World Electric Vehicle Journal

MDPI

Article

Modeling and Validation of Acoustic Comfort for Electric Vehicle Using Hybrid Approach Based on Soundscape and Psychoacoustic Methods

Keysha Wellviestu Zakri [1,2,*], Raden Sugeng Joko Sarwono [1,*], Sigit Puji Santosa [2,3] and F. X. Nugroho Soelami [4]

[1] Laboratory of Building Physics and Acoustics, Engineering Physics, Institut Teknologi Bandung, Jl. Ganesa No. 10, Lb. Siliwangi, Bandung 40132, Indonesia
[2] PT Pindad, Jl. Gatot Subroto No. 517, Bandung 40284, Indonesia; sigit.santosa@itb.ac.id
[3] Faculty of Mechanical and Aerospace Engineering, Institut Teknologi Bandung, Jl. Ganesa No. 10, Lb. Siliwangi, Bandung 40132, Indonesia
[4] Faculty of Industrial Technology, Institut Teknologi Sumatera, Jl. Terusan Ryacudu, South Lampung 35365, Indonesia
* Correspondence: keysha@pindad.com (K.W.Z.); jsarwono@itb.ac.id (R.S.J.S.)

Abstract: This paper evaluated the acoustic characteristics of electric vehicles (EVs) using both psychoacoustic and soundscape methodologies by analyzing three key psychoacoustic parameters: loudness, roughness, and sharpness. Through correlation analysis between perceived values and objective parameters, we identified specific sound sources requiring improvement, including vehicle body acoustics, wheel noise, and acceleration-related sounds. The relationship between comfort perception and acoustic parameters showed varying correlations: loudness (0.0411), roughness (2.3452), and sharpness (0.9821). Notably, the overall correlation coefficient of 0.5 suggests that psychoacoustic parameters alone cannot fully explain human comfort perception in EVs. The analysis of sound propagation revealed elevated vibration levels specifically in the driver's seat area compared to other vehicle regions, identifying key targets for improvement. The research identified significant acoustic events at three key frequencies (50 Hz, 250 Hz, and 450 Hz), requiring in-depth analysis to determine their sources and understand their effects on the vehicle's NVH characteristics. The study successfully validated its results by demonstrating that a combined approach using both psychoacoustic and soundscape parameters provides a more comprehensive understanding of passenger acoustic perception. This integrated methodology effectively identified specific areas needing acoustic refinement, including: frame vibration noise during rough road operation; tire-generated noise; and acceleration-related sound emissions.

Keywords: noise; vibration and harshness (NVH); electric vehicle; soundscape; psychoacoustic

check for updates

Academic Editors: Weika Lu and Zhihong Yao

Received: 28 November 2024
Revised: 13 January 2025
Accepted: 16 January 2025
Published: 22 January 2025

Citation: Zakri, K.W.; Sarwono, R.S.J.; Santosa, S.P.; Soelami, F.X.N. Modeling and Validation of Acoustic Comfort for Electric Vehicle Using Hybrid Approach Based on Soundscape and Psychoacoustic Methods. *World Electr. Veh. J.* **2025**, *16*, 64. https://doi.org/10.3390/wevj16020064

Copyright: © 2025 by the authors. Published by MDPI on behalf of the World Electric Vehicle Association. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

The global transition to electric vehicles (EVs) represents a crucial strategy in addressing climate change and reducing greenhouse gas emissions. This shift is particularly significant in developing nations like Indonesia, where transportation significantly contributes to environmental pollution. According to Central Statistics Agency data [1], the number of operational passenger cars reached 15,797,746 units in 2020. This number has experienced an annual growth of one million units, reaching an estimated 17,175,632 units by 2022. EVs offer distinct advantages through their emission-free operation and reduced de-

pendence on fossil fuels [2], aligning with Indonesia's commitment to the Paris Agreement and UNFCCC to reduce greenhouse gas emissions by 29% by 2030 [3].

Indonesia has demonstrated its commitment to this transition through Presidential Regulation No. 55 of 2019, which established ambitious targets for EV adoption. The Ministry of Industry's goal of producing one million four-wheeled EVs by 2035 [4] underscores the nation's dedication to sustainable transportation solutions. However, this transition from internal combustion engine vehicles (ICEs) to EVs introduces new challenges in vehicle design and user experience, particularly in acoustic characteristics.

Mechanical noise quality significantly influences customer acceptance criteria, as users often make subjective judgments about design and manufacturing quality based on a product's acoustic characteristics. When undesirable sound qualities or excessive noise levels are present, they inevitably create negative perceptions of product inferiority. Historically, noise and vibration control in motor vehicles has primarily focused on energy measurements, particularly sound-pressure level values [4,5]. Consequently, noise and vibration control strategies typically involve reducing or eliminating sound sources that generate high sound-pressure levels.

