Pedestrian crossing behaviour in front of electric vehicles emitting synthetic sounds: A virtual reality experiment

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ABSTRACT

The increasing adoption of electric vehicles (EVs), which operate more quietly than internal combustion engine vehicles, raises concerns about their detectability, particularly for visually impaired road users. Regulations mandate exterior sound signals for EVs, ensuring minimum sound pressure levels at low speeds. However, these signals are often used in already noisy urban environments, creating a challenge: enhancing detectability without adding excessive noise pollution. This study explores the use of synthetic exterior sounds that balance high noticeability with low annoyance. An audiovisual experiment was conducted with 20 participants in 15 virtual reality scenarios featuring an EV passing in front of them. Different sound signals, including pure, intermittent, and complex tones at varying frequencies, were tested alongside two baseline cases (a diesel engine and tyre noise alone, i.e., no synthetic sound added). Participants rated sounds for annoyance, noticeability, and informativeness using 11-point ICBEN scales. Trigger measurements provided additional insights into their willingness to cross in front of the EV. The results highlight optimal sound characteristics for EVs, offering guidance on improving pedestrian safety while minimising noise pollution. By refining exterior sound design, this research contributes to the development of effective and user-friendly EV sound standards, ensuring safer and more inclusive urban environments.

1. INTRODUCTION

According to the World Health Organization [1], pedestrians account for approximately 21% of the 1.19 million global traffic fatalities annually, which is equivalent to roughly 250,000 deaths per year. A substantial proportion of these incidents occur during road crossing events [2]. Contributing factors include the misjudgment of crossing time, limited visibility, and visual obstructions that hinder the timely detection of approaching vehicles [3–5]. To address these challenges, augmenting auditory

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cues emitted by vehicles has been proposed, particularly in the context of electric vehicles (EVs), which are generally quieter than their internal combustion counterparts, and automated vehicles employing external Human–Machine Interfaces (eHMIs) [6–10].

The primary function of synthetic exterior vehicle sounds is to enhance the detectability of EVs by vulnerable road users (VRUs), particularly pedestrians, including individuals with visual or auditory impairments. Lai *et al.* [11] demonstrated that sound parameters such as intensity, temporal structure, and modulation characteristics significantly influence pedestrian detection latency.

In addition to noticeability, noise annoyance is a crucial factor in the design of synthetic vehicle sounds. Excessive or poorly designed sounds can contribute to environmental noise pollution in already noisy urban environments, and hence user discomfort. Prior research indicates that perceived annoyance is affected by the spectral composition, duration, and temporal repetition of auditory signals [11–13]. For instance, intermittent sounds are often judged to be more intrusive than continuous ones [14], and high-frequency components tend to be more irritating than lower-frequency sounds [15]. As such, optimal sound design should aim to maximise detectability at low vehicle speeds while minimising acoustic disturbance to urban populations [16, 17].

A further objective in EV sound design is to convey meaningful information on vehicle behaviour, such as acceleration or deceleration, to improve situational awareness among VRUs. Informative auditory cues support improved judgement of vehicle proximity and trajectory [18]. Complex acoustic signals that incorporate pitch variation and modulation patterns have been shown to enhance the informativeness of EV sounds while maintaining social acceptability [11].

1.1. Aim of Study

This preliminary study investigates the performance of various EV exterior sounds in terms of noticeability, information provided to the pedestrian, and noise annoyance. For this purpose, a virtual reality (VR) experiment was conducted in which participants rated different scenarios according to those criteria. In addition, participants were asked to press a key when they felt safe to cross the road in each scenario. This trigger press data offers additional insights into their crossing behaviour. The findings of this study aim to inform the design of exterior auditory signals for EVs that optimise both detectability and acceptability for pedestrians in urban environments. This manuscript elaborates on the preliminary study focused on perceived noise annoyance [19].

Section 2 explains the methodology used, including the synthetic sounds considered and the VR experiment. The results of this study are presented and discussed in Section 3, while the conclusions and recommendations for future work are collected in Section 4. Moreover, supplementary material is provided in Section 4.

