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Detection and emotional evaluation of an electric vehicle's exterior sound in a simulated environment

Sneha Singh[1], Sarah R Payne[2], and Paul A Jennings[3]

[1-3] WMG

University of Warwick

United Kingdom

ABSTRACT

Electric vehicles are quiet at low speeds and thus potentially pose a threat to pedestrians' safety. Laws are formulating worldwide that mandate these vehicles emit sounds to alert the pedestrians of the vehicles' approach. It is necessary that these sounds promote a positive perception of the vehicle brand, and understanding their impact on soundscapes is also important. Detection time of the vehicle sounds is an important measure to assess pedestrians' safety. Emotional evaluation of these sounds influences assessment of the vehicle brand. Laboratory simulation is a new approach for evaluating exterior automotive sounds. This study describes the implementation of laboratory simulation to compare the detection time and emotional evaluation of artificial sounds for an electric vehicle.

An Exterior Sound Simulator simulated audio-visual stimuli of an electric car passing a crossroad of a virtual town at 4.47 ms^{-1} (10 mph), from the perspective of a pedestrian standing at the crossroad. In this environment, 15 sounds were tested using experiments where participants detected the car and evaluated its sound using perceptual dimensions.

Results show that these sounds vary significantly in their detection times and emotional evaluations, but crucially that traditional metrics like dB(A) do not always relate to the detection of these sounds.

Detection time and emotional evaluation do not have significant correlation. Hence, sounds of a vehicle could be detected quickly, but may portray negative perceptions of the vehicle. Simulation provides a means to more fully evaluate potential electric vehicle sounds against the competing criteria.

Keywords: Vehicle exterior sounds, Detection, Evaluation

1. INTRODUCTION

Electric vehicles are quieter at low speeds compared to combustion engine vehicles. Research suggests that the sound pressure level of an electric vehicle can be 3 to 20 dB(A) lower than an internal combustion engine vehicle of a similar make and weight when operating below 6 ms^{-1} [1]. Concerns are being raised that this may pose a threat to the safe travelling of pedestrians, cyclists and other road users [1-2]. Upcoming laws mandate that electric vehicles emit sounds to alert the pedestrians, cyclists and other road users of the vehicles' approach [3-5]. Detection time of these vehicles is

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[1] sneha.singh@warwick.ac.uk
[2] s.r.payne@warwick.ac.uk
[3] paul.jennings@warwick.ac.uk

therefore important to assess their safety risk. The exterior sounds of these vehicles should aid in the detection of the vehicles' approach. For this purpose, these sounds should be recognised as emanating from a vehicle as well as alerting the pedestrians appropriately in advance to avoid potential collision. Additionally, it is important that these sounds promote positive perceptions of the vehicle brand, and have overall neutral or positive effects on the soundscapes. Safety, brand, and soundscapes are the competing issues for the evaluation of exterior sounds of electric vehicles.

Emotional evaluations of a vehicle's sound influences the assessment of the vehicle's brand overall. The emotional dimensions of a vehicle's sound quality have been found to form a perceptual space that discriminates between different types of car sounds with sounds of different characters like 'luxury' and 'sportive' occupying different positions in the perceptual space [6-7]. Sounds of different brands have been found to occupy different positions in the perceptual space formed by the emotional dimensions of a car's sound quality [8]. Therefore emotional evaluations are an important feature for manufacturers to consider in their vehicle design and production.

Laboratory simulation is a new technique for evaluating vehicles' exterior sounds which may provide advantages over conventional on-road and laboratory listening methods. To help develop appropriate evaluation methods, this study compares the detection time and emotional evaluation of 15 different electric car sounds in a simulated environment created by an Exterior Sound Simulator inside a laboratory.

