Assessing the Effectiveness of Acoustic Vehicle Alerting Systems (AVAS) for Pedestrians with Visual Disabilities

Insights from the EVA Survey

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***Abstract*— The increasing adoption of quiet Electric Vehicles (EVs) raises significant concerns about pedestrian safety, particularly for individuals who rely on auditory cues to navigate public spaces, such as those with visual disabilities. Although the United Nations Economic Commission for Europe (UNECE) Regulation No. 138 mandates the use of Acoustic Vehicle Alerting Systems (AVAS) in EVs to mitigate this risk, notable gaps remain between regulatory requirements and the real-world effectiveness of AVAS. This paper presents findings from the Electric Vehicle Acoustics (EVA) survey, which collected responses from pedestrians with and without visual disabilities to assess their experiences and perceptions of EV sounds. Statistical analysis, including median differences, effect sizes, and correlation matrices revealed disparities in how different pedestrian groups perceive AVAS effectiveness. The results underscore the need to refine AVAS design, ensuring improved real-world applicability and greater safety for visually disabled pedestrians.**

Keywords- inclusive design; electric vehicles; pedestrian safety.

I. INTRODUCTION

The increasing prevalence of Electric Vehicles (EVs) on public roads [1] presents both opportunities and challenges. While EVs travelling at low speed benefit noise reduction efforts in urban environments [2][3], their quiet operation also introduces safety risks [4][5][6], particularly for pedestrians at road crossings, in parking lots, and other environments where traffic speed is below 20- or 30-km/h. The challenge is most pronounced for individuals with visual disabilities [7][8] who rely exclusively on sound to detect vehicle presence and movement. For example, imagine a bustling and noisy city street where a quiet EV runs a red light just as a visually disabled pedestrian begins to cross.

Regulatory frameworks have attempted to address this issue through the mandating of the Acoustic Vehicle Alerting System (AVAS) - a system that artificially generates a sound signature using external speakers on modern EVs. Typically, such systems are engaged below certain speed limits (i.e., 20 km/h [9] or 30 km/h [10]), since above these speeds, tyre-on-road noise is considered sufficiently loud to make EVs acoustically comparable to combustion engine vehicles [11].

To assess the real-world effectiveness of AVAS, this paper is structured as follows: Section 2 outlines the regulatory context and technical background of AVAS implementation, highlighting its current limitations. Section 3 describes the design of the EVA survey, including participant criteria and the structure of the Likert-scale questions. Section 4 presents the statistical analysis of survey responses, incorporating descriptive statistics, effect sizes, and correlation matrices. Section 5 discusses the statistically significant differences in perception between pedestrians with and without visual disabilities. Finally, Section 6 offers directions for future research and calls for a reassessment of the fundamental design principles underpinning AVAS.

II. BACKGROUND

In the European Union, AVAS compliance is mandated under Regulation (EU) 2019/2144 [12], aligning closely with UNECE Regulation No. 138 [9], while the International Organization for Standardization (ISO) document ISO 16254 [13] provides the testing methodology to assess AVAS compliance. Regulatory approaches and testing frameworks vary globally, but the core objective remains the same: ensuring that EVs and hybrids operating in electric mode produce sufficient auditory cues for pedestrian to hear them.

Although regulatory implementation and compliance-testing represent significant progress, the real-world effectiveness of AVAS remains uncertain [14][15][16]. While AVAS is intended to enhance pedestrian safety, it is unclear whether current implementations fully meet the needs of pedestrians who rely entirely on auditory cues. Existing standards and regulations have established useful but rather broad requirements, such as minimum sound pressure levels as a function of speed (i.e., AVAS loudness); the inclusion of certain frequency components (i.e., AVAS tonality); and the requirement for AVAS when the EV is stationary but ready to move. Although UNECE regulation and the ISO standard have recently undergone important revisions and further

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refinement, they continue to offer significant flexibility to vehicle manufacturers - allowing them to generate unique AVAS signatures and in some cases, even allowing consumers to select from a palette of sound options. While all AVAS signatures are required to pass ISO 16254 and comply with UNECE 138, the degree of design flexibility raises concerns that AVAS is increasingly being used as a sonic-branding tool rather than as a safety feature [17][18].