2. METHOD

2.1. Synthetic Sounds

Table 1 lists the 15 synthetic sounds that were used in the study, which can be categorised into four groups: (1) continuous pure tones at a single frequency, (2) intermittent pure tones with alternating 500-ms on/off intervals, (3) combined tones at a principal frequency plus secondary tones at frequencies ±90 Hz from the principal tone, and (4) double beeps at 1800–1900 Hz. The double beeps consisted of a 240 ms beep, a 10 ms pause, a 240 ms beep, and a 1000 ms pause. Furthermore, a diesel engine sound[2] was included as a reference case for internal combustion engine vehicles due to its distinctive and more familiar noise. To evaluate the sound profile of a quiet electric or automated

[2] https://youtu.be/watch?v=2Y33bTlAA-E

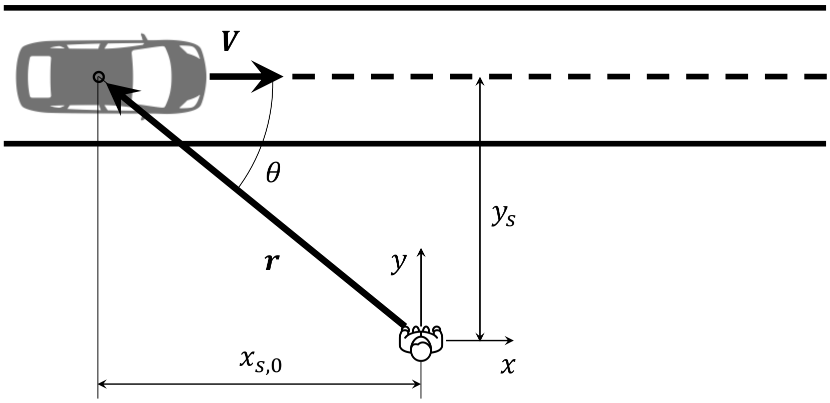

Figure 1: Scheme of the considered sound source and observer geometry [6].

vehicle, a stimulus containing only tyre noise[3] (i.e., without any synthetic sound added) was also incorporated. All evaluated sound stimuli were combined with a background noise recording of a quiet street[4]. These sounds were previously used in an online crowdsourcing listening experiment (i.e., without VR) reported in [6].

This study considers a relatively simple sound source and observer geometry in a two-dimensional arrangement, i.e., the observer and the sound source are on the same plane; see Figure 1. For simplicity, the sound source is considered a point source with a constant velocity of 30 km/h (i.e., 8.33 m/s) in the positive x direction $\boldsymbol{V} = (V_x, 0)$, i.e., the source has a linear trajectory along a straight line at a distance y_s of 3 m from the observer, see Figure 1. The initial position of the sound source at is defined at $\boldsymbol{r}(0) = (x_{s,0}, y_s)$ and at a general instant τ_e as $\boldsymbol{r}(\tau_e) = (x_{s,0} + V_x\tau_e, y_s)$. For the purpose of sound signal generation, the source moved from $x_{s,0} = -60$ m to $x_s = 60$ m. Therefore, a signal length of 14.4 s was generated and used in each case. All sound stimuli (except for the case with only tyre noise) had an equivalent A-weighted sound pressure level ($L_{p,A,eq}$) of 65 dBA in the observer position. The VR environment employed enables binaural rendering of the sound, accounting for the relative position of the sound source, the orientation of the participant's head, and the Doppler shift due to the relative motion of the sound source. The reflection of sound on the ground or any reflecting surfaces (such as buildings) was neglected for simplicity.

Two exemplary spectrograms are provided in Figure 2 for test cases No. 12 (Combined tone, continuous, 2000 Hz) and 13 (Double beeps). For the first case, the tone at said frequency (plus the two secondary tones at ±90 Hz) is clearly identified as the primary sound source. For the double beeps, the transient nature of this signal is also clearly observed. In both cases, broadband noise is visible, especially below 3000 Hz, mostly due to the simulated noise of the tyres on the asphalt and background noise. The motion of the source can also be observed in Figure 2 in the slight Doppler frequency shift and in the higher levels observed when the source is closer to the observer (roughly around half the recording time). The short vertical lines centred around 4000 Hz between 6 s and 13 s correspond to birds tweeting within the background noise recording.

2.2. Virtual Reality Experiment

A total of 20 participants (13 males and 7 females) with an average age of 29.35 years (SD = 4.80 years) from Eindhoven University of Technology and Delft University of Technology in the Netherlands participated in the experiment. In both universities, the experiment was conducted in

[3] https://youtu.be/watch?v=X0wpizkkH_Q

[4] https://youtu.be/watch?v=6C-W_7BZBxQ

Table 1: Synthetic sounds used in the experiment.

