On the Influence of AVAS Directivity on Electric Vehicle Speed Perception

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ABSTRACT

Electric vehicles (EVs) typically produce minimal noise at low driving speeds, increasing the risk of accidents for pedestrians and other vulnerable road users. Therefore, regulations require EVs to use acoustic vehicle alerting systems (AVAS) that emit artificial warning sounds. Investigating the human response to these AVAS sounds requires laboratory listening experiments, often based on auralizations. One of the challenges when auralizing electric vehicles is to include AVAS radiation directivity. However, it is currently unknown how this directivity affects the perception of a vehicle passing by and whether an accurate reproduction is necessary for auralizations. We present a study on the influence of AVAS directivity on perceived vehicle speed, comparing different radiation patterns in combination with narrowband and tonal AVAS signals in a paired comparison listening experiment with 31 participants. The results show that AVAS radiation directivity can significantly influence the perception of vehicle pass-by speed, with a tendency for omnidirectional patterns to be perceived slower than more directional patterns. Additionally, most participants consistently rated either the tonal or the narrowband noise AVAS signal as faster throughout most comparisons. This indicates that AVAS signal type can affect vehicle speed perception with a subjective preference between tonal and narrowband noise AVAS.

1. INTRODUCTION

Electric vehicles (EVs) are becoming an integral part of today's urban environments [1]. Compared to combustion engine vehicles, EVs typically radiate less sound at low driving speeds, which can pose a risk for vulnerable road users such as pedestrians, cyclists, or the visually impaired. To reduce this risk, regulations demand the implementation of acoustic vehicle alerting systems (AVAS) that radiate artificial warning sounds below driving speeds of approximately 20 km/h, indicating the vehicle location and driving speed [2, 3]. However, in the EU, these regulations only specify minimum AVAS sound pressure levels, driving speed range of operation and that the signal should cover at least two third-octave bands, have content within or below the 1600 Hz third-octave band and that at least one tone should shift in frequency proportional to vehicle speed by an average of at least 0.8% per 1 km/h. This relatively open specification leaves manufacturers leeway to design vehicle-specific AVAS sounds, which might not only be based on pure warning efficiency but also consider other sound quality-related factors such as brand identity. As a result, currently implemented AVAS sounds vary significantly between manufacturers and vehicle models. This raises the question of how well those AVAS implementations fulfill their primary purpose of alerting vulnerable road users, which might become even more complex for scenarios of multiple cars with different or similar AVAS sounds approaching simultaneously. Additionally, unwanted consequences for the acoustic environment, such as noise annoyance, need to be investigated.

Such research on the perception of electric vehicle sounds requires laboratory listening experiments. For this purpose, we recently introduced the electric vehicle auralization toolbox

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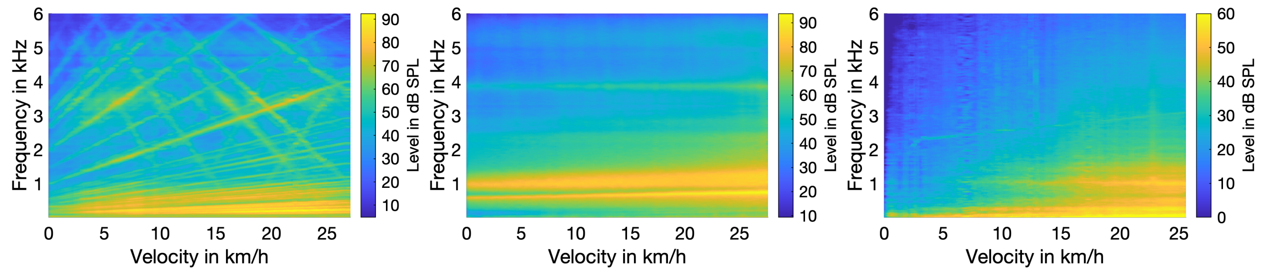
(EVAT) [4], a collection of methods allowing for the auralization of electric vehicle passages with, for example, different AVAS signals, vehicle speeds, or AVAS directivities. In the context of traffic noise auralization, directivity, i.e., the spatial dependency of the sound radiation, is an attribute that might be considered less relevant than other parts of the simulation, not least because estimating the directivity with a high spatial resolution demands elaborate measurements or numerical calculations. In our recent work, we used the boundary element method (BEM) to numerically estimate the AVAS radiation directivity for three different electric vehicles [4]. Even though this approach aimed to reproduce the actual vehicles' directivities as accurately as possible, the auralized vehicle passages showed a mismatch in time structure compared to in-situ measurements, likely caused by a different radiation directivity. During the perceptional validation of the electric vehicle auralization toolbox, we also found that subjects perceived auralized passages faster than the corresponding in-situ recordings. We, therefore, hypothesized that a discrepancy in AVAS directivity could cause a difference in vehicle pass-by speed perception. To our best knowledge, the influence of a moving sound source's radiation directivity on the speed perception of a stationary observer has yet to be investigated. Understanding the perceptual consequences of different AVAS radiation patterns would allow us to improve our auralization methods and contribute to developing more efficient AVAS systems. This study, therefore, aims to close this gap by performing a listening experiment on the perception of electric vehicle pass-by speed for four different AVAS radiation patterns in combination with two different types of AVAS signals. The following sections describe the applied auralization and evaluation methods and present and discuss the experiment results.