Notably, most AVAS designs have not attempted to replicate the acoustic cues of internal combustion engines, which traditionally offered pedestrians reliable auditory information [19][20]. In response to this gap, several studies have explored more nuanced sound characteristics aimed at effectively alerting pedestrians to oncoming EVs, particularly those with sensory impairments. For example, e-scooter studies by Suzuki et al. [21] and work by Tyler [22] focus on the psychoacoustic and cognitive aspects of alert-inducing sound design, demonstrating that empirically derived acoustic profiles can improve pedestrian awareness and safety outcomes. Similarly, time-to-collision studies comparing AVAS signatures with internal combustion engine sounds have shown that AVAS fails to convey sufficient cues for pedestrians to accurately judge vehicle approach speed and estimate safe crossing distances [23][24]. These studies collectively highlight the importance of auditory familiarity, cue salience, and psychoacoustic subtleties in vehicle sound design. The present study builds on this work by providing structured survey data from pedestrians with and without visual impairments, offering new insights into how current AVAS implementations are perceived in uncontrolled, real-world environments.

Despite the role of AVAS in pedestrian safety, current standards and regulations have not systematically evaluated their effectiveness across diverse pedestrian groups, especially those who rely exclusively on sound when navigating built-up environments populated by EVs. Moreover, current frameworks cannot fully account for variations in ambient sound conditions, which can significantly impact a pedestrian's ability to detect an approaching EV. Looking ahead, the increasing adoption of EVs raises additional concerns about how pedestrians will distinguish between vehicles that pose an immediate safety risk and those that do not - especially for individuals unable to visually confirm vehicle movement. Addressing these gaps requires a structured evaluation of AVAS perception under real-world conditions. The present study serves as an initial step in this direction, gathering insights from pedestrians with and without visual disabilities regarding their experiences and perceptions of EV sounds.

III. SURVEY DESIGN

The EVA survey was developed to assess pedestrian perceptions of AVAS, with particular focus on individuals who rely on auditory cues for navigation. The survey was disseminated through a combination of outreach to disabled persons organisations, relevant pedestrian safety mailing lists, and social media platforms. Ethical approval was obtained from the Ethics Committee of the Technological University of the Shannon prior to survey distribution.

Accessibility was a core consideration in the survey design. The online survey instrument was tested and optimised for use with screen readers. Participants were encouraged to use assistive technologies, and all survey components were structured to support independent completion by individuals with visual disabilities.

A. *Participant Criteria and Anonymity*

Participants were eligible to take part in the survey if they were aged 18 years or older, capable of providing informed consent, and had previously encountered one or more EVs (either by seeing or hearing them in operation). Visual disability was self-reported by participants via a survey question that also allowed respondents to indicate no visual disability. An indication of visual disability encompassed individuals with no vision as well as those with partial vision, in line with definitions provided by the National Disability Authority (NDA) Advice Paper [25].

To protect participant privacy, the survey did not collect any personally identifiable information and Internet Protocol (IP) tracking was disabled. All responses were reviewed to ensure anonymity was preserved. Participants were informed of the study's purpose, who comprised the research team, the institutions involved, and their right to withdraw at any time prior to submission. Submission of the completed survey was taken as a final consent to participate. Due to the anonymous nature of the data collection, responses could not be withdrawn after submission.

B. *Likert Statements*

The survey was structured to gather quantitative data on pedestrian experiences with EV sounds. It focused on ordinal questions using a 5-point Likert scale, where participants rated their level of agreement with statements related to AVAS perception, detectability, and effectiveness (Table I).