No.	Characteristics
1	Pure tone, continuous, 350 Hz
2	Pure tone, continuous, 500 Hz
3	Pure tone, continuous, 1000 Hz
4	Pure tone, continuous, 2000 Hz
5	Pure tone, intermittent (13 × [500 ms emitting, 500 ms not emitting]), 350 Hz
6	Pure tone, intermittent (13 × [500 ms emitting, 500 ms not emitting]), 500 Hz
7	Pure tone, intermittent (13 × [500 ms emitting, 500 ms not emitting]), 1000 Hz
8	Pure tone, intermittent (13 × [500 ms emitting, 500 ms not emitting]), 2000 Hz
9	Combined tone, continuous, 350 Hz (±90 Hz)
10	Combined tone, continuous, 500 Hz (±90 Hz)
11	Combined tone, continuous, 1000 Hz (±90 Hz)
12	Combined tone, continuous, 2000 Hz (±90 Hz)
13	Double beeps (8 × [240 ms beep, 10 ms pause, 240 ms beep, 1000 ms pause]), 1800–1900 Hz
14	Diesel engine
15	Tyres on asphalt

a quiet environment and with the same equipment. In particular, the sessions at Delft University of Technology were performed in the Psychoacoustic Listening Laboratory (PALILA) [20], see Figure 4. The participants represented a diverse set of nationalities, including Dutch (3), Indian (3), Chinese (2), Romanian (2), Italian (2), and one each from South Africa, Greece, Ghana, Peru, Indonesia, USA, Poland, and Bulgaria. The study was approved by the Ethics Review Boards of both universities, and the participants gave their informed consent to use their data.

The VR setup was developed using Unity 2022.3.5f1 (see Section 4). Participants wore a Meta Quest 3 head-mounted display (HMD), which was connected via cable to a Lenovo Legion 81YT laptop featuring an Intel Core i7-10750H 2.60GHz CPU, 32.0 GB RAM and an NVIDIA GeForce RTX 2080 Super graphics card. The audio stimuli were reproduced using Sennheiser HD 560S headphones. Figure 3 shows the view of the participant. During each trial, the car emitting synthetic sound drove by the participant standing on the kerb of the road. The moment of passing was at 8.7 s. The street in the VR environment was empty, with no other traffic or pedestrians. Each trial lasted for 11 s. The ambient noise (measured as $L_{p,A,eq}$) during the sessions in Eindhoven was 35.7 dBA, while in PALILA it was 13.4 dBA, which is considerably below the levels of the stimuli reproduced and therefore it is not expected to affect sound perception.

At the beginning of the experiment, participants completed a consent form and provided demographic details such as gender, age, and nationality. The floor level was calibrated by the experimenter using the HMD, after which the participants were then asked to stand at a predefined location within the respective laboratory. The participants were then handed the HMD to establish their virtual boundary, ensuring an accurate recording of the participant's height and spatial location within the VR system. The HMD was then connected to the laptop via Quest Link. The Unity application was launched, and the experiment began after activating the play button within Unity.

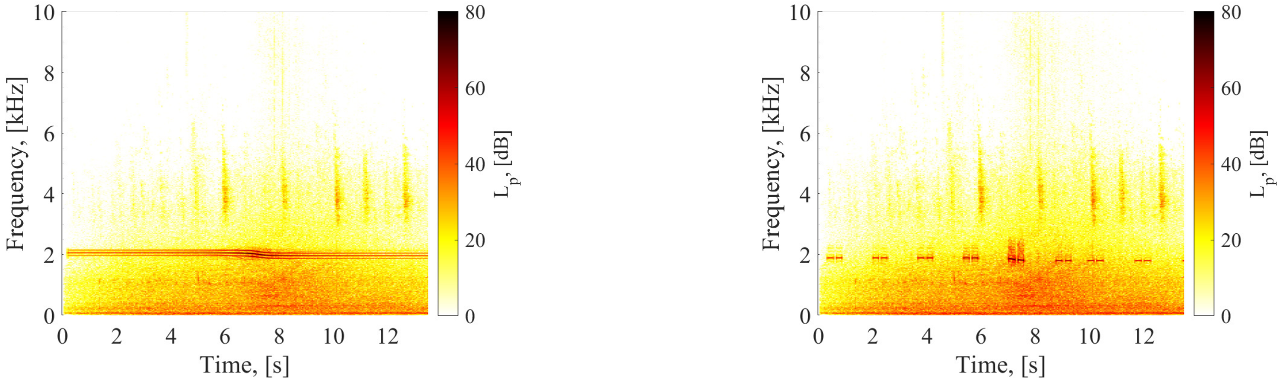

Figure 2: Spectrograms for the sound stimuli: (Left) Combined tone, continuous, 2000 Hz (case No. 12) and (Right) Double beeps (case No. 13).

Figure 3: (Left) Example view of participant in VR environment. (Right) VR experiment at Eindhoven University of Technology.