The acoustic environment of EVs differs fundamentally from traditional ICEs, significantly impacting user experience, safety, and comfort [6]. The absence of traditional engine noise creates new considerations for vehicle sound design, requiring careful attention to previously masked sound sources and the introduction of artificial sound cues for safety. Understanding and optimizing these acoustic characteristics is crucial for user acceptance and safety compliance. Psychoacoustic evaluation provides a scientific framework for analyzing and optimizing EV sound characteristics. Key parameters such as loudness, roughness, and sharpness offer quantifiable metrics for assessing sound quality and user perception [7]. These parameters help designers understand the perceived volume of various sound sources, the quality and character of acoustic feedback, and the tonal qualities that influence user comfort and safety awareness.

Developing powertrains for HEVs and BEVs presents unique engineering challenges, particularly in NVH management. Electric motors generate different vibration patterns compared to traditional combustion engines, and their integration with reduction gearboxes creates new high-frequency concerns. The complexity increases due to component interactions and their collective impact on vibration characteristics. Engineers must have a deep understanding of electric motor behavior, drivetrain integration, and overall system dynamics [8,9]. This requires comprehensive analysis, including vibration testing, noise measurement, and dynamic system modeling to effectively identify and resolve NVH issues for improved driving comfort. Adding to these technical challenges, the EV industry faces material supply challenges affecting permanent magnet synchronous motor (PMSM) production costs. While switched reluctance motors (SRMs) offer a cost-effective alternative, they present inferior acoustic properties due to their non-sinusoidal operation and significant harmonic content. At high speeds, these harmonics can trigger structural resonances more readily than PMSMs [10,11].

This study addresses the critical need for comprehensive acoustic analysis of EVs in the Indonesian context, focusing specifically on:

a. Characterizing the acoustic profile of domestically produced EVs
b. Evaluating user perception and comfort factors
c. Developing recommendations for acoustic design optimization

The aim of this study is to contribute to the growing body of knowledge on EV acoustics while providing practical insights for manufacturers and policymakers in emerging markets. This study analyzes and evaluates PT Pindad's production vehicles, specifically the MV2 type electric vehicle (EV) configurations, as tactical vehicles for the military, in

a significant and focused research endeavor. The illustration of the research object can be seen in Figure 1. The adaptation of the MV2 to include components necessary for an electric vehicle (EV) reflects an innovative approach to integrating sustainable technology into military and civilian off-road vehicles. For instance, the electric motor and battery represents a significant shift in the traditional design and functionality of the vehicle. The EV, which is the object of this study, does not yet have an artificial sound design in the vehicle cabin.



Figure 1. MV2 type electric vehicle (EV).

2. Experimental Design and Hybrid Approach

This paper evaluates the acoustic characteristics of electric vehicles (EVs) using both psychoacoustic and soundscape methodologies. Through a psychoacoustic approach, this study recorded objective data from the acoustic environment in the vehicle, both in static and dynamic scenarios, adopting a comprehensive approach to understanding the sound characteristics of the MV2-type electric vehicle (EV). In this experiment, the acoustic data were gathered through audio recording methods, with measurements taken three times at each specified location for 30-min intervals. An illustration of the measurement is shown in Figure 2.



Figure 2. Illustration of acoustic environmental recording using a microphone.

The collected sound recordings underwent psychoacoustic analysis, examining parameters including loudness, roughness, and sharpness, to identify distinct acoustic characteristics across the test conditions. By utilizing MOSQITO to evaluate loudness, roughness, and sharpness, it can identify perceptual differences in sound characteristics between various scenarios. The Modular Sound Quality Integrated Toolbox (MOSQITO) is developed using Python 3.9, a widely adopted and freely available high-level programming language. MOSQITO aims to deliver a unified and adaptable framework for analyzing sound quality and psychoacoustic measurements, offering both free and open-source capabilities that enable consistent testing procedures. Its modular design allows for customization to meet specific analysis requirements [12]. MOSQITO utilizes open-source scientific computing libraries, including SciPy, which provides research-focused computational algorithms for

tasks like signal processing (including convolution, filtering, transfer functions, waveforms, and spectral analysis) [13]. It also employs NumPy for efficient array operations [14] and Matplotlib for creating diverse data visualizations [15].

This information is valuable for understanding how changes in driving conditions affect the overall auditory experience in this study. As a psychoacoustic metric, loudness is crucial for understanding how the human ear perceives sound intensity [16]. In addition, the roughness evaluation quantifies the subjective perception of sound modulated within a specific frequency range (15–300 Hz). This metric is particularly relevant for identifying any unpleasant or discomforting sensations in the auditory experience [17], and sharpness, representing the high-frequency component of the sound signal, helps capture the auditory sensation related to high-frequency content, which can influence the perceived clarity and sharpness of sounds [18].

The soundscape method is an approach in environmental science that focuses on the analysis and interpretation of natural or environmental soundscapes. In measuring subjective data, it is carried out in two stages. The first stage is in-situ measurements, with respondents directly driving the research object and filling in the questionnaire. Meanwhile, in the second stage, the acoustic environment that has been recorded and played back through a virtual environment simulator is reproduced [19]. The total number of respondents who participated was 100 people. Figure 3 shows respondents who participated in providing an assessment of the acoustic environment in-situ (directly in the vehicle) and via a virtual environment. The study involved 50 participants in each test environment. The actual cabin test group comprised 37 males and 13 females, while the virtual environment test had 31 males and 19 females. Participants ranged from 20 to 40 years old and came from both engineering and non-engineering backgrounds.