TABLE I. NINE LIKERT STATEMENTS USED IN THE EVA STUDY

#	Statement
L1	I feel safe when I think there might be an EV close by.
L2	It is easy to notice an EV approaching because of its sound.
L3	Sounds made by EVs help me understand what the vehicle is doing
L4	I feel confident I understand an EV's next action based on its sound.
L5	I can react quickly to the sound of an EV when necessary.
L6	I find the sound of EVs pleasant.
L7	It takes little effort for me to listen to an EV's sound and understand what it is doing.
L8	I believe that the sound from all electric cars will be a positive thing for noise levels in busy cities and towns.
L9	Imagine you are standing on a busy street with lots of electric cars making sounds. Do you think it would be easy or hard to know when it is safe to cross the road?

Participants were asked to rate their level of agreement along the following scale (note L9 had a differently worded scale but complied with the negative to positive sentiment):

(1) I disagree a lot *(L9: Very difficult)*
(2) I disagree just a little *(L9: Difficult)*
(3) I don't know *(L9: Neither difficult or easy)*
(4) I agree just a little *(L9: Easy)*
(5) I agree a lot *(L9: Very easy)*

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C. Data Preparation

To ensure accessibility and clarity, the survey wording was developed in line with National Adult Literacy Agency (NALA) guidelines [26], ensuring that participants of varying literacy levels could engage with the questions effectively.

A total of 86 survey responses were collected. Initial screening resulted in the removal of incomplete submissions, particularly those where respondents answered only one or two preliminary questions before exiting the survey. After this phase, 72 responses remained. Further data cleaning was performed to ensure that all participants had fully completed the Likert-scale questions necessary for statistical analysis, resulting in a final valid dataset of 54 responses.

The final dataset was split into two groups:

- **No Disability (ND)**: 33 participants
- **Visual Disability (VD)**: 21 participants

Other disability categories (such as hearing impairments or sound sensitivity) had insufficient sample sizes for comparative statistical analysis and were therefore excluded from the main group comparisons.

The cleaned dataset was stored in CSV format and subsequently used for statistical analysis using R Version 4.4.2.

IV. Survey Analysis

The analysis of the EVA survey data was conducted in two stages: an initial descriptive analysis, followed by inferential statistical testing. Descriptive statistics were used to summarise central tendencies and variability within the dataset, providing a broad view of general response patterns across the two participant groups (ND and VD). This included calculations of medians, interquartile ranges (IQRs), and effect sizes to highlight differences in perception. These results laid the foundation for the inferential analyses presented in Section 5, which assess the statistical significance of observed group-level differences.

A. Median Values and Interquartile Ranges

The first stage of analysis summarised the Likert-scale responses using the median and IQR for both ND and VD groups. These measures provide insights into the central tendencies and variations in responses across the groups.

A key trend observed was that the VD group generally reported lower median scores across most statements, indicating a stronger tendency to disagree with the survey statements compared to the ND group. In contrast, the ND group exhibited more neutral or positive responses, with medians ranging between 3 and 4, and displayed greater variation in their responses (see Figure 1).

Statements L1, L2, L3, and L7 showed the most pronounced differences, with VD participants consistently reporting strong disagreement. Notably, responses to L2, L4, and L7 were unanimous within the VD group, with an IQR of 0, indicating complete agreement in their perception that EV sounds were insufficient for safe navigation. In contrast, the ND group exhibited greater variation, with responses spanning a wider range.

Statements L6 and L8 displayed the most notable divergence in agreement, with ND participants tending to agree, while VD participants leaning towards neutrality or disagreement. This suggests that ND respondents may have a more favourable perception of AVAS in terms of their effectiveness and impact on urban noise levels, whereas VD participants were less convinced.

Overall, the results indicate that visually disabled participants are more critical of AVAS effectiveness, whereas sighted participants express a wider range of views, including some level of agreement. The strong uniformity of responses within the VD group suggests that their experiences with AVAS are more consistent, highlighting a potential inadequacy in current AVAS implementations.

B. Largest Differences in Medians and Effect Sizes

To identify the most significant differences in responses between the ND and VD groups, the absolute median difference was calculated alongside effect size using Cliff's Delta.