2. METHODS

This section gives a general overview of the employed auralization method and presents the evaluated AVAS directivities, the reproduction method, the experiment design, and the recruited group of participants.

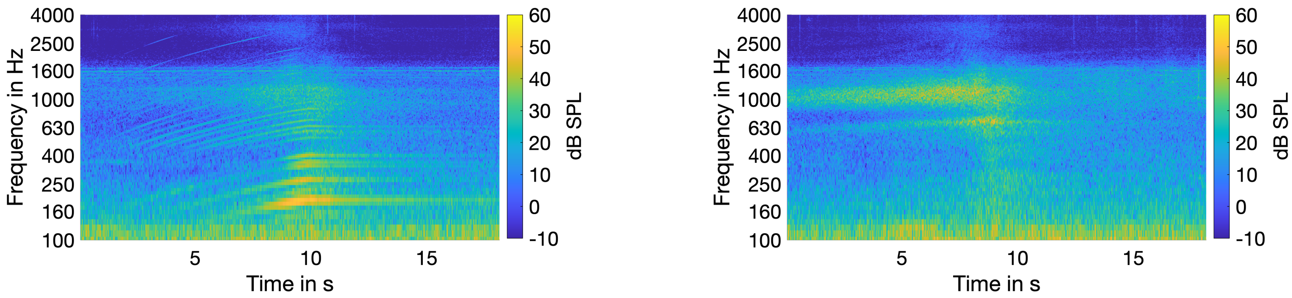
2.1. Auralization

The stimuli used in this paper were generated using the electric vehicle auralization toolbox [4], which consists of different analysis and synthesis methods to create binaural electric vehicle passages with arbitrary velocity profiles based on in-situ measurements of electric vehicles. In the following, we give a high-level overview of the auralization method but ask the reader to refer to [4] for a more detailed description of the auralization method as well as a numerical and perceptional validation. For this study, two different AVAS signals were considered: a tonal AVAS signal based on measurements of a *Volkswagen ID.3 Pro Performance 2021* and a narrowband noise AVAS based on recordings of a *Tesla Model Y 2021*. Both signals are vehicle velocity dependent, as shown in Figure 1a and Figure 1b. To generate AVAS signals with similar characteristics as the measured references, an additive synthesis approach was used for the tonal AVAS, and a subtractive synthesis approach was used for the narrowband noise AVAS as well as for additional tire/road noise, which is, again, based on in-situ measurements as shown in Figure 1c. The synthesized AVAS and tire/road noise source signals are combined with radiation directivities encoded into spherical harmonic expansion coefficients as described in Section 2.2. These directivities then allow for estimating transfer functions from an arbitrary point in space to a receiver position by scaling them with spherical Hankel functions. Using the concept of moving Green's functions, i.e., calculating transfer functions for each discrete point in time and convolving them with the corresponding samples of the source signal, allows source movement with an arbitrary vehicle trajectory. Finally, static binaural signals are obtained by applying head-related transfer functions depending on the incidence angle relative to the receiver position. The resulting binaural AVAS and tire/road noise signals are summed up, and a binaural ambience recording is added to create the impression of an urban environment rather than simulating a vehicle passage in perfect



(a) (b) (c)

Figure 1: Measured velocity spectra for tonal AVAS (a), narrowband noise AVAS (b), and tire/road noise (c).



(a) (b)

Figure 2: Auralized passage with tonal AVAS and BEM directivity (a) and narrowband noise AVAS with BEM directivity (b). Re-recorded by placing an artificial head at the participant position for the listening experiment. Only the left-ear signal is shown.

silence. Due to the limited frequency resolution of the employed radiation directivities, both AVAS and tire/road noise signals were limited to 3 kHz, which is still sufficient to cover most relevant AVAS and tire/road noise components and expected to be perceptually acceptable in combination with a full range ambience recording. Figure 2 shows exemplary auralized passages for both the tonal and the narrowband noise AVAS signal, simulating a linear pass-by of a vehicle accelerating from 0 km/h to 20 km/h at 5 m road-to-observer distance.