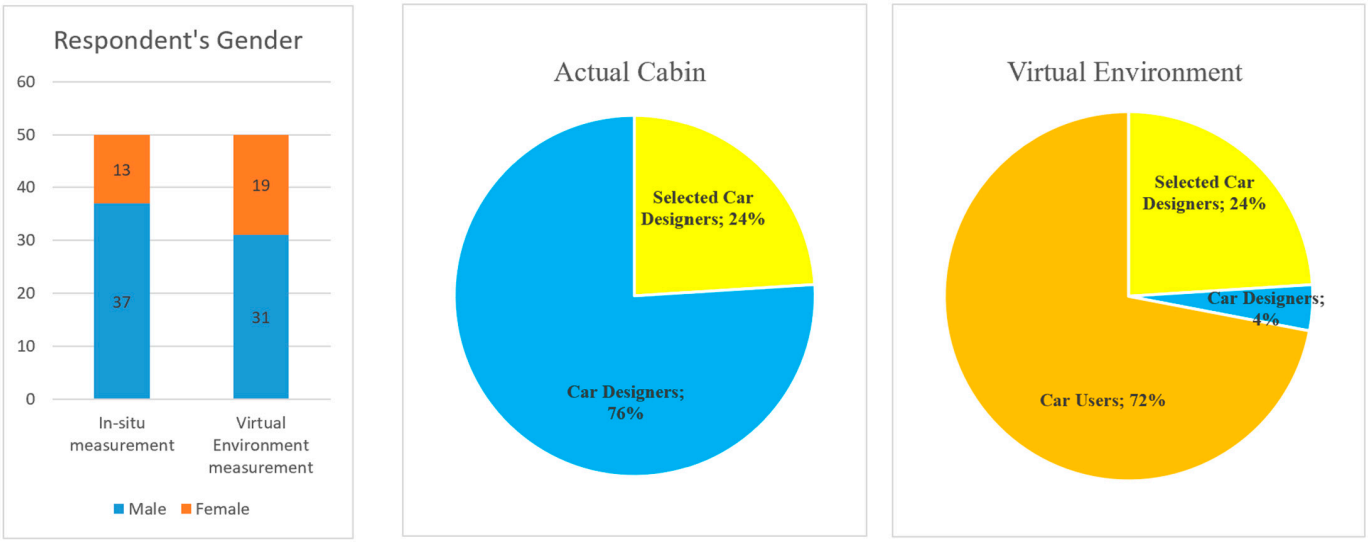


Figure 3. Subjective Measurement Respondent Demographics.

The participant distribution showed that the actual cabin perception test was conducted entirely with car designers, whereas the virtual environment test included both car users (72%) and car designers (28%). Notably, 12 car designers, representing 24% of the participants, took part in both experiments. The vast majority of the participants (over 97%) had normal hearing and vision, including color vision. The selection process was designed to ensure a well-rounded and representative participant sample.

The aim is to understand and characterize all aspects of sound that occur in an environment, including natural sounds, human voices, and artificial sounds. Meanwhile, the psychoacoustic method is a field of scientific research that studies the relationship

between the physical properties of sound (acoustics) and the subjective human perception of that sound. Psychoacoustics examines how humans hear, understand, and respond to different types of sounds. It involves the use of experimental methods to understand human cognitive processes and auditory perception. Hybrid methods in soundscape and psychoacoustics can combine approaches from both fields to gain a more holistic understanding of the sound environment and human auditory perception. Some examples of the use of hybrid methods in both fields include:

- Psychoacoustic-Based Soundscape Analysis: In soundscape research, the use of psychoacoustic methods can help understand how certain acoustic features in the sound environment (such as intensity, frequency, or duration) affect human auditory perception and response. For example, by integrating an understanding of human hearing thresholds with the characteristics of recorded environmental sounds, researchers can identify the sound features that most impact human perception of the quality of the sound environment [20,21].
- Psychoacoustic-Based Sound Environment Design: In sound environment design, a hybrid approach can combine psychoacoustic knowledge of how humans hear and respond to sound with soundscape principles to create more pleasant and productive sound environments. For example, designers can consider the acoustic characteristics of a space (such as the use of appropriate building materials or the placement of sound devices) by taking into account how they will affect the auditory perception and comfort of the space's users.
- Hybrid-Based Sound Quality Assessment: In sound quality assessment, hybrid methods can be used to integrate soundscape and psychoacoustic approaches to provide a more comprehensive understanding of the human auditory experience of a particular sound environment. For example, using a combination of psychoacoustic experimental approaches and qualitative soundscape analysis to evaluate how various sound features in a particular environment affect listener quality and satisfaction.

At this stage, the input of vibration values becomes an additional parameter to support the comfort model in the acoustic environment of EV vehicles. Meanwhile, an analysis of the propagation path of noise, vibration, and harshness sources will be carried out to meet user expectations as stated in the design of the expected acoustic environment character of EV vehicles. The results of this analysis will provide information in the form of confirmation of the propagation path from noise and vibration sources to user perception input.