This analysis revealed that the largest disparities were observed in statements L1, L6, and L7, where VD participants strongly disagreed, whereas ND participants were more neutral or positive. The effect sizes for these statements (~0.60) indicate that these differences are statistically meaningful and not due to random variation.

Beyond these strongest disparities, moderate differences were found in statements L2, L3, L5, L8, and L9. The VD group was consistently more negative than the ND group, but the differences were less extreme, with effect sizes around 0.45. This suggests that while the two groups differ in their perceptions, the gap is narrower than in the highest-ranked statements.

Interestingly, statement L4 was the only one where both groups showed identical responses, with both strongly disagreeing. The small effect size (0.31) confirms that there is minimal variation in how this statement was perceived, indicating a shared viewpoint across both groups.

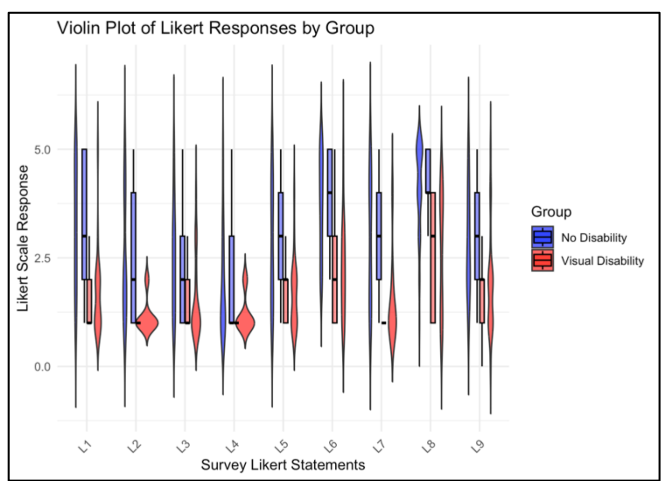

Figure 1. Violin plot showing Likert-scale response distributions for ND and VD groups across nine statements.

The width of each violin in Figure 1 indicates response density. The ND group (blue) shows greater variation in responses along the scale, while the VD group (red) demonstrates more compact distributions, particularly at the lower end of the Likert values - reflecting a consistently negative perception of AVAS. These patterns reinforce the trend observed in the median and effect size analysis: VD participants were generally more critical of AVAS effectiveness, while ND participants express more varied and sometimes more favourable views. The pronounced clustering in the VD group and the large effect sizes in key statements suggest that these differences are substantial and likely reflect real-world disparities in how AVAS is perceived and experienced by pedestrians who are visually-disabled.

C. *Correlation Analysis*

To further explore relationships between Likert-scale responses, Spearman's rank correlation was used to measure the strength and direction of associations between responses within each participant group. See Tables II and III for a summary of results.

TABLE II. SPEARMAN'S CORRELATION COEFFICIENTS ND GROUP

Likert Statements	Spearman's ρ (Correlation)	Interpretation
L1 & L9	0.68 (Strong)	Those who rate L1 in the positive also tend to rate L9 in the positive.
L2 & L3	0.62 (Strong)	Those who rate L2 in the positive also rate L3 in the positive.
L1 & L6	0.61 (Strong)	Responses for L1 are strongly related to L6.
L5 & L1	0.61 (Strong)	High agreement on L5 means high agreement on L1.
L4 & L3	0.48 (Moderate)	There is a moderate relationship between responses to L4 and L3.
L7 & L1	-0.08 (Weak/ Negative)	No meaningful relationship between L7 & L1.

TABLE III. SPEARMAN'S CORRELATION COEFFICIENTS VD GROUP

Likert Statements	Spearman's ρ (Correlation)	Interpretation
L3 & L4	0.73 (Very Strong)	Those who rate L3 high also rate L4 high.
L4 & L2	0.50 (Moderate)	Responses for L4 are moderately correlated with L2.
L6 & L3	0.49 (Moderate)	L6 responses are related to L3 responses.
L9 & L1	-0.09 (Weak)	No meaningful relationship.
L6 & L7	0.02 (Very Weak)	Almost no relationship.