The participants received instructions at the beginning of the experiment inside the VR, which were as follows: "*Imagine that you are a pedestrian standing on the side of the road. You will experience 15 audiovisual scenarios of a vehicle driving by you. During each scenario, press and HOLD the trigger when you feel safe to cross the road in front of the car. You can release the button and then press it again multiple times during the scenario. After each scenario, you will be asked to answer a few questions. Press the button to proceed. The experiment will start with a training scenario to familiarise yourself with the environment. During this scenario, press and HOLD the trigger when you feel safe crossing the road in front of the car. You can release the button and then press it again multiple times during the scenario. Press the button to start.*".

A preliminary training trial was conducted to allow participants to acclimate to the VR setup and practice the response task. Subsequently, the participants completed 15 experimental trials presented in random order to mitigate learning effects. During these trials, participants were asked to indicate their willingness to cross the road in front of the vehicle by following the instruction: "*Start by HOLDING the trigger button. Release the trigger button when it becomes unsafe to cross; press it again when safe to cross*". Following each trial, including the test scenario, the participants were presented with three questions using 11-point slider scales (from 0 to 10) displayed within the VR environment. The question assessed noticeability ("*The vehicle sound was easy to notice (0 = not easy to notice, 10 = easy to notice)*"), informativeness ("*The sound gave me enough information to realise that a vehicle was approaching (0 = not enough information, 10 = enough information)*") and annoyance ("*The vehicle sound was annoying (0 = not annoying, 10 = extremely annoying)*"). In addition to the trigger press data and the answers to the three questions, the HMD also recorded the angle of yaw of the point of view of the participants during the duration of each scenario.

Upon completion of all trials, the HMD was removed and the participants completed a post-experiment questionnaire (see Section 4). Participants rated their experience on several dimensions

Figure 4: Example of a VR experiment in PALILA at Delft University of Technology. In practice, participants stood up during the experiment.

using 10-point scales (1 = not at all, 10 = extremely). On average, they reported relatively low levels of stress (M = 3.35, SD = 1.87) and anxiety (M = 2.90, SD = 1.86), while the realism of the experiment was rated relatively high (M = 6.50, SD = 1.32), and the overall experience received a positive evaluation (M = 7.80, SD = 1.44). Each experimental session lasted approximately 15 minutes, on average. Following the session, the participants received a 10 € voucher as compensation for their time and participation.

2.3. Data Analysis

3.1 Computation of Yaw Angle of Head Movement

To investigate whether the type of synthetic sound affected the head movement of the participants, the yaw angle from multiple rotation measurements was computed. First, unit quaternions were averaged using an eigenvalue-based method introduced by Markley et al. [21], and then the result was converted into Euler angles. Given a set of n unit quaternions $\{\mathbf{q}_1, \mathbf{q}_2, \ldots, \mathbf{q}_n\}$, where each $\mathbf{q}_i = [w_i, x_i, y_i, z_i]$, all quaternions were normalised and ensured that they lie in the same hemisphere (i.e., have a positive dot product with a reference quaternion). This prevented antipodal quaternions from cancelling each other. A 4×4 symmetric accumulator matrix was then formed:

$$A = \frac{1}{n} \sum_{i=1}^{n} \mathbf{q}_i \mathbf{q}_i^T, \tag{1}$$

where each $\mathbf{q}_i$ was treated as a column vector. The matrix A is symmetric and positive semidefinite.

The average quaternion $\bar{\mathbf{q}}$ was estimated as the eigenvector corresponding to the largest eigenvalue of A:

$$\bar{\mathbf{q}} = \mathrm{eig}_{\max}(A) \tag{2}$$

This method yielded a statistically optimal average under the assumption of small perturbations about a mean rotation. After computing the average quaternion $\bar{\mathbf{q}} = [w, x, y, z]$, it was converted into Euler angles (roll, pitch, yaw) using standard trigonometric relations. The yaw angle ψ, representing rotation about the vertical (z) axis, was extracted as:

$$\psi = \tan^{-1}\left(\frac{2(wz + xy)}{1 - 2(y^2 + z^2)}\right) \tag{3}$$

This approach provides a robust estimate of the yaw angle at each timestamp, allowing the analysis of the horizontal viewing direction between multiple samples or participants.