2. EXPERIMENTAL SET UP

2.1 Choice of Evaluation Environment

Conventional listening experiments for exterior automotive sounds are usually conducted on-road or inside a laboratory. Both these methods have their advantages and limitations. On-road evaluations can resemble real-life pedestrian-vehicle interactions where the pedestrian receives visual and auditory stimuli and evaluates the vehicle's sound in the presence of appropriate background sounds, additional vehicles, and other sound sources. Hence, on-road evaluations provide the correct "context" for evaluating vehicle sounds [9]. However, they do not provide control on external factors, such as, changes in the background sounds, visuals, traffic, and weather. Therefore, it is difficult to maintain consistency and repeatability in the results [9]. On-road evaluations also require long testing durations as it is difficult to achieve various driving conditions of the test vehicle while maintaining a similar ambience. In contrast, laboratory evaluations provide better control on a vehicle's driving conditions and most external factors. Thus, consistency and repeatability are improved and back-to-back comparative tests can be performed thereby reducing the experimental duration [9]. However, conventional laboratory approaches use a single stimulus (the test vehicle's sound) therefore they can lack the appropriate contextual information.

Using a more immersive simulation has the advantages of both conventional approaches. It provides an appropriate context by simulating an environment for pedestrian – vehicle interaction using sounds, visuals, and/or vibrations. At the same time, the experimental conditions are fully controlled by the researcher. Therefore, this study used an Exterior Sound Simulator inside a laboratory to create both audio and visual stimuli of an electric car moving in a town.

2.2 Exterior Sound Simulator

Exterior Sound Simulator (ESS) is a software tool by Brüel and Kjær that can simulate visual and audio stimuli of an electric vehicle moving in a town and carrying out different manoeuvres, as it would be seen and heard by a pedestrian [10]. ESS is an extended version of 'NVH vehicle simulator' [11]. Evaluations of a vehicle's sound can be performed where a participant is exposed to the visual and audio stimuli synthesized by the simulator in a controlled laboratory. This simulated environment provides a more realistic context for exterior sound evaluations.

ESS has an in-built model representative of a typical UK town. This virtual town includes various places where a pedestrian-vehicle interaction is most likely to occur, such as: car parks, pedestrian crossings, traffic lights, roundabouts, bus stops, streets, and market areas. Figure 1 shows some visual scenarios available in ESS. The scenario chosen for this study was a pedestrian arriving at a crossroad with no traffic lights and waiting there while a car passes the perpendicular road at a constant speed of 4.47 ms^{-1} (10 mph) (See figure 3). This scenario was chosen because previous research identified it among the most common scenarios for pedestrian-electric vehicle interactions that are critical to a pedestrian's safety [2, 12].

Figure 1 – Visual scenarios in Exterior Sound Simulator

2.3 Choice of Measures

This study measured the time when a vehicle is detected for assessing the exterior sounds for pedestrians' safety in line with recent research involving vehicles that are harder to hear [2, 13].

In addition to measuring the detection time, this study conducted emotional evaluations of a vehicle's exterior sound quality. Bisping proposed that emotional evaluations are fundamental to the perception of interior car sound quality [6, 7]. He suggested 'pleasantness' and 'powerfulness' forms a two-dimensional perceptual space for the evaluation of car interior sound quality. Powerful and pleasant have also been used successfully to evaluate time varying exterior sounds [14]. These perceptual dimensions convey impressions of the vehicle from listening to its sound [8]. Most sound quality practitioners have also used two underlying dimensions of emotional evaluation - where one dimension describes the strength or the power aspect of the vehicle and the other describes the comfort related aspects of the vehicle, as perceived from its sounds [8]. For this study '**powerful**' and '**pleasant**' were used as the two dimensions to evaluate the impressions of the vehicle from listening to its exterior sounds.

3. EXPERIMENTS

3.1 Aim

This study was conducted as part of a doctoral research project aimed at improving methods for evaluating electric vehicles' exterior sounds. This study aimed to develop appropriate methods for detecting and emotionally evaluating an electric car's exterior sounds in a simulated environment of a town's crossroad, as created by ESS.

Specifically, this study aimed to test the application of laboratory simulation by ESS for evaluating vehicles' exterior sounds, by comparing participants' detection time, and their emotional evaluation of powerfulness and pleasantness of the target vehicle.

3.2 Participants

The data for analysis was obtained from 31 participants, 19 males – 12 females with the mode age group of 26-35 years. Participants comprised of staff and students from the University of Warwick.