3. Results and Discussions

The acoustic sources in both electric and internal combustion engine vehicles were characterized by analyzing multiple audio recording metrics. Spectral and amplitude analyses were performed on the recorded acoustic data to map out the various noise contributions, including powertrain, tire-road interaction, aerodynamic, and HVAC system sounds. This sound source identification process is essential for evaluating the in-cabin acoustic environment and highlighting potential refinement opportunities in vehicle development. The results align with earlier research that established engine noise, tire noise, and wind noise as the primary acoustic contributors in vehicles [22,23].

Acoustic measurements revealed distinct differences in A-weighted sound-pressure levels (dB(A)) between EVs and conventional ICE vehicles across various operating conditions. The analysis, which accounts for human hearing frequency sensitivity through A-weighting, demonstrated contrasting noise profiles as illustrated in Figure 4, comparing both static and dynamic scenarios.

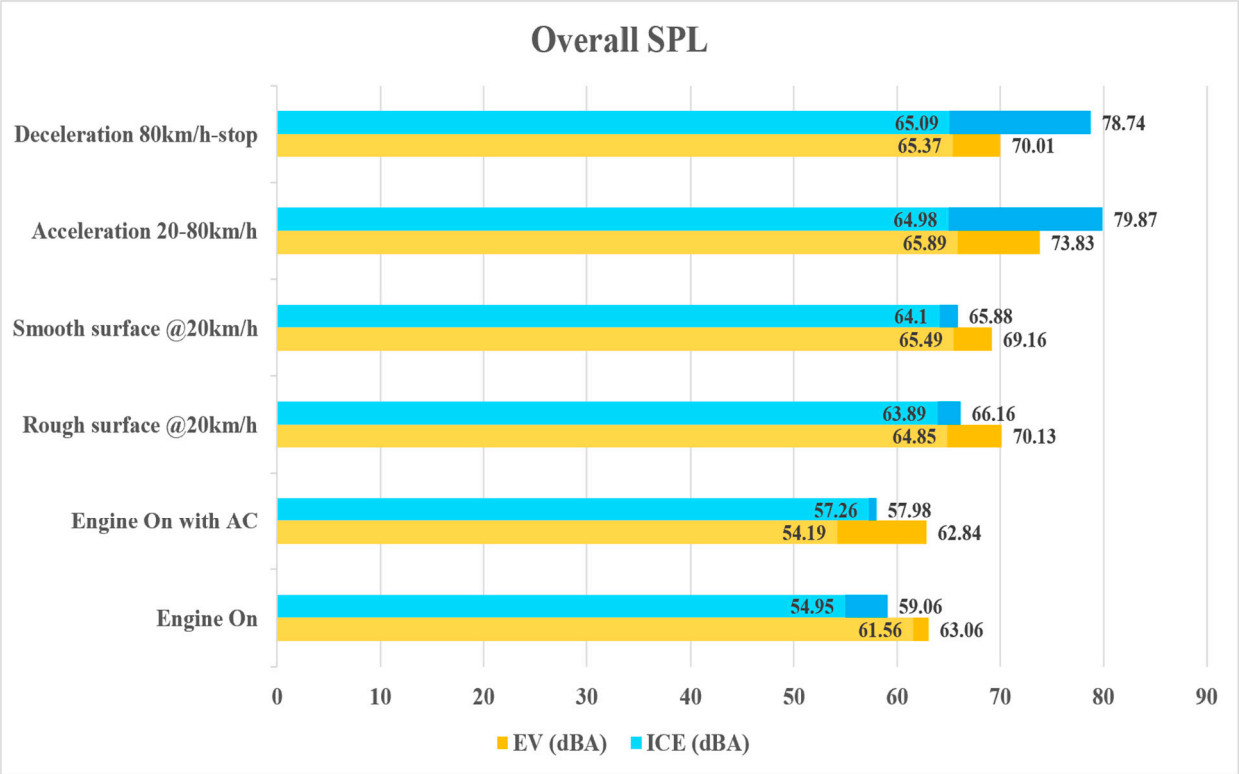


Figure 4. Overall SPL Range Comparison Diagram on EVs and ICEs.(The dark orange or the dark blue represent the range data (minimum and maximum) of SPL for every scenario and vehicle).

Based on the combined static and dynamic measurements shown in Figure 1, the acoustic analysis demonstrated that EVs produced lower overall noise levels compared to ICE vehicles. The acoustic measurements revealed that EVs generated sound-pressure levels between 54.19 dB(A) and 73.83 dB(A), while ICE vehicles produced levels between 57.44 dB(A) and 79.87 dB(A). The noise characteristics varied with operating conditions—ICE vehicles exhibited higher noise levels during movement but lower levels when stationary compared to EVs. The data analysis revealed notable differences between the two vehicle types, with EVs being generally quieter by an average of 4.64 dB(A) and showing a 6.04 dB(A) lower peak noise level compared to their ICE counterparts.