3.2 Composite Score for Noticeability, Informativeness, and Annoyance

To summarise the participant ratings in the three perceptual dimensions analysed of *Noticeability* (N_s), *Informativeness* (I_s), and *Annoyance* (A_s), the Sauro and Kindlund's single usability measure (SUM) approach [22] was employed, ensuring an equal contribution of each dimension after normalisation[5]. A composite score was computed by first inverting annoyance, where Max is the maximum rating (e.g., 10):

$$A'_s = \text{Max} - A_s \tag{4}$$

It was then normalized via a Z-score:

$$z(X_s) = \frac{X_s - \mu_X}{\sigma_X}, \quad X \in \{N_s, I_s, A'_s\} \tag{5}$$

And, then the composite score was computed:

$$\text{Composite}_s = \frac{1}{3}\left(z(N_s) + z(I_s) + z(A'_s)\right) \tag{6}$$

3. RESULTS

Figure 5 shows the trigger press data (participant indicating that they felt safe to cross the road) for all stimuli. The 1€ filter [23] was applied to the data in this graph and in Figure 6 (frequency = 120, minimum cut-off = 0.1, β = 0.1). A large decrease in trigger press was observed starting at about 6 s for all stimuli. This decrease is smaller for the stimulus with only the sound of tyres on the asphalt, showing that the case without added synthetic sound provides less information on pedestrian safety. During 6–10 s, there are notable significant differences within the stimuli, especially the pure and intermittent pure tones, compared to the 'Diesel' sound that serves as a baseline.

Figure 6 shows how participants moved their heads for all the sound stimuli. Pure continuous tones of 350 and 500 Hz are associated with the noticeable movement of the head in relation to the passing moment, where the participants looked left (denoted by the positive yaw values) during 4–5 s and then right (denoted by the positive yaw values) during 6–8 s. There were no significant ($p < 0.001$) differences within the stimuli.

The responses to the three questions are collected in Figure 7 per sound stimulus. In terms of noticeability and informativeness, the diesel engine and the pure tones at 2000 Hz (continuous and intermittent) appear to score the highest mean values. However, as reported by Bazilinskyy et al., stimuli with a higher tonal frequency (2000 Hz) are perceived as more annoying for all types of tonal sounds (pure, combined and intermittent) [19]. Interestingly, diesel engine sound, which represented conventional internal combustion engine vehicles, only causes a relatively low mean annoyance rating of 3.3/10, scoring the third lowest value after the case with only the tyre noise (i.e., without any synthetic sound added) and the combined tone at 350 Hz. This is likely to be due to the intrinsic semantic meaning of a diesel engine sound, which is familiar to most people and easily associated with a moving vehicle. In general, intermittent tones have relatively lower noise annoyance ratings but slightly higher noticeability, and information is provided. Therefore, their use is recommended in comparison to pure or combined tones. As expected, the stimulus with only the tyre noise is perceived as the least annoying, but it also provides the least noticeability and information to pedestrians.

[5] In this study, an equal contribution per dimension was employed, but depending on the main goal, these proportions can be varied.