3.3 Evaluation Environment

Experiments were conducted using ESS inside a sound room located at WMG, at the University of Warwick. The sound room is a closed room with three screens and eight floor speakers arranged in a regular octagon. Figure 2 shows the floor plan of the sound room. A participant was seated on a chair at the centre of this octagon, equidistant from each floor speaker. All speakers were calibrated at the listening position at the centre of the floor speaker arrangement. The visuals synthesized by ESS were projected on screens and the sounds were played through the speakers.

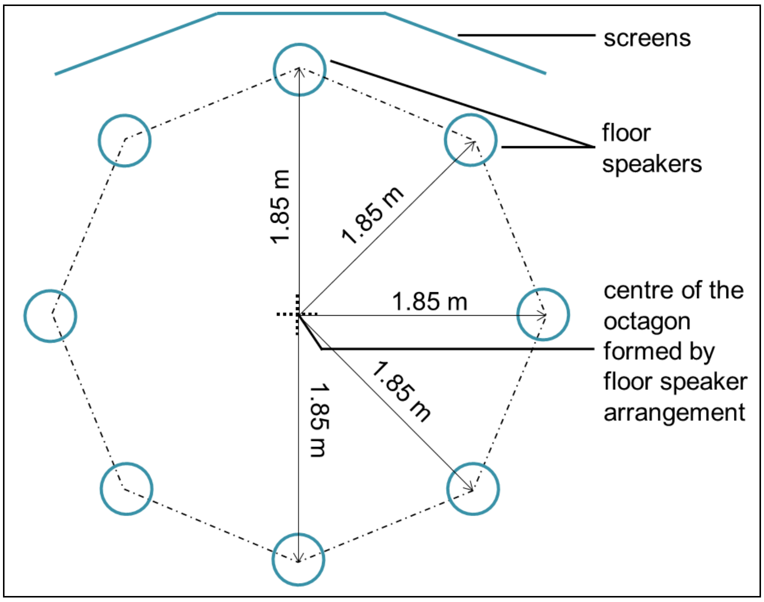


Figure 2 – Layout of the sound room used for experiments

3.4 Stimuli

Every participant was exposed to 30 experimental conditions each involving a different combination of auditory and visual stimuli.

3.4.1 Visual Stimuli

The visual stimuli are described below as a combination of a virtual town location (crossroad), the pedestrian's manoeuvre, and the target vehicle's manoeuvre.

Virtual town location: The participant was exposed to a straight road with a crossroad ahead that has no traffic lights (See figure 3).

Pedestrian's manoeuvre: 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 seconds of walking s/he arrived at the crossroad and waited there until the target vehicle passed by (See figure 3). Everything that a participant saw corresponds to the things that the pedestrian would see when carrying out this manoeuvre. 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 crossroad, the participant saw the visuals pause at the crossroad as would be seen by the pedestrian (see figure 4). The view the participant saw was restricted by buildings on either side of the road.

Target vehicle's manoeuvre: An electric car started from a distant off-screen position on the road perpendicular to the pedestrian's pavement which they were currently walking up. It moved at a constant 4.47 ms^{-1} (10 mph) speed. The target car arrived at the crossroads appearing on screen either after 21.4 seconds, 29.7 seconds or 36.6 seconds from the start of the visuals. In visual stimulus 1 (V1) the car approached the crossroad from the pedestrian's left hand side. In visual stimulus 2 (V2), the car approached from the pedestrian's right hand side. Figure 3 shows the layout of both the visual stimuli 1 and 2 together.

3.4.2 Auditory Stimuli

Fifteen different simulated sounds were used as the target car's exterior sounds. An 18 seconds binaural recording made in a quiet parking space was played in a loop as ambience soundscape for every stimulus. The $\mathrm{dB(A)}_{eq}$ of all the target sounds, measured at the pedestrian's end position, were in the range of 48 – 61 dB(A) and that of the ambient sound was 42 dB(A).

Each participant was exposed to 30 such stimuli where the ambient sound and the 15 target sounds were played once each with V1 and V2.