Spearman correlation heatmaps are presented in Figures 2 and 3. These heatmaps visualise correlation coefficients in a matrix format, where warmer red colours indicate stronger positive correlations, while cooler blue colours indicate negative or weak correlations.

In relation to L1 (safety perception) and L9 (ease of detecting EVs in a busy street), these are strongly correlated ($\rho = 0.68$) in the ND group, suggesting participants who feel safer around EVs also find them easier to detect. In contrast, this correlation is actually absent in the VD group ($\rho = -0.09$), indicating that perceived safety and detectability are independent factors for these participants.

Correlation between L3 (understanding EV sound cues) and L4 (confidence in predicting EV movements) is very strong ($\rho = 0.73$) in the VD group, while it is only moderate ($\rho = 0.48$) in the ND group. This suggests that for visually disabled pedestrians, understanding an EV's sound is directly linked to their confidence in predicting vehicle movements, reinforcing the importance of AVAS effectiveness.

In the ND group, L6 (perception of EV sound pleasantness) and L7 (ease of interpreting EV sounds) are moderately correlated ($\rho = 0.15$). However, in the VD group, this correlation is almost non-existent ($\rho = 0.02$), suggesting that EV sound pleasantness does not significantly influence the ease of interpreting sound cues for visually impaired pedestrians.

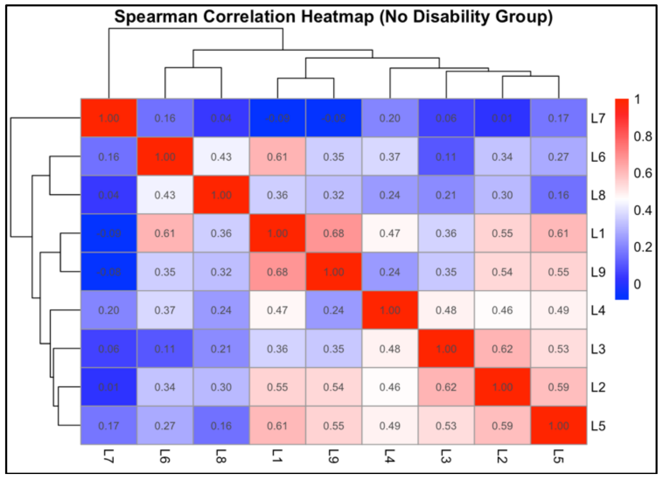

Figure 2. Spearman correlation heatmap for ND group Likert responses.

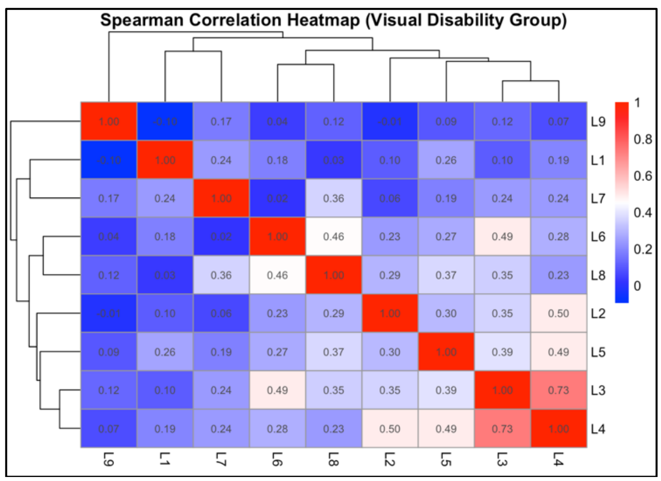

Figure 3. Spearman correlation heatmap for VD group Likert responses.