2.2. AVAS Directivity

The AVAS radiation directivity used as a reference for this study was obtained by setting up a boundary element model (BEM) of a *Tesla Model Y 2021*, using the commercial software package *COMSOL Multiphysics* as described in [4]. In this simplified model, the AVAS loudspeaker was replaced by a simple piston, and an acoustic half-space formulation was used to include ground reflections in the simulation. The model was solved up to 3 kHz, and the resulting pressure was evaluated on a spherical grid surrounding the vehicle. This radiated pressure was then encoded into a set of spherical harmonic (SH) expansion coefficients of order 64, allowing for a straightforward extrapolation and reduction of spatial resolution. The resulting BEM directivity in polar representation is shown in Figure 3a. Based on the obtained BEM radiation pattern, simplified directivities with the same average spectral balance as the reference BEM directivity but different degrees of spatial complexity were constructed. Therefore, a reference filter function was obtained by taking the sum of the squared pressure over all BEM spherical harmonic coefficients and constructing a minimum phase filter representation, H_{ref}, using the real cepstrum method. This minimum phase filter was manually assigned to different SH coefficients to construct simple radiation patterns based on the spherical harmonic basis functions Y_l^m with order l and degree m

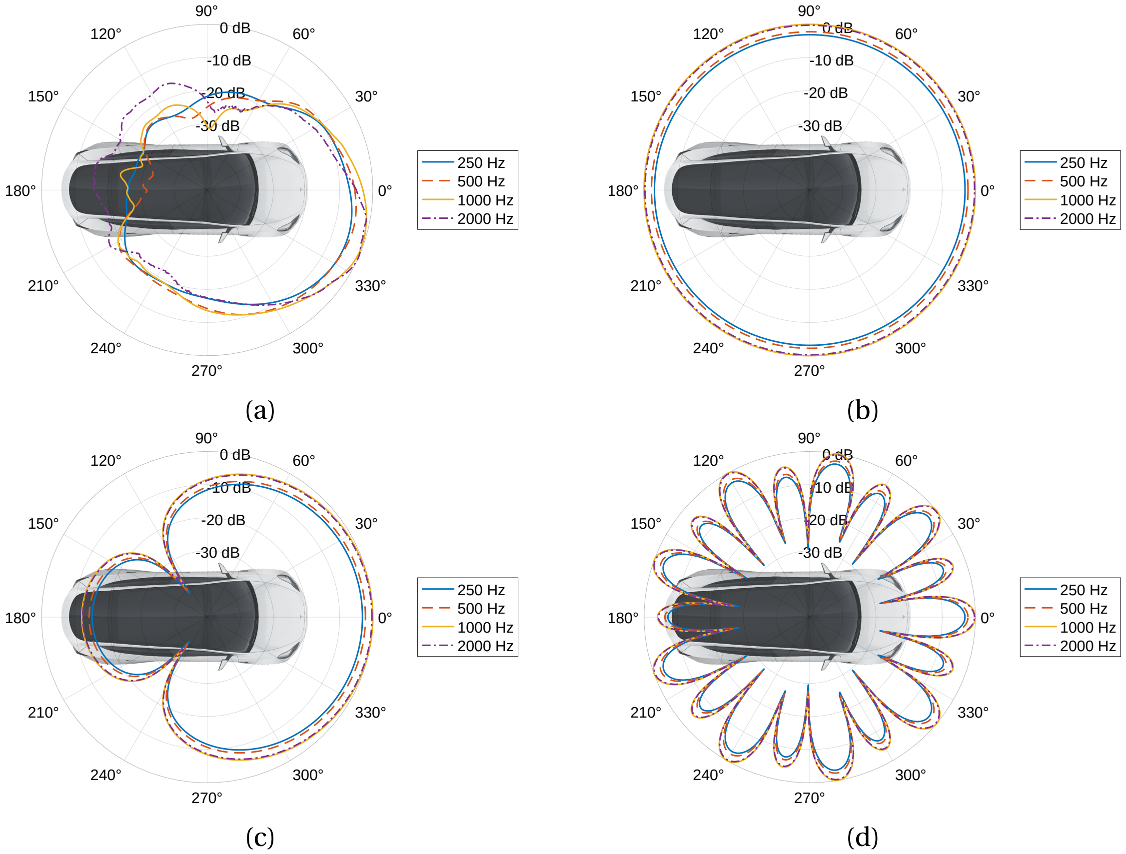


Figure 3: Polar representations of BEM (a), omnidirectional (b), cardioid (c), and star-shaped (d) AVAS directivity patterns.

as

$$
\begin{aligned}
\text{Omnidirectional:} \quad & H_{\text{ref}} \cdot Y_0^0 \\
\text{Cardioid:} \quad & H_{\text{ref}} \cdot (0.5 \cdot Y_1^1 + 0.5 \cdot Y_0^0) \\
\text{Star:} \quad & H_{\text{ref}} \cdot (0.7 \cdot Y_9^9 + 0.3 \cdot Y_0^0)\,.
\end{aligned}
\tag{1}
$$

All directivities were normalized to the same maximum energy to ensure a similar maximum sound pressure level at a roadside observer position. The resulting polar directivity patterns are shown in Figures 3b to 3d.

2.3. Reproduction

The auralization method described in Section 2.1 produces binaural stimuli that would typically be reproduced via headphones. However, for the purpose of this study, it was decided to implement a speaker-based reproduction approach instead by using binaural crosstalk cancellation [5]. This reproduction method has the advantage that the participants do not need to wear headphones and, hence, potentially experience a higher degree of immersion. While a speaker-based reproduction of binaural signals, in general, poses more challenges than headphone-based reproduction, the scenario of interest for this study, i.e., a stationary roadside listener with fixed head orientation, allows for a straightforward implementation as described in the following.