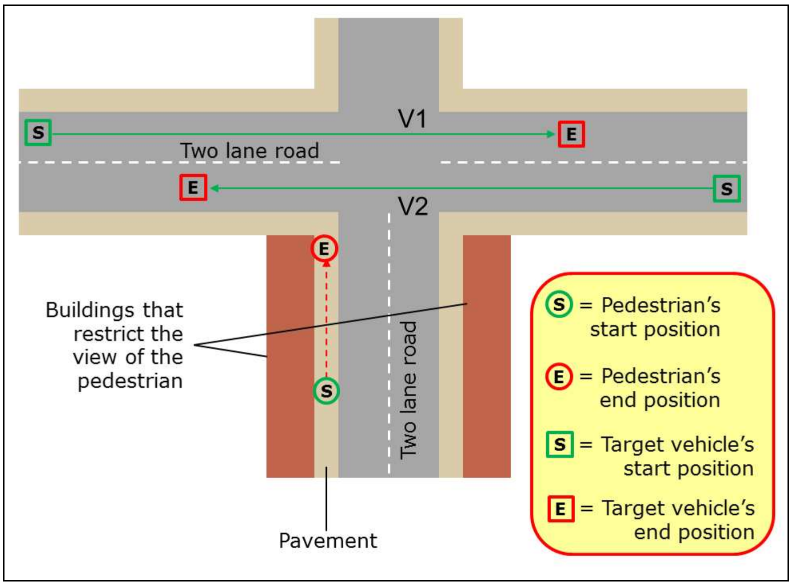


Figure 3 - Layout of the experimental scenario within the virtual town. Red dotted lines indicate a pedestrian's path as experienced by a participant. Green solid lines indicate target vehicle's path for visual stimulus 1 and visual stimuli 2.

Figure 4 – The experimental set-up

3.5 Measures

3.5.1 Detection

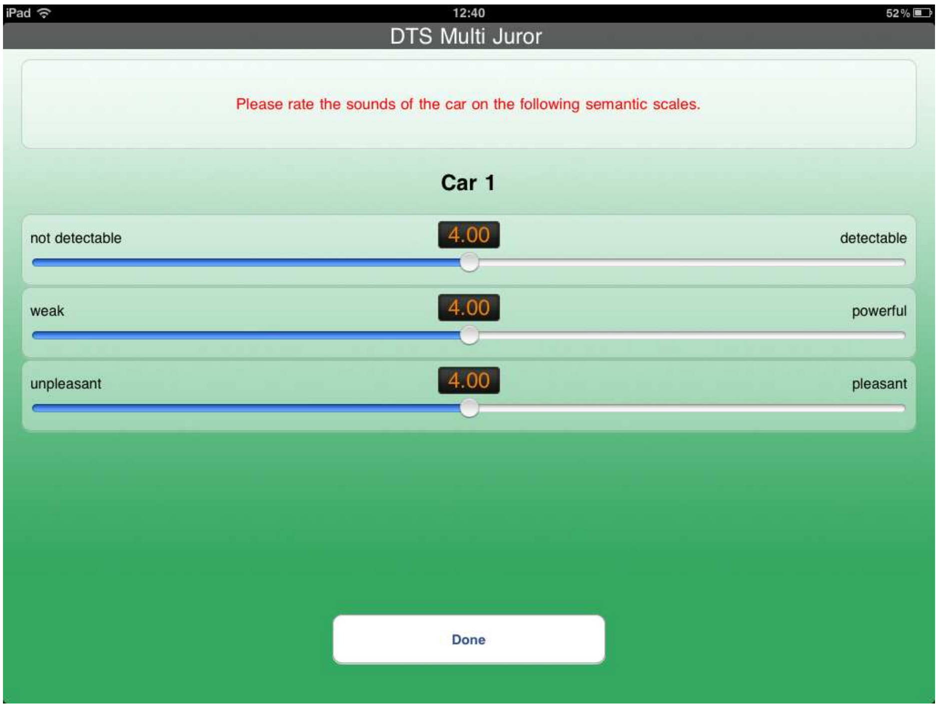
Participants were asked to indicate as soon as they detected a car, visually or aurally, by pressing a scale on an interface (See figure 5). The measure used was '**detection time**' which is defined here as the time in seconds taken by the target car to appear on screen from the instant it was detected by the participant. It was calculated by subtracting the time when the participant pressed the scale from the time the car appeared on screen.