The two heatmaps reveal that some Likert statements exhibit strong correlations in one group but not the other, indicating fundamental differences in how pedestrians with and without visual disabilities process and respond to EV sounds. These group-specific patterns suggest that visually disabled pedestrians possibly interpret AVAS cues in a more interconnected and function-driven way, whereas sighted pedestrians may rely on a wider range of auditory and visual inputs, resulting in more varied perceptual relationships.

V. Statistical Significance Analysis

To assess whether differences in AVAS perception between participant groups are statistically significant, a series of inferential statistical tests were conducted. These analyses build upon the descriptive statistics by determining whether observed differences are likely due to genuine group-level disparities rather than random variation. For inferential analysis, the Mann-Whitney U test was chosen because the ND and VD groups represent independent samples rather than repeated measures or matched pairs. The test is also appropriate for ordinal Likert-scale data and does not require assumptions of normality, making it suitable for detecting differences in central tendency between these two participant groups. Additionally, PERMANOVA (Permutational Multivariate Analysis of Variance) was employed to assess broader response patterns across all Likert items simultaneously. This method is also well-suited to non-parametric, ordinal data and enables the detection of group-level differences across multidimensional response profiles without assuming normality or homogeneity of variances.

A. Likert Comparisons between Groups

To assess whether the distributions of Likert-scale responses differed significantly between the ND and VD groups, a Mann-Whitney U (U) test was conducted for each Likert statement. Additionally, Rank-Biserial Correlation (r) was computed to measure the magnitude of effect size (Z), providing insight into the practical significance of observed differences – see Table IV.

TABLE IV. Summary of Results for each Likert Statement

#	U	p-value	Z	r	Interpretation
L1	554	0.00016	3.68	0.50	Strong significant difference; VD group rates much lower.
L2	555	< 0.0001	3.70	0.50	Significant difference; VD group more negative in response.
L3	507	0.0027	2.85	0.39	Moderate but significant difference.
L4	456	0.023	1.94	0.26	Weaker difference, though still statistically significant.
L5	503	0.0040	2.78	0.38	Significant difference, though less extreme than L1 & L2.
L6	563.5	< 0.0001	3.85	0.52	Strong difference; VD group disagrees more.
L7	549.5	0.00015	3.60	0.49	Strong difference; VD group rates significantly lower.
L8	552	0.00016	3.65	0.50	Clear difference, VD group more neutral or negative.
L9	461.5	0.013	2.41	0.33	Medium-level difference between groups.

The results indicate statistically significant differences between the ND and VD groups for all Likert statements. The strongest differences were observed for L1 (perceived safety), L2 (detectability of EVs), L6 (pleasantness of EV sounds), and L7 (effort required to interpret AVAS cues), all of which had large effect sizes ($r \approx 0.50$ or above).

Moderate differences were found for L3, L5, and L9, while L4 showed the weakest but still significant difference. This suggests that while both groups shared concerns about AVAS effectiveness, visually disabled participants rated their experience more negatively.

B. Multivariate Analysis - PERMANOVA

Given the significant group differences observed in individual Likert responses, a PERMANOVA was conducted to help determine whether overall response patterns across all Likert statements differed significantly between groups. A Gower distance matrix was used, as it is well-suited for mixed and ordinal data. Group differences was the only evaluation under consideration, hence 1 Degree of freedom (Df) in the analysis. The results are summarised in Table V.

TABLE V. Summary of Results for each Likert Statement

Factor	Df	Sum of Squares	R^2 (%)	F-Stat	p-value	Comment
Group ND vs VD	1	1.0546	27.1	19.37	< 0.001	Significant difference between groups.
Residual	52	2.8311	72.9	-	-	Remaining variance due to individual differences.

The grouping variable (ND vs VD) explains 27.1% of the variance ($R^2 = 0.2714$) in the dataset. The F-statistic (19.37) is high, indicating a strong effect and the p-value (< 0.001) is highly significant, confirming that the overall response pattern differs substantially between groups.

While 27.1% of the variance is attributed to group differences, the remaining 72.9% suggests that additional factors such as age or individual attitudes toward EVs may potentially also contribute to variability.

