, 2011.

[21] B. K. Barton, T. A. Ulrich, and R. Lew, "Auditory detection and localization of approaching vehicles," *Accid. Anal. Prev.*, vol. 49, pp. 347–353, 2012.

[22] D. H. Ashmead *et al.*, "Auditory perception of motor vehicle travel paths," *Hum. Factors J. Hum. Factors Ergon. Soc.*, vol. 54, no. 3, pp. 437–453, Jun. 2012.

[23] F. Kavarana, G. Taschuk, T. Schiller, and D. Bogema, "An efficient approach to improving vehicle acceleration sound quality using an NVH simulator," SAE International, Warrendale, PA, USA, Tech. Rep. 2009-01-2190, 2009.

[24] D. Quinn, P. Speed-andrews, M. Allman-ward, and T. Heinz, "How advances in on-road NVH simulator technology have enabled firm targets for delivery at the concept phase," SAE International, Warrendale, PA, USA, Tech. Rep. 2009-01-2178, 2009.

[25] R. Williams *et al.*, "Using an interactive NVH simulator for target setting and concept evaluation in a new vehicle programme," SAE International, Warrendale, PA, USA, Tech. Rep. 2005-01-2479, 2005.

[26] M. Allman-ward *et al.*, "The interactive NVH simulator as a practical engineering tool," SAE International, Warrendale, PA, USA, Tech. Rep. 2003-01-1505, 2003.

[27] A. Gillibrand, I. Suffield, X. Vinamata, R. Williams, and A. Brückmann, "An initial study to develop appropriate warning sound for a luxury vehicle using an exterior sound simulator," SAE International, Warrendale, PA, USA, Tech. Rep. 2011-01-1727, 2011.

[28] R. Hanna, Incidence of Pedestrian and Bicyclist Crashes by Hybrid Electric Passenger Vehicles 2009.

[29] S. Kerber and H. Fastl, "Prediction of perceptibility of vehicle exterior noise in background noise," in *Proc. DAGA*, Dresden, Germany, 2008, pp. 623–624.

[30] R. Bisping, "Emotional effect of car interior sounds: Pleasantness and power and their relation to acoustic key features," SAE International, Warrendale, PA, USA, Tech. Rep. Paper No. 951284, 1995.

[31] R. Bisping, "Car interior sound quality: Experimental analysis by synthesis," *Acta Acust. United Acust.*, vol. 83, no. 5, pp. 813–818, Sep./Oct. 1997.

[32] D. Västfjäll, M.-A. Gulbol, M. Kleiner, and T. Gärling, "Affective evaluations of and reactions to exterior and interior vehicle auditory quality," *J. Sound Vib.*, vol. 255, no. 3, pp. 501–518, Aug. 2002.

[33] C. E. Osgood, G. J. Suci, and P. H. Tannenbaum, "The logic of semantic differentiation," in *The Measurement of Meaning*. Urbana, IL, USA: Univ. of Illinois Press, 1957, pp. 1–30.

[34] F. Faul, E. Erdfelder, A. G. Lang, and A. Buchner, "G∗Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences," *Behav. Res. Methods*, vol. 39, pp. 175–191, 2007.

[35] J. Cohen, "The concepts of power analysis," in *Statistical Power Analysis for the Behavioral Sciences*., 2nd ed. Hillsdale, NJ, USA: Lawrence Erlbaum Associates, 1988, pp. 1–17.

[36] C. J. Goodwin, "Control problems in experimental research," in *Research in Psychology: Methods and Design*., 6th ed. Hoboken, NJ, USA: Wiley, 2010, pp. 205–232.

[37] R. S. Kennedy, N. E. Lane, K. S. Berbaum, and M. G. Lilienthal, "Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness," *Int. J. Aviat. Psychol.*, vol. 3, no. 3, pp. 203–220, 1993.

[38] S. Singh, S. R. Payne, and P. A. Jennings, "Detection and emotional evaluation of an electric vehicle's exterior sound in a simulated environment," presented at the Internoise, Innsbruck, Austria, 2013, pp. 1–9, Paper 0807, pp. 1–9.

Sneha Singh received the B. Tech. degree in manufacturing science and engineering from Indian Institute of Technology Kharagpur, Kharagpur, India, in 2011. She is currently working toward the Ph.D. degree in engineering in WMG, University of Warwick, Coventry, U.K. Her doctoral project is aimed at developing and improving methods for evaluating electric vehicles' exterior sounds.

Her research interests include automotive sound quality evaluations, human factors design, and virtual and mixed reality.

Sarah R. Payne received the B.Sc. degree in psychology from The University of Sheffield, Sheffield, U.K., in 2001; the M.Sc. degree in environmental psychology from University of Surrey, Guildford, U.K., in 2003; and the Ph.D. degree in architecture from The University of Manchester, Manchester, U.K., in 2009.

She was a Postdoctoral Research Fellow with McGill University, Montreal, QC, Canada, and the University of Warwick, Coventry, U.K., before she joined Heriot-Watt University, Edinburgh, U.K., in 2014 as a Lecturer. Her research interests are in people's health in urban environments, including topics on soundscapes, fatigue, restoration, fear of crime, green spaces, and the design of environments and transportation.

Paul A. Jennings received the B.A. degree in physics from University of Oxford, Oxford, U.K., in 1985 and the Doctorate degree in engineering from University of Warwick, Coventry, U.K., in 1996.

From 1985 to 1988 he was a Physicist with Rank Taylor Hobson. Since 1988, he has worked on industry-focused research with WMG, University of Warwick, where he is also currently the Deputy Chief Technology Officer of the WMG center High Value Manufacturing Catapult. His interests include vehicle electrification, particularly energy management and storage, and user engagement in product and environment design, with a particular focus on automotive and healthcare applications.