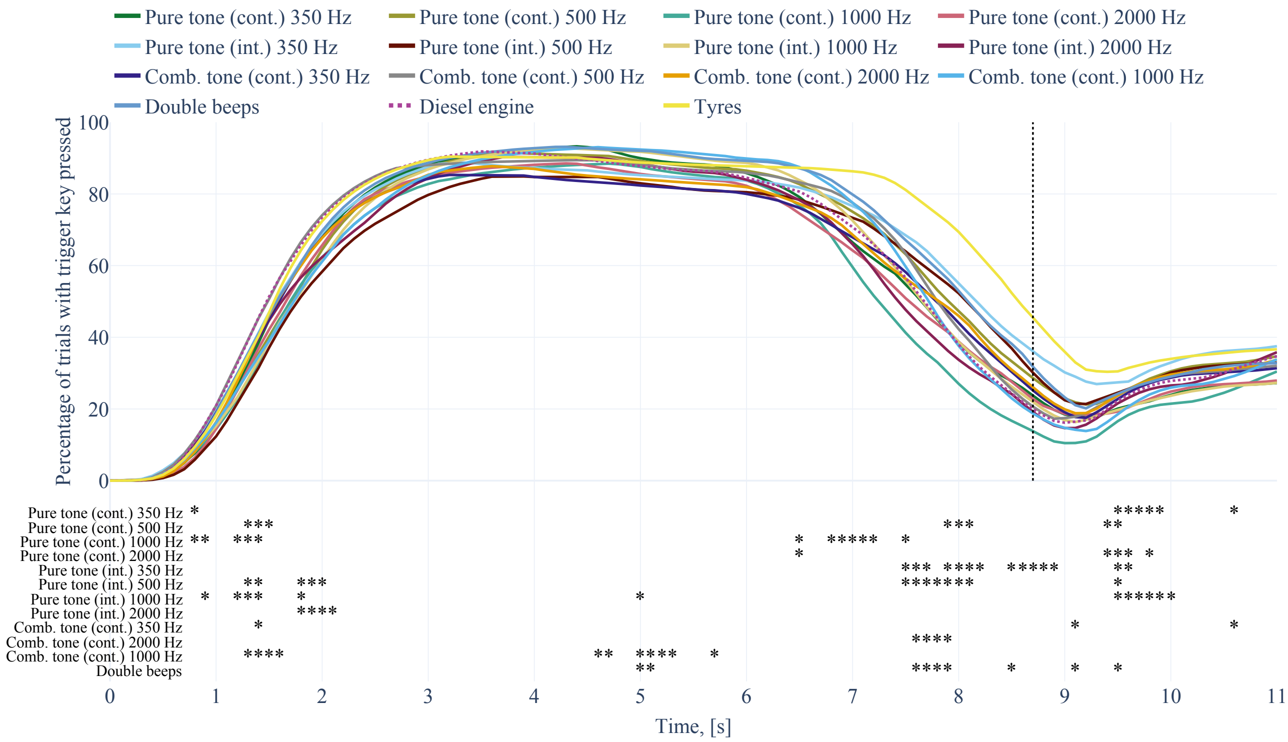

Figure 5: Percentage of the participants who pressed the key (i.e., felt safe to cross in front of the EV) as a function of time for each sound stimulus. The vertical line represents the passing moment. The asterisks at the bottom indicate significant differences with respect to the 'Diesel' sound (shown as dotted line) during 100-ms periods, $p < 0.001$.

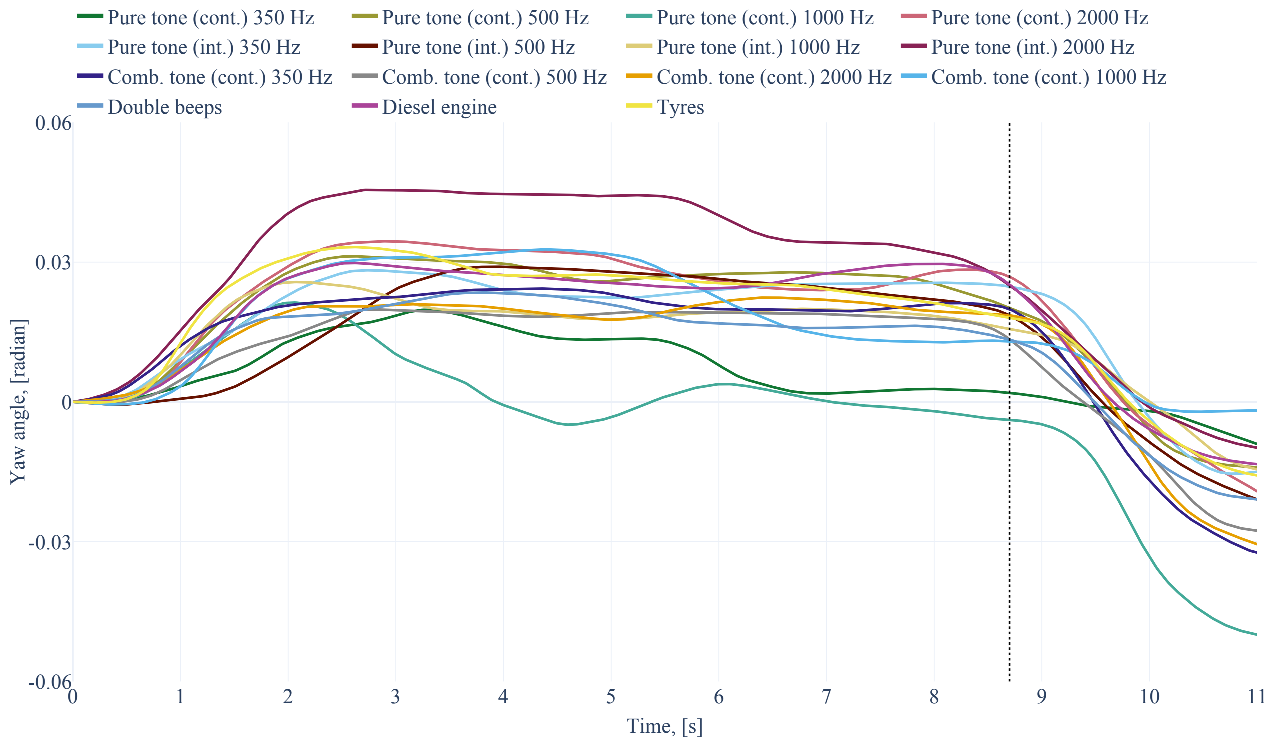

Figure 6: Mean yaw angle of head movement of pedestrians as a function of time for each sound stimulus. The value of 0 denotes participants looking perpendicular to the road, positive values correspond to the left direction (vehicle approach), and negative values show head movement to the right (vehicle departure). The vertical line represents the passing moment.