Two loudspeakers of the type *Genelec 8030* were mounted at a distance of 3.1 m and with an angle of ±50° relative to a listening position in an anechoic chamber as shown in Figure 4. To mimic the feeling of standing at the side of a road, the subjects stood throughout the entire experiment while being instructed to keep their heads oriented straight toward the virtual road when listening to the stimuli. Transfer functions between loudspeakers and an artificial head

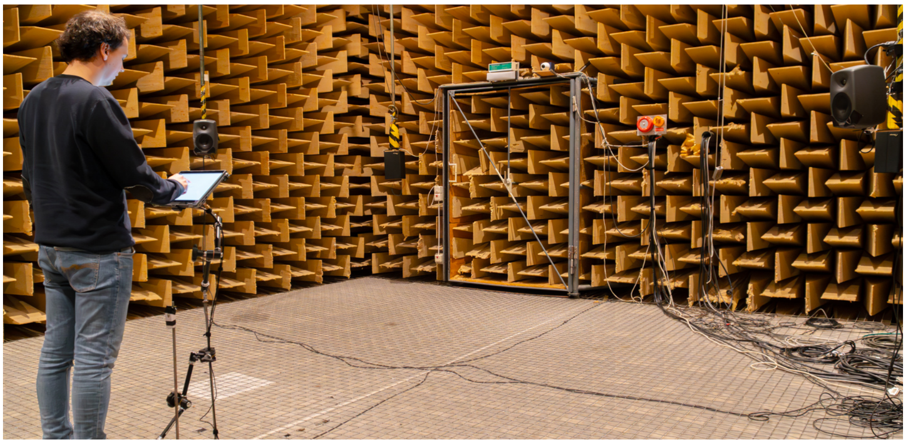
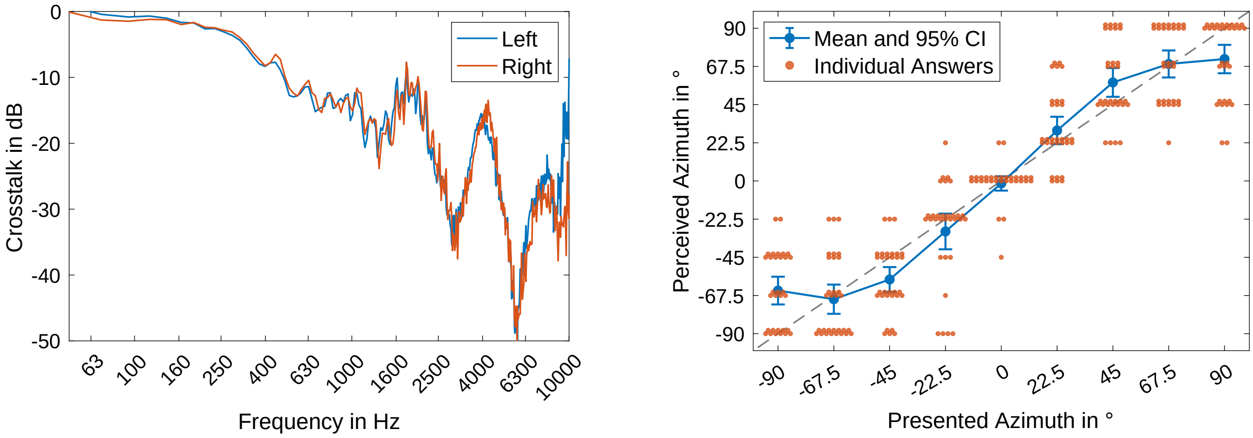


Figure 4: Listening Experiment Setup.



(a) (b)

Figure 5: Crosstalk level for both speakers (a) and results of perceptual localization validation (b).

(*HEAD Acoustics HMS-V*) placed at the participant position were measured and used to construct a matrix that describes the sound propagation from each loudspeaker to each ear. This matrix was then inverted using a frequency domain least-squares-optimal solution with Tikhonov regularization, resulting in a set of crosstalk cancellation filters that allow a channel separation between both ear signals [6].