VI. Conclusion

The findings from the EVA survey highlight significant disparities in how different pedestrian groups experience AVAS. The statistical analysis revealed that visually disabled pedestrians consistently rated AVAS as less effective in providing the necessary auditory cues for safe navigation compared to those without visual impairments. These results raise concerns regarding the adequacy of current AVAS implementations in real-world pedestrian environments.

From a regulatory perspective, while UNECE 138 and ISO 16254 establish fundamental requirements for AVAS and its compliance testing, they do not mandate in-depth psychoacoustic design-criteria that would ensure AVAS sounds are intuitively interpretable by all pedestrians. Flexibility in AVAS design may contribute to inconsistencies in pedestrian responses, as evidenced by the survey results. Additionally, the analysis of response variability suggests that visually disabled participants were more consistent in their perception of AVAS inadequacies, whereas sighted participants exhibited a broader range of opinions, likely influenced by their ability to rely on visual cues.

The inferential statistical analysis further confirms that the differences in AVAS perception between the two groups are statistically significant, with large effect sizes and very small p-values for key Likert statements related to detectability, safety, and confidence in interpreting AVAS signals. The multivariate analysis reinforces these findings, demonstrating that response patterns between the two groups are distinct, where participants with a visual disability exhibiting more clustered responses indicating a uniform dissatisfaction with AVAS effectiveness.

While these findings provide important insights, the study has several limitations that should be acknowledged. First, the sample size (particularly for the VD group) was modest, which may limit the generalisability of the results. Nonetheless, the presence of very small p-values and large effect sizes across multiple Likert items suggests that the observed differences are both statistically and practically meaningful, which goes some way toward mitigating this concern. Second, visual disability was self-reported without clinical verification. Although this approach aligns with inclusive research practices and respects participant anonymity, it may introduce variability in how individuals interpret and report their disability. Third, although the online survey was optimised for accessibility, individuals with more severe impairments or limited digital access may have been underrepresented. Additionally, the survey relied on structured, close-ended responses, and did not capture long-form or qualitative feedback that could provide deeper insight into participants' reasoning. This limited the ability to explore contextual factors or explanatory themes underlying their perceptions. Future phases of the EVA study will address this by incorporating open-ended prompts with subsequent sentiment analyses to enrich the understanding of how AVAS is experienced across diverse pedestrian groups. Finally, as the study focused on self-reported perceptions, future research would benefit from triangulating these findings with behavioural or auditory-response data collected under controlled or real-world conditions.

Despite the limitations outlined above, the findings strongly support the need to reassess AVAS design, placing greater emphasis on psychoacoustic principles to ensure that sounds are both detectable and interpretable. In particular, future design efforts should prioritise reliability and consistency for pedestrians who rely exclusively on auditory cues for situational awareness. To this end, future EVA research will involve controlled auditory experiments to evaluate AVAS effectiveness across diverse urban soundscapes and will explore the development of universal-design sound profiles that prioritise functional safety over branding considerations. These profiles will draw more explicitly on ecological psychoacoustic principles - for example, incorporating auditory cues that trigger innate perceptual responses, such as the urgency conveyed by looming sounds [27], or applying design strategies that account for asymmetry in frequency–intensity combinations and other nuanced psychoacoustic traits [28].

Psychoacoustic and ecological approaches to sound design have long been recognised as effective strategies for enhancing the communicative power of sound. These approaches aim to make auditory cues more reliable, intuitive, and universally understandable - particularly when conveying information of varying urgency or importance to listeners [29][30][31]. In this context, ecological psychoacoustics offers a valuable framework for balancing perceptual clarity with user comfort [32], making it especially relevant to the future design of AVAS systems.

In addition to this, further research will be required to examine how long-term exposure to AVAS affects pedestrian adaptation, risk perception, and behavioural response. Ultimately, advancing AVAS through perceptually grounded, inclusive design can help ensure that the growing presence of EVs enhances safety for all.

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