The current findings align with previous research conducted by de Graff and Von Blokland [24] and Ford Motor Company Germany [25]. De Graff and Von Blokland observed a 7 dB noise level difference between EVs and ICE vehicles at low speeds, though this gap diminished with increasing velocity until becoming negligible above 60 km/h. Similarly, Ford Motor Company Germany's research indicated that battery electric vehicles were 2–4 dB quieter than comparable ICE vehicles at 30 km/h, with this acoustic advantage decreasing at higher speeds. Our observation of higher ICE noise levels during dynamic operation corresponds with Jabben, Verheijen, and Potma's findings [26], which documented noise differentials of approximately 10 dB at 10 km/h and 2.5 dB at 50 km/h between an electric Think City (74 kW) and a diesel VW Polo (34 kW).

A comparative analysis of cabin sounds in electric vehicles (EVs) and internal combustion engine (ICE) vehicles reveals both similarities and distinct differences in their acoustic characteristics. While both vehicle types generate similar categories of sounds, they differ significantly in intensity, characteristics, and noise contribution patterns.

The sound profile of EVs includes powertrain (electric motor), EV engine check, HVAC noise, squeak and rattle, rolling noise, aerodynamic noise, acceleration, deceleration, and road bump noise. In contrast, ICEs produce sounds from the ICE starter, powertrain (ICE),

HVAC system, squeak and rattle, rolling noise, aerodynamic noise, shifting gears, acceleration, deceleration, and road bumps. These findings align with research conducted by Rakhim [27], who identified distinct frequency patterns between the two vehicle types. Frequency analysis reveals that EVs demonstrate dominant frequencies in the mid-frequency range (100–4000 Hz), with peak frequencies around 800 Hz. ICEs, however, show dominant frequencies in the bass category (31.5–5000 Hz), with peak frequencies of approximately 630 Hz [27].

As illustrated in Figure 5, ICE vehicles demonstrate that engine and transmission systems constitute major noise and vibration contributors. In contrast, Figure 6 shows that EV noise profiles are dominated by tire-road interaction noise, due to the elimination of combustion engine noise and reduced drivetrain noise. The electric propulsion system also generates notable high-frequency noise and vibration contributions [28]. The analysis confirms that EVs produce distinct acoustic signatures at lower overall sound levels compared to ICE vehicles, with a characteristic tonal component at 500 Hz originating from the electric motor. The low-frequency tonal noise at 500 Hz emitted by electric vehicles can cause significant discomfort and potential health concerns with prolonged exposure. This type of constant, low-frequency sound can impact human wellbeing by causing fatigue, stress, difficulty concentrating, and other physiological effects when individuals are subjected to extended periods of exposure [29].

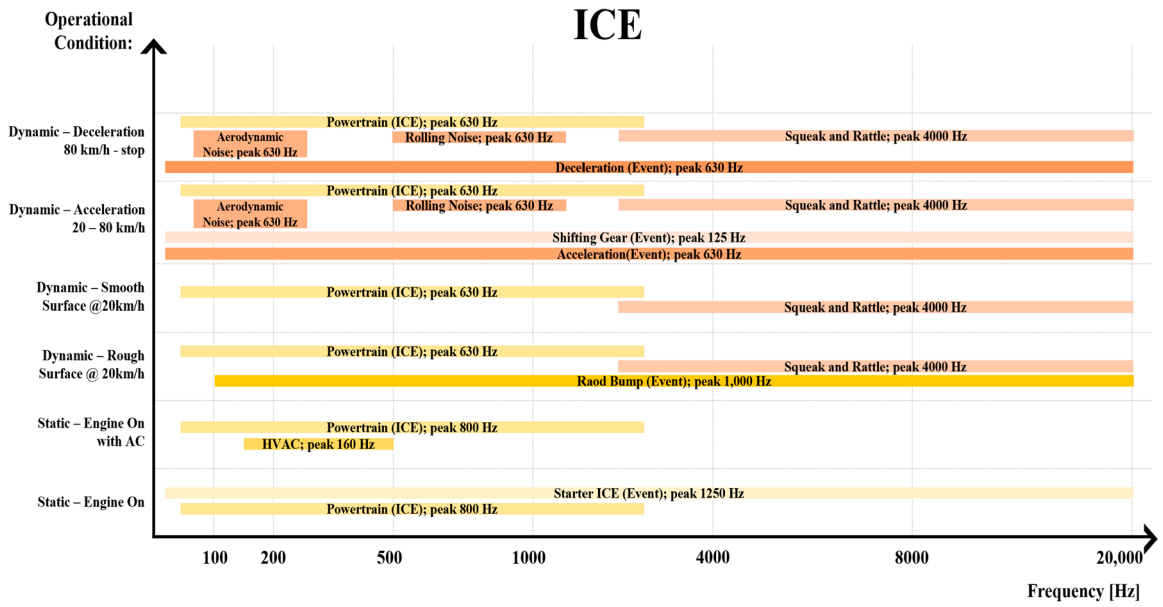


Figure 5. Distribution of sound sources by frequency on ICEs.