3.5.2 Emotional Evaluation

This study measured the attributes '**powerful**' and '**pleasant**' which are independent dimensions. Therefore it was necessary that the scale used for data collection provides an independent measurement for every attribute. The scale must also provide a relative rating so that the sounds being evaluated can be compared with each other and also the responses from different participants can be compared. Furthermore, the data collection technique must provide interval level data to perform further statistical analysis. A 7-point semantic differential scale is a validated and most widely used scale for sound quality research [15]. It also facilitates using the ratings obtained from the scale as interval level data [15]. Therefore, a 7-point semantic differential scale was used for measuring the semantics - powerful and pleasant.

3.5.3 Method of Data Collection

The participant was given an iPad that had a touch screen evaluation interface developed as part of the ESS. Figure 5 shows the evaluation interface used for this study. The participant was instructed to first press the detection scale (the first scale in the interface) by moving the centre button of the slider as soon as s/he heard or saw a vehicle approaching. Participants were instructed to press the detection scale again in case they made a wrong detection earlier, say, confused the vehicle sound with the ambient sound. The interface came with a facility to record the time of every instance a participant interacted with a scale. The detection time was calculated from the time recorded when the detection scale was last pressed. After detection, s/he was instructed to rate the impressions of the vehicle from listening to its sounds on powerful and pleasant attributes by sliding the respective semantic scales to a value from 1 to 7 using the centre button. ESS has an inbuilt facility to import the data collected from the evaluation interface and store it in an excel sheet. The data containing the time of interaction with every scale and the subjective rating value on each scale was successfully stored at the end of the experiment.



Please rate the sounds of the car on the following semantic scales.

Car 1

not detectable 4.00 detectable

weak 4.00 powerful

unpleasant 4.00 pleasant

Figure 5 − Evaluation interface

3.6 Experimental Design

A repeated-measures design was selected for this study because it required fewer number of participants compared to a between-subjects design [16]. This design also eliminated the requirement of having equivalent groups [16]. The presentation order of the stimuli for each participant was randomised using the ‘balanced Latin square’ method to control for sequence effects [16]. The arrival time, i.e. the time when the car appeared on screen, was randomised using complete counterbalancing for each target sound both across and within participants. Altering 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.

3.7 Procedure

The experiments were performed with one participant at a time. The participant sat at the centre of the sound room and was briefed about the experiment. Participants were instructed that this experiment aimed at finding the rate of detection of the target sounds without considering the recognition of the sounds as emanating from a car. Therefore, five second clips of all 15 sounds were played before the start of experiment to make the participant aware of the variety of sounds used for this experiment. This was also done to ensure that the participants made a relative rating of the sounds. Ambient sound was also played so that a participant did not confuse this sound with the target car's sound. Following this, the experiment began and the stimuli were presented in a pre-determined order obtained from latin square method. The participant detected and evaluated the car's sounds on the semantic scales for each experimental condition. At the end of the experiment participants were thanked and debriefed. An optional feedback form was kept in the sound room. The whole study lasted about 40 minutes.

3.8 Results

Table 1 shows the combined means for sounds 1 to 15 and mean dB(A)$_{eq}$ recorded at the pedestrian's position when the car, approaching from left and right, was directly in front of the pedestrian. The combined means were obtained by calculating the mean scores of the 30 stimuli for all participants and then taking the mean score of each sound for left and right direction of the car's approach.

Table 1 – Combined means of the target sounds

Sound	powerfulness	pleasantness	detection time	Sound pressure level (dB(A)$_{max}$)
1	3.92	2.98	7.61	55
2	3.38	4.52	6.91	54
3	4.58	4.23	15.09	55
4	3.4	3.65	1.6	48
5	4.58	3.38	17.6	61
6	3.33	4.93	**14.99**	**52**
7	3.8	2.55	10.01	55
8	3.6	3.95	8.33	53
9	2.83	4.73	11.44	51
10	4.17	3.85	3.04	51
11	3.42	4.35	6.08	52
12	5.28	1.97	32.08	60
13	5.3	2.88	**5.52**	**57**
14	5.1	3.97	12.43	58
15	3.97	3.5	12.51	52

It is observed that sounds with similar detection times, sound 3, 6, 14 and 15, were evaluated differently in terms of powerfulness and pleasantness. Another observation is that dB(A)$_{eq}$ is not always correlated to detection of sounds. For example, sound 13 was detected much slower than sounds 1 to 3, 6 to 9, 11, and 15, but it had higher dB(A)$_{eq}$ than these sounds. Sound 6 had among the lowest dB(A)$_{eq}$ of the other sounds, but it was detected faster than all sounds except sounds 5 and 12.