The composite scores as introduced in Eq. (6) are depicted in Fig. 7 (bottom right). As aforementioned, the diesel engine stimulus appears to provide the best overall performance and scores a mean value of 0.93, which is considerably higher than the rest of the stimuli. The next best-performing sounds are the intermittent pure tones at 350 Hz and 2000 Hz, with a mean score of 0.4. Overall, continuous combined tones seem to perform better than their pure counterparts but not as well as intermittent tones. In contrast, the tyre-only condition (i.e., no added synthetic sound) shows the lowest composite score by a large margin, with a negative value of -1.53, confirming its ineffectiveness to provide pedestrians with clear auditory cues. In general, the composite scores reveal the trade-offs between effectiveness and comfort and underscore the importance of designing EV sounds that are both perceptually informative and emotionally acceptable.

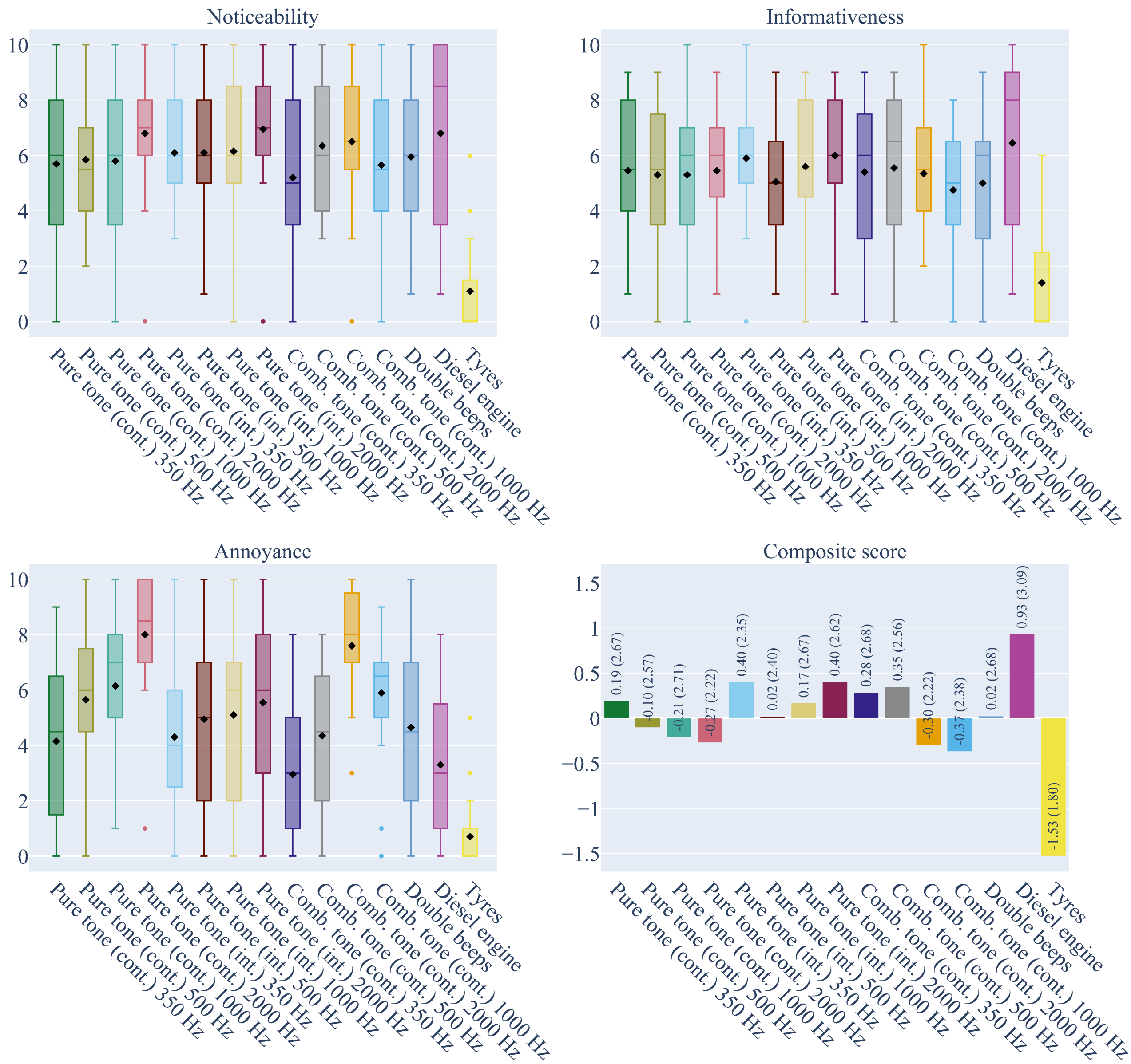

Figure 7: Box plots of the ratings for the questions regarding (top left) noticeability, (top right) informativeness, (bottom left) annoyance, and bar plot for composite score with mean and standard deviation values (bottom right) per sound stimulus. In each box plot, the boxes represent the interquartile ranges, the whiskers extending from the boxes indicate the ± 1.5 times the interquartile range, the median values are represented with horizontal lines, the mean values with black diamond markers, and individual outliers are plotted as dots.

4. DISCUSSION

In this research, 15 synthetic sounds produced by EVs were evaluated within a VR environment involving 20 participants from two universities in the Netherlands. The findings contribute to the exploration of the interaction between EVs and pedestrians. In particular, the use of synthetic sounds was shown to influence pedestrian decision making in road-crossing scenarios, both in terms of objective behavioural indicators (trigger press data and head movement) and subjective perception (noticeability, informativeness and annoyance).

In accordance with the literature [6, 11], participants were more likely to cross safely and confidently when the EV emitted a synthetic sound compared to when there was only noise from the tyres (i.e., no synthetic sound added). This supports a growing body of evidence that indicates that the relative quietness of EVs may pose a safety risk to VRUs, particularly in urban settings where visual distractions or obstructions are common [1, 2].

Importantly, the specific characteristics of synthetic sound had measurable effects on pedestrian crossing behaviour. Intermittent tones at 2000 Hz were rated as highly noticeable and informative, but also more annoying, aligning with findings from psychoacoustic studies on sound sharpness and modulation [11, 15]. This trade-off between functional effectiveness and perceptual comfort remains a challenge in the design of sounds emitted by EVs [6, 12, 17].