In order to validate the quality of this reproduction method, the crosstalk level between the left channel and the right receiver ear and vice versa was measured. A single-channel white noise signal was sent through the crosstalk cancellation filters so that the signal only occurs on one of the ears when assuming a perfect cancellation. The signal measured on the other ear is unwanted crosstalk and can be expressed as a level relative to the desired signal as shown in Figure 5a. The measurements show that the channel separation generally increases for higher frequencies and that crosstalk levels below -20 dB were achieved for large parts of the relevant frequency range. However, these measurements alone do not allow for predicting whether the reproduction method is sufficiently accurate for the intended purpose as, for example, additional inaccuracies such as a mismatch in HRTFs might affect the individual perception [7,8]. Two common problems of binaural crosstalk cancellation with generalized HRTFs are localization inaccuracies and spectral colorations. While the latter was considered less relevant for this study, an inaccurate reproduction of binaural localization cues might significantly affect the participants' vehicle pass-by speed perception. Therefore, a perceptional validation was performed in which all 31 participants of the main experiment (c.f. Section 2.5) performed a simple localization test. During this test, the subjects were presented with nine binaural speech stimuli equally distributed on the horizontal plane in the azimuth angle range from −90° to 90°. The stimuli were generated by convolving an anechoic speech signal with the same generic head-related transfer functions used for the EV auralization. The participants were then instructed to report the perceived azimuth angle on a nine-point scale ranging from left (90° azimuth) to right (−90° azimuth). Figure 5b shows the individual localization results, arithmetic mean, and 95% confidence intervals for all evaluated positions. The resulting localization curve shows a saturation towards extreme values, which indicates that, while the localization on the horizontal plane works well for moderate azimuth angles, lateral stimuli are not always correctly localized. This outcome is expected since source positions at ±90° result in maximum interaural time and level differences, which, in turn, require a high binaural channel separation for correct reproduction. Nevertheless, as the vehicle passages used in this study are limited to azimuth angles of ±80°, the speaker-based reproduction method was assumed sufficiently accurate for the performed listening experiment.

2.4. Experiment Design and Stimuli

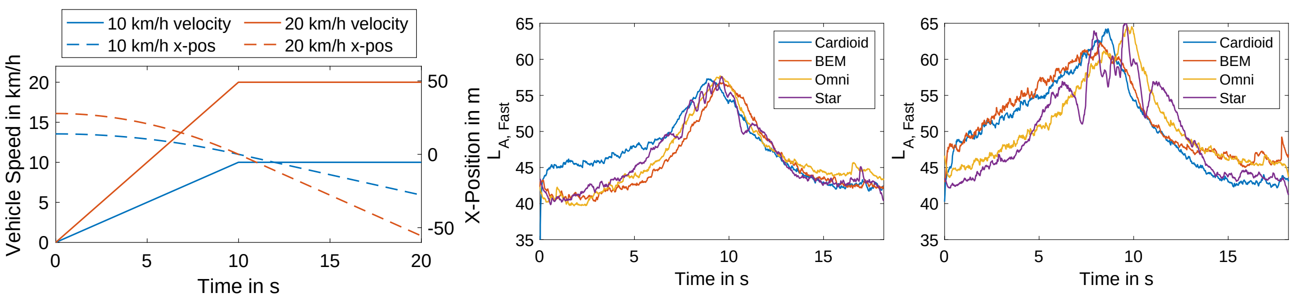
Table 1: Stimuli name coding (a) (Example: TB20 is tonal AVAS with BEM directivity and a maximum speed of 20 km/h), and the three paired comparison stimuli groups (b).

AVAS Signal	**Directivity**	**Vehicle Speed**
T: Tonal	B: BEM	10: 10 km/h
(VW ID.3)	C: Cardioid	20: 20 km/h
N: Noise	S: Star	
(Tesla Model Y)	O: Omnidirectional	

(a)

PC1	**PC2**	**PC3**
TB20	NB20	TB20
TO20	NO20	TO20
TC20	NC20	NB20
TS20	NS20	NO20
TB10	NB10	TB10

(b)



(a) (b) (c)

Figure 6: Vehicle velocity profile and x-position relative to roadside observer position for both 10 km/h and 20 km/h stimuli (a) and A-weighted fast sound pressure levels for 20 km/h passages with tonal AVAS (b) and noise AVAS (c).

To evaluate whether the AVAS signal or radiation directivity influences the pass-by speed perception of a roadside listener, a paired comparison test [9], also referred to as two-alternative forced choice (2-AFC) method, was used. In this test, participants were presented with stimuli pairs of two electric vehicle passages and asked to select the sound that they think corresponds to a faster maximum vehicle speed. If the participants could not perceive a difference, they were forced to choose based on guessing. The order of stimuli within each pair was randomized, and the participants could listen to each stimulus twice. In total, ten different stimuli were compared, i.e., 20 km/h passages with tonal and noise AVAS and four different directivities (Omnidirectional, BEM, Cardioid, and Star, c.f. Section 2.2) as well as one passage with 10 km/h speed and BEM directivity for both AVAS types. In the following, these stimuli are described by the name coding presented in Table 1a. To reduce the total amount of comparisons, these ten stimuli were divided into three different paired comparison groups (PC1, PC2, and PC3), each consisting of ten comparisons between five stimuli as shown in Table 1b. Thereby, PC1 compares tonal AVAS passages with four different directivities, PC2 compares narrowband noise AVAS passages with four different directivities, and PC3 compares tonal and noise AVAS passages for BEM and omnidirectional directivities. All paired comparison groups contain one 10 km/h pass-by to serve as a lower-speed anchor. The order of comparisons within each group was randomized for each participant. All passages had a total duration of 20 s, started with a linear acceleration from 0 km/h and reached their final speed of 10 km/h or 20 km/h after 10 s as visualized in Figure 6a. The normalized directivities resulted in a similar maximum sound pressure level among stimuli with the same AVAS signal as shown in Figure 6b and Figure 6c and the ISO 532-3 free-field binaural long-term loudness of all stimuli was in the range from 11.1 sone to 12.3 sone. All stimuli can be accessed at www.doi.org/10.5281/zenodo.10912186. The experiment was implemented using *HEAD Acoustics SQala* jury testing software, running on a tablet computer placed in front of the participant as shown in Figure 4. A continuous binaural ambience sound (c.f. Section 2.1) was played back independently from the pass-by stimuli to avoid sudden changes in background noise and silence when switching between stimuli.