The analysis of psychoacoustic parameter values was conducted to evaluate the statistical significance of the absolute differences in mean psychoacoustic measurements across various EV test scenarios. The detailed comparison of absolute differences in average loudness, roughness, and sharpness values is presented in Table 1 of the study.

To understand the relationship between objective measurements and subjective perceptions, correlation analysis was performed. The study aimed to identify how changes in objective parameters influence human perception in the EV cabin environment. It is hoped that control of objective parameters can give rise to subjective perceptions in humans [30], which are intensified in an EV cabin environment. A correlation analysis was carried out between the main perceived values and objective parameters with the aim of identifying the relationship or potential relationship between the variables. The results obtained from the

correlation analysis can be used as a basis for understanding the extent to which changes in objective parameter values can influence changes in key perceptions.

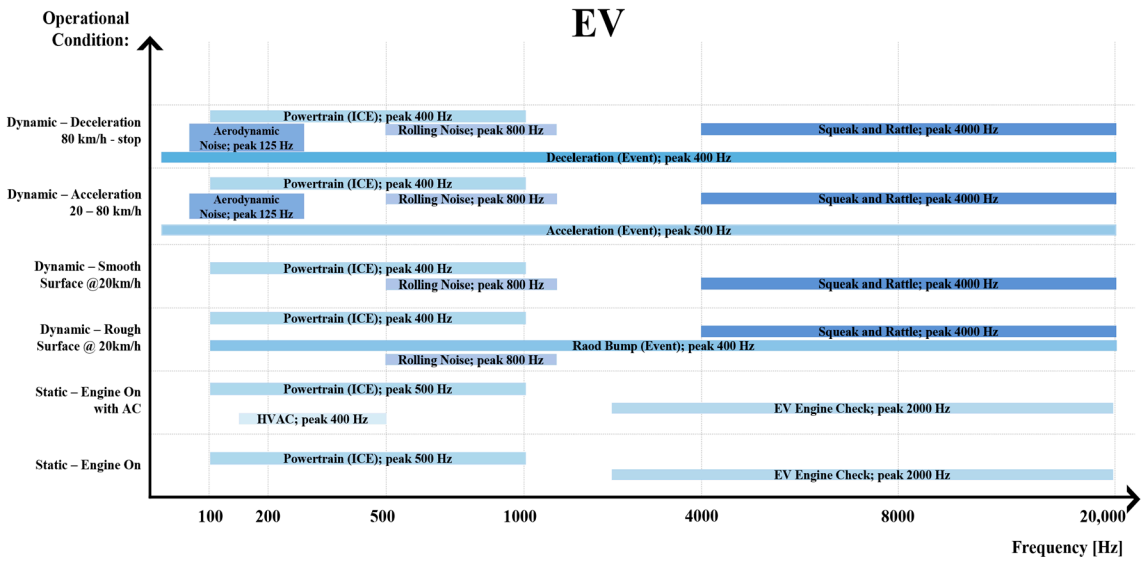


Figure 6. Distribution of sound sources by frequency on EVs.

Table 1. The Average Psychoacoustic Parameter Values on EVs.

Operational Condition	Loudness	Roughness	Sharpness
Engine On	12.71	0.18	2.78
Engine on with AC	19.90	0.14	2.50
Smooth surface @20 km/h	26.55	0.25	2.45
Rough surface @20 km/h	24.76	0.20	2.42
Acceleration 20–80 km/h	35.50	0.28	2.38
Deceleration 80 km/h-stop	30.61	0.28	2.38

Multilinear regression analysis revealed that psychoacoustic variables can predict the main perceptions of "Comfort" and "Dynamics". The comfort model demonstrated an R-value of 0.589, indicating a moderate correlation between psychoacoustic parameters and perceived comfort. Similarly, the dynamics model showed an R-value of 0.412, suggesting a significant relationship between psychoacoustic variables and perceived dynamic characteristics. A negative correlation between psychoacoustic parameters (loudness, roughness, and sharpness) and perception dimensions indicates an inverse relationship with participants' subjective responses. For instance, the comfort dimension's negative correlation suggests a low to moderate inverse relationship with these psychoacoustic parameters, meaning comfort tends to decrease as these parameters increase.

Conversely, the dynamics aspect shows positive correlations with loudness and roughness, indicating that as these sound characteristics increase, the perception of dynamics also increases. However, sharpness demonstrates a negative correlation with the dynamic's aspect, meaning that as sharpness increases, the perception of dynamics tends to decrease. The patterns identified in this study can be understood through the mathematical models presented in Equations (1) and (2). Equations (1) and (2) present the detailed prediction models for both comfort and dynamics perceptions using psychoacoustic variables.

$$Comfort = -0.1648 - 0.0411(Loudness) - 2.3452(Roughness) + 0.9821(Sharpness) \quad (1)$$

$$Dynamic = -2.5167 + 0.0751(Loudness) + 2.9135(Roughness) + 1.0276(Sharpness) \quad (2)$$

Analysis of the comfort prediction model, expressed in Equation (1), reveals the sensitivity patterns between perceived "Comfort" and specific psychoacoustic parameters. The model demonstrates varying degrees of influence across parameters: loudness shows a coefficient of 0.0411, while roughness and sharpness parameters exhibit stronger relationships with coefficients of 2.3452 and 0.9821, respectively. The model's correlation coefficient of 0.5 indicates that psychoacoustic parameters account for approximately 25% of the variance in perceived comfort ratings. This moderate correlation suggests that significant aspects of comfort perception exist beyond measurable acoustic characteristics. The findings demonstrate that, while psychoacoustic parameters contribute to comfort perception, they alone cannot fully represent the complex nature of human auditory experience.