In particular, the sound of the diesel engine included as a baseline was rated highly for noticeability and informativeness, but was perceived as less annoying, providing the highest overall performance. This suggests that familiarity plays a crucial role in how pedestrians interpret vehicle sounds. Previous studies have highlighted the role of semantic familiarity in recognising vehicle movement and intention [11, 18], implying that leveraging familiar acoustic cues, such as the sounds of internal combustion engines, can improve perceived safety without increasing discomfort.

The observed patterns of head movement further support the efficacy of certain synthetic sounds. Low-frequency pure tones (e.g., 350–500 Hz) prompted anticipatory lateral head turns, reflecting heightened spatial awareness. These findings align with research showing that well-designed auditory signals can guide attention and support safer decision making during road crossings [8, 9].

Despite the strengths of the VR setup, some limitations must be acknowledged. The participant sample was limited to 20 individuals, primarily university-affiliated, which may reduce the generalisability of the results. Future research should include children, older adults and people with sensory impairments, groups that can rely more heavily on auditory information [3, 5]. It may be beneficial to replicate the study as a crowdsourced experiment with auditory stimuli [6, 24]. Furthermore, real-world variables such as social context, weather, and environmental distractions could influence pedestrian behaviour differently than in a controlled VR setting and should therefore be investigated. Then, the study did not evaluate the use of combined and intermittent tones, which may offer promising trade-offs between noticeability and annoyance. Future work should also explore multimodal approaches, such as combining visual eHMIs with auditory signals, to maximise the clarity and safety of EV interactions with pedestrians [7, 10].

In conclusion, this study provides empirical evidence that the acoustic design of EVs plays a significant role in shaping pedestrian crossing behaviour. Sound characteristics, such as frequency, temporal modulation, and familiarity, influence both perception and action. These findings support a human-centred approach to EV sound design and contribute to the development of evidence-based standards to improve pedestrian safety in increasingly electrified urban environments.

SUPPLEMENTARY MATERIAL

The VR environment, sounds, materials used in the experiment, analysis code, and anonymised raw data can be found at https://doi.org/10.4121/629cae37-76e7-4b14-8693-25c96a263b4b. A maintained version of the code is available at https://github.com/Shaadalam9/sound-ev.

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