2.5. Participants

The experiment was performed by 31 participants (16 female, 14 male, and one non-binary), mainly recruited from Chalmers University students and faculty members. The participants were between 22 and 36 years old, with a median age of 27 years. All participants had self-reported normal hearing and gave their written consent for participation as well as collection, processing, and publication of their data. Twelve of the participants stated they had never performed a listening experiment before, two seldom (1-2 times), eight several times (3-5 times), and nine many times (> 5 times). Participants were also asked: *How often do you notice electric vehicles (cars/busses/trucks) and the special sounds they emit in your everyday life?* to which no one responded *never*, one participant responded *rarely*, 14 responded *occasionally*, 14 responded *frequently* and two participants responded *very frequently*, which indicates that all subjects had some prior exposure to electric vehicle sounds.

3. RESULTS

The following section evaluates the listening experiment results regarding the effects of AVAS directivity and AVAS signal type on the perceived electric vehicle pass-by speed.

3.1. Effect of AVAS Directivity

In order to obtain an overall ranking of the stimuli in each paired comparison group, the participants' responses were analyzed using a Bradley-Terry-Luce (BTL) Model [10, 11], a commonly applied probabilistic choice method for evaluating paired comparison data. The model outputs probability scores for each stimulus; the difference in their probability scores gives the log-odds of one stimulus being preferred above another [12]. For this study, a Matlab implementation of the BTL method provided by [13] was used. In addition to probability scores and estimated confidence intervals, this implementation outputs the likelihood of the model with a saturated model that fits the data perfectly. This likelihood value confirmed that the BTL method is a suitable analysis for the obtained data ($p > 0.85$ for all three paired comparison groups).

Figure 7 shows the resulting probability scores and 95% confidence intervals for the paired comparison groups PC1 and PC2. For both stimuli groups, the 10 km/h pass-by obtained the

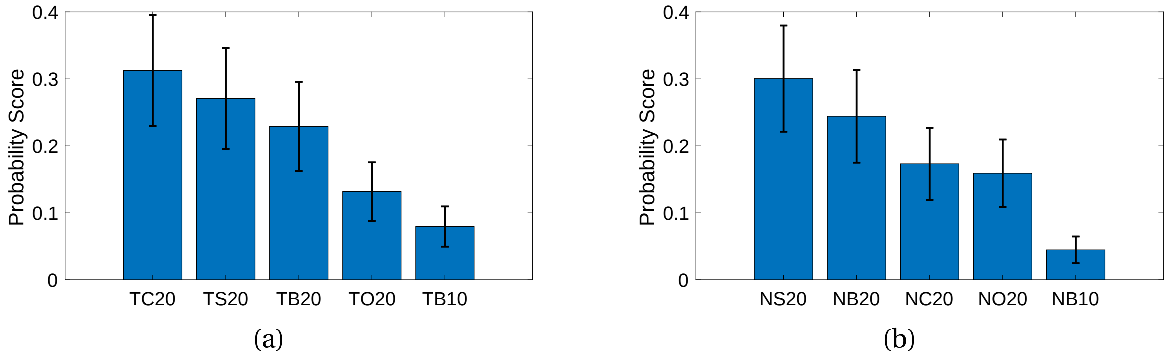


Figure 7: Probability scores and 95% confidence intervals for tonal AVAS in PC1 (a) and narrowband noise AVAS in PC2 (b).

lowest probability scores, meaning they are the least likely to be perceived as faster than the other 20 km/h stimuli in the same comparison group. This outcome is expected and indicates that, overall, the experiment design and auralization seem to give valid results. Additionally, the results of both PC1 and PC2 show that stimuli with omnidirectional AVAS radiation are unlikely to be perceived faster than stimuli with cardioid, BEM, or star-shaped AVAS directivity at the same vehicle speed. This effect seems more pronounced for the tonal AVAS signals in PC1 than for the narrowband noise AVAS stimuli in PC2. Besides this tendency of the omnidirectional radiation pattern being perceived as slower, the ranking of the three other directivities is inconsistent between the two AVAS signal types. While the cardioid directivity is most likely to be perceived as the fastest for the tonal AVAS signal, the star-shaped directivity obtained the highest probability score for the narrowband noise AVAS signal. This discrepancy could either indicate that the effects of radiation directivity on vehicle pass-by speed perception depend on the AVAS signal type or that there is no significant difference between cardioid, BEM, and star-shaped AVAS directivity.