To develop a more comprehensive understanding of comfort perception, future models should incorporate additional variables beyond psychoacoustic parameters. Specifically, the integration of identifiable sound source characteristics, based on user assessments, would likely enhance the model's predictive capability. This multi-factorial approach would better capture the full range of elements contributing to perceived acoustic comfort in vehicle environments.

The quadrant analysis displayed in Figure 7 reveals distinct patterns in the distribution of acoustic data across all four quadrants, each representing different combinations of comfort and dynamic characteristics under various operational conditions. This shows that there is a certain tendency in each operational condition towards the comfort and dynamics aspects. Quadrant I, representing both high comfort and dynamic qualities, contains primarily data from static conditions with the engine running. However, this only happens when the static condition of the engine is on. During these conditions, the main acoustic event is the EV engine check sequence. This acoustic signature appears to meet user expectations, providing necessary vehicle status feedback without compromising comfort. Therefore, this condition can be categorized as something that is desired by the user to know the status of the vehicle in the on condition but does not interfere with user comfort.

The quadrant II data show a strong bias toward dynamic characteristics during deceleration from 80 km/h to a complete stop, though comfort ratings remain relatively low. This suggests that while the vehicle's deceleration sounds convey a sense of responsiveness and control, they may benefit from acoustic refinement to enhance passenger comfort.

In contrast to the operational conditions in quadrant II, quadrant IV demonstrates opposing characteristics, with high comfort but low dynamic ratings under two specific conditions: constant speed operation at 20 km/h on smooth road surfaces; and static conditions with both engine and air conditioning running. The air conditioning system, despite generating dominant acoustic output during static conditions, does not significantly impact passenger comfort negatively. This finding is particularly noteworthy given the relatively high sound-pressure levels measured during these conditions. This suggests that the quality and character of the sound, rather than merely its intensity, plays a crucial role in passenger comfort perception. The perception of users with a tendency to feel more comfortable but lacking in dynamics also occurs during static conditions, especially when the engine is running together with the AC. In the first stage, it was found that the AC has a dominant sound character and a fairly high sound source level during static conditions, but it turns out that this does not have a disturbing impact on passenger comfort.

Analysis of quadrant III data reveals critical acoustic challenges in specific operational conditions. Figure 7 demonstrates that vehicle operation under two specific scenarios produces particularly unfavorable acoustic outcomes: maintaining a constant speed of 20 km/h on rough road surfaces; and accelerating from 20 km/h to 80 km/h. These

conditions generate acoustic signatures that rate negatively in both comfort and dynamic aspects, indicating an acoustic environment that fails to meet user expectations.