Pearson's correlation coefficients were calculated for the three measures. Powerfulness score was found to be significantly correlated to the pleasantness score, r= -.613, p<.05. However, detection time was not significantly correlated to either powerfulness, r= .447, p>.05 or to pleasantness, r= -.356, p>.05. Detection time and emotional evaluations do not have a strong correlation which hints that detection time and the emotional evaluation are likely to be independent measures. Thus, sounds with similar detection time could be evaluated differently in the emotional dimensions. This shows that detection time used to assess pedestrians' safety, and emotional evaluations that influence impressions of the vehicle brand are competing issues for future electric vehicle sounds.

Participants' feedback and an observation of the way participants interacted with the evaluation interface were used to learn more about the evaluation methods used in this study. All participants reported enjoying the experiments. Only seven participants gave written feedback for improvement of the experimental methodology, others gave some verbal feedback. Many participants asked for clarification of the semantics powerful and pleasant at the beginning of the experiment. This experiment indicates that detecting vehicles can be a complex task. Many participants found the detection task difficult as they got confused with the background sound; hence they pressed the scale multiple times. Some participants suggested they would find the task of evaluating the detectability of sounds subjectively on a 7-point scale easier than sliding a scale to indicate their exact detection time. Some participants commented that many sounds used in this experiment sounded artificial and even though they could detect these sounds during the actual experiment, they would not be able to recognise these sounds as a vehicle sound in real life.

4. CONCLUSIONS

This study showed that sounds of an electric vehicle may be detected faster than other vehicle sounds and alert a pedestrian of the electric vehicle's approach. However, these sounds may result in negative perceptions of the vehicle. This study has highlighted the competing issues of safety and vehicle brand for the exterior sounds of electric vehicles. It is also important to ensure that the new sounds have an overall positive or neutral effect on urban soundscapes. The selection criteria of these sounds should be a trade-off between safety, brand, and soundscapes.

It is also observed that traditional metrics such as A-weighted sound pressure level do not always relate to the detection of sounds. Thus, pass-by measurements of sound pressure levels may not be sufficient for assessing vehicle exterior sounds. Subjective evaluations need to be conducted to assess the safety risk of the vehicles as well as to evaluate the vehicle brand and effect on soundscapes.

This study was conducted as part of a bigger research project aimed at improving methods for evaluating vehicles' exterior sounds. The experiments in this study used a simple scenario of a pedestrian – vehicle interaction. Laboratory simulation, a new approach for evaluating exterior automotive sounds, was successfully implemented using the Exterior Sound Simulator. The simulator provided a more realistic context for evaluations using visuals and sounds compared to conventional laboratory listening methods. At the same time the researcher had full control on experimental conditions, which is not possible in conventional on-road evaluations. The simulator also provided options to manipulate certain factors such as the direction of approach and the arrival time of the target car while controlling all other factors. The evaluation interface available with the simulator was successfully used to collect data using bipolar semantic scales. The simulator also provides options to create multiple visual scenarios to compare vehicles' sounds under different ambience and traffic. There is further option where a participant can freely walk in the virtual town and the stimuli changes in real time. These options would be explored in future studies. This study indicates that simulation is a useful means to complete a full evaluation of potential electric vehicle sounds against all the competing issues.

Participatory feedback and results suggest minor improvements in the presented study. Firstly, studies could be conducted to evaluate pedestrians' safety using subjective evaluations of perceived safety as well as measurements of the detection time of electric vehicles' exterior sounds. Secondly, methods need to be developed to evaluate these sounds in more scenarios of pedestrian – vehicle interactions in the presence of different ambient sounds, additional vehicles, and other sound sources. Recognition of sounds as emanating from a vehicle also needs testing. Future studies will be conducted to address these opportunities.

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