Table 2: Number of participants perceiving the column stimulus to sound faster than the row stimulus for tonal AVAS comparison (a) and narrowband noise AVAS comparison (b). Green boxes indicate significance at $p < 0.05$; yellow boxes are significant at $p < 0.075$.

	TC20	TS20	TB20	TO20	TB10
TC20		14	14	8	7
TS20	17		12	11	8
TB20	17	19		10	8
TO20	23	20	21		10
TB10	24	23	23	21	
$\sum$	81	76	70	50	33

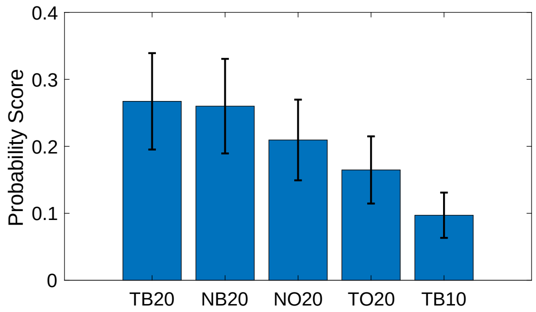
(a)

	NS20	NB20	NC20	NO20	NB10
NS20		13	10	12	5
NB20	18		13	12	4
NC20	21	18		13	7
NO20	19	19	18		6
NB10	26	27	24	25	
$\sum$	84	77	65	62	22

(b)

To further evaluate which stimuli pairs were perceived as significantly different from each other regarding vehicle speed, the results for each individual comparison pair were analyzed as shown in Table 2. If no difference in speed is perceivable between two stimuli, participants are expected to base their response on guessing. Assuming that no other factors influence the subjects' decisions and that all comparisons are independent, this would lead to a 50% probability of choosing either stimulus in each comparison, making each paired comparison a Bernoulli trial. This means that the binomial distribution can be used to calculate the chance of a specific outcome for a given number of subjects if no perceivable difference exists. For significance testing, it is reasonable to determine the minimum number of responses in favor of one stimulus required so that the chance of randomly obtaining at least this number of responses is lower than $p = 0.05$. For the given $N = 31$ participants and assuming no a priori knowledge concerning the expected direction of differences, at least 22 subjects need to select one stimulus over the other for the chance of randomly obtaining this result to be smaller than $p = 0.05$ [14]. Comparisons that exceed this threshold are significant with $p < 0.05$ and were highlighted green in Table 2. Comparisons that are significant at $p < 0.075$ are highlighted in yellow. This form of evaluation confirms the previous findings that the 20 km/h passages are perceived as significantly faster than the 10 km/h stimuli. The only difference for the same pass-by speed significant at $p = 0.05$ in direct comparison is the cardioid directivity compared to the omnidirectional directivity for tonal AVAS signals. This outcome, on the one hand, proves that AVAS directivity can influence vehicle pass-by speed perception but, on the other hand, also indicates that this effect is only significant for specific AVAS signals and when comparing two "extreme cases," i.e., a highly directional and an omnidirectional radiation pattern.

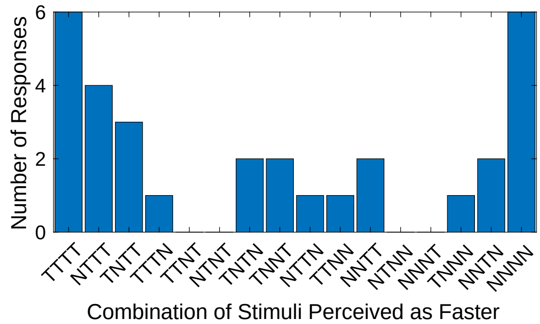
3.2. Effect of AVAS Signal Type



(a)

	TB20	NB20	NO20	TO20	TB10
TB20		16	13	11	9
NB20	15		16	10	9
NO20	18	15		14	11
TO20	20	21	17		9
TB10	22	22	20	22	
Σ	75	74	66	57	38

(b)



(c)

Figure 8: PC3 probability scores with 95% confidence intervals (a), number of participants perceiving the column stimulus of PC3 to sound faster than the row stimulus (b) and distribution of results for comparisons between the two tonal and the two noise AVAS stimuli in PC3 (c)

The purpose of the third paired comparison group was to investigate whether the AVAS signal type can affect electric vehicle pass-by speed perception. However, except for the previously observed difference between BEM and omnidirectional directivities, neither the BTL probability scores shown in Figure 8a nor the paired comparison results shown in Figure 8b reveal any systematic effect of AVAS signal type on vehicle speed perception when considering the entirety of participant responses. Nevertheless, on an individual subject level, there are at least some indications for an influence of the AVAS signal type: Comparing the tonal AVAS stimuli (TB20 and TO20) to the noise equivalents (NB20 and NO20) results in four relevant comparisons (TB20 vs. NB20, TB20 vs. NO20, TO20 vs. NB20, TO20 vs. NO20) which can lead to 16 different outcomes. Figure 8c shows the distribution of the 31 individual subject responses among those 16 possible combinations, revealing that the majority of participants consistently preferred either the tonal AVAS or the narrowband noise AVAS throughout most of those four comparisons. Applying the same binomial probability approach as before, the chance that at least six out of 31 participants always select the same AVAS signal when assuming that all trials are random and independent is less than 5%. This indicates that the responses are unlikely to be random but that participants tend to always choose the same AVAS signal, whereas the perception of which of both evaluated signal types sounds faster differs between individuals. Finally, revisiting the results for PC1 and PC2 shown in Table 2 reveals that more participants wrongly selected the tonal 10 km/h stimulus (TB10) in PC1 to sound faster than the 20 km/h stimuli than for the narrowband noise AVAS stimulus NB10 in PC2. This error difference implies that participants might find it more challenging to choose the correct stimulus for the tonal AVAS than for the narrowband noise AVAS signal.

4. DISCUSSION

Regarding the initial research question of whether the AVAS radiation directivity can affect the perception of electric vehicle pass-by speed, the most relevant experiment outcome is that tonal AVAS passages with a cardioid-shaped directivity were perceived as significantly faster than the corresponding passages with omnidirectional directivity. The stimuli ranking by BTL probability scores strongly supports this observation, showing that omnidirectional passages are least likely to be perceived as faster than other stimuli with the same speed for both AVAS signal types. This finding might confirm the perceptional validation results of [4], where we hypothesized that a mismatch in the employed BEM directivity could cause a faster speed perception compared to in-situ recordings. Based on informal interviews after the experiments, a possible explanation for this effect could be that at least BEM and cardioid directivities radiate significantly less sound to the back of the vehicle than to the front (c.f. Figure 3). This might result in an impression of the car "disappearing" faster after it passes the listener. However, this assumption does not hold for the star-shaped directivity, which obtained the highest probability score in PC2, even though it radiates the same amount of energy to the back and the front. For this directivity, the large number of strong lobes in the pattern significantly alters the time structure of the pass-by signal (c.f. Figure 6), almost like an amplitude modulation, which might be perceptually associated with a higher vehicle speed.

In terms of a possible influence of the AVAS signal type on electric vehicle pass-by speed perception, no significant evidence for an overall faster perception of either the tonal or the narrowband noise AVAS was found, even though there is a trend of the tonal AVAS to result in more erroneous judgments than the narrowband noise AVAS. However, an analysis of the individual results indicates that some subjects always perceived the tonal AVAS as faster, while others consistently preferred the narrowband noise. This trend is consistent with informal interviews after the experiment, where, based on personal associations with the different sounds, some of the participants stated that they clearly perceived the passages with narrowband noise AVAS as the fastest. In contrast, others felt no difference or thought the passages with tonal AVAS always sounded faster. This underlines that the perception of such complex auditory scenes may be subjective and depend on prior exposure and personal associations. While most people are likely to be familiar with the noise of combustion engine vehicles, the broad population may still need to learn how to interpret electric vehicle sounds. The fact that currently sold EV models implement a variety of different AVAS signals might not contribute to a simplified familiarization process.

While the obtained results are a first step towards a better understanding of the influences of complex acoustic properties on the perception of electric vehicle sounds, the findings might be most relevant for auralization purposes where the perception of an entire vehicle passage is of interest. For conclusions about possible implications on traffic safety, one could argue that only the first part of a pass-by where the vehicle approaches a pedestrian is of interest. For this case, the difference between a cardioid and an omnidirectional AVAS directivity is significantly smaller than when considering an entire vehicle passage. Therefore, a more sophisticated paradigm, such as time-to-collision estimation [15], could be used in a future listening experiment to investigate whether AVAS directivity matters for real-life traffic scenarios.

5. CONCLUSION

This study presented a laboratory experiment on the influence of AVAS radiation directivity on the perception of electric vehicle pass-by speed. It was shown that AVAS radiation directivity can affect speed perception, with a tendency for directional patterns to be perceived as faster than passages with omnidirectional AVAS radiation. However, this effect was only found to be significant for one specific combination of directivities and AVAS signal. While there was no significant overall difference between the investigated tonal and narrowband noise AVAS signals, the results suggest that the AVAS signal type can influence vehicle speed perception depending on individual preference and that the tonal AVAS tends to cause more erroneous speed judgments than the narrowband noise AVAS signal. Those observations and the actual impact of these findings on real-life traffic scenarios need to be confirmed in further listening experiments.

DATA AVAILABILITY STATEMENT

The stimuli and anonymized listening experiment results associated with this article are available on Zenodo under the reference www.doi.org/10.5281/zenodo.10912186. The code and documentation of the employed electric vehicle auralization toolbox are published on GitHub under www.github.com/leonpaulmueller/evat.

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