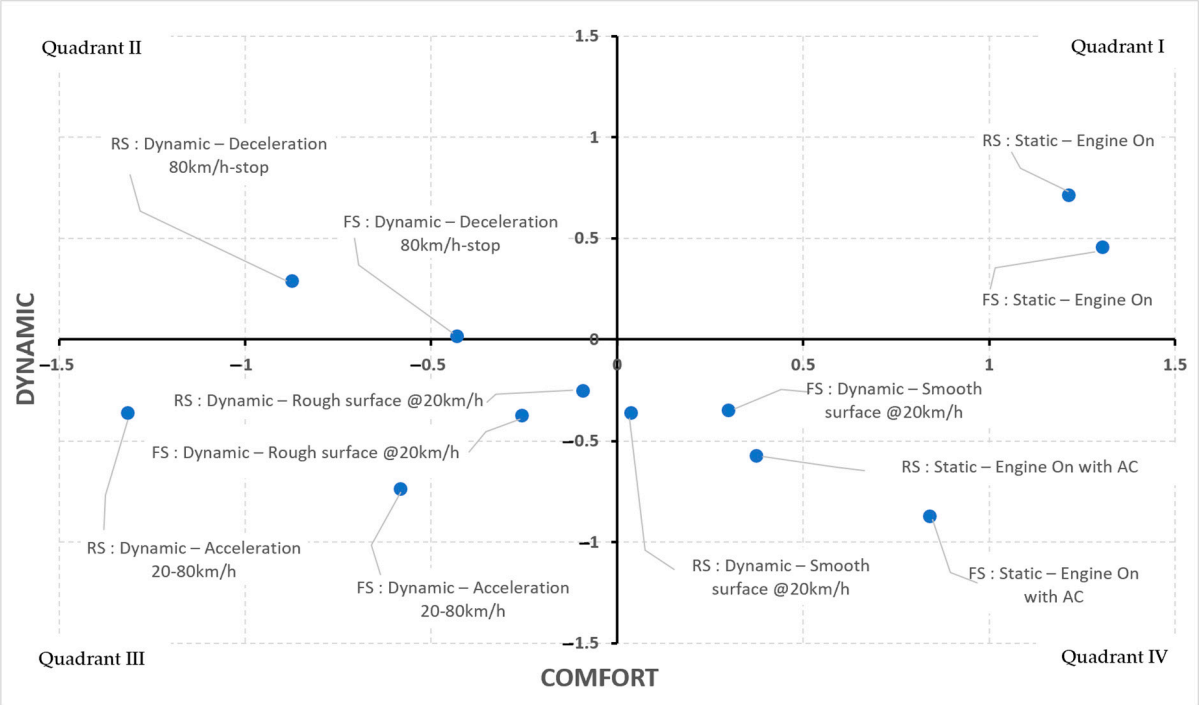


Figure 7. Distribution quadrant of the score components.

This objective analysis aligns with subjective user feedback collected through questionnaire responses (Figure 8), which identified three primary areas requiring acoustic improvement:

- Vehicle frame noise on uneven roads (64% of respondents)
- Tire noise (36% of respondents)
- Acceleration noise (18% of respondents)

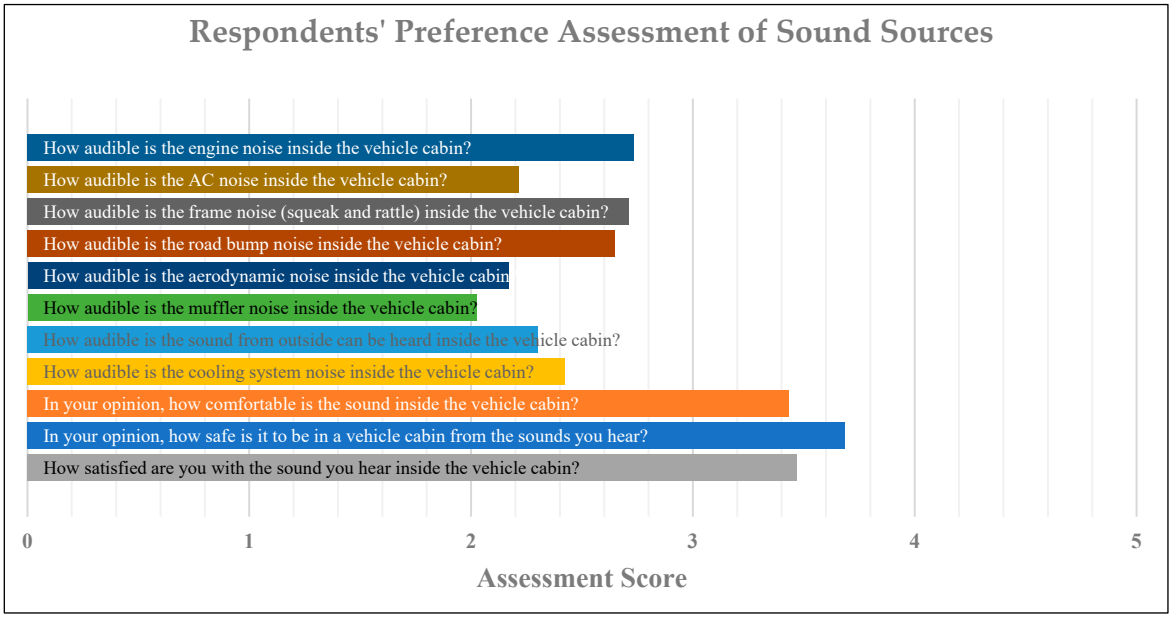


Figure 8. Respondents' Preference Assessment of Sound Sources.

The strong correlation between the quadrant analysis and survey results validates the identification of these operational conditions as priority areas for acoustic refinement. The high percentage of respondents (64%) identifying frame noise on uneven roads as problematic particularly reinforces the findings from the quadrant analysis regarding poor acoustic performance on rough surfaces. This combination of objective measurements and subjective feedback suggests that engineering efforts should prioritize improving the vehicle's acoustic performance during rough road operation and acceleration events. These improvements would address both the measured negative acoustic characteristics and the expressed concerns of EV users.

The next step was providing vibration data to support the validation of a correlation between noise and vibration that produces the effect of NVH to human perception. Based on the vibration data, this study applied an SAE filter to removing high-frequency noise from the measurement data, focusing the analysis on the human-perceptible frequency range and standardizing data processing for vehicle development. The SAE 1000 filter refers to a standard low-pass filter specification from the Society of Automotive Engineers (SAE) commonly used in vehicle data analysis, particularly for NVH measurements. The SAE filter operates by utilizing the Finite Impulse Response (FIR) technique in conjunction with the Remez Exchange Algorithm to establish calculation coefficients that minimize analytical errors. The filter processes raw test data, which typically include high-frequency components generated by mechanical and electrical systems, including sensors. A low-pass filter, specifically the SAE filter, is applied to these data to enhance trend visibility and enable better correlation with target performance parameters. The filters were categorized into four classes based on their cut-off frequencies. For Class 1000 digital filtering, a single 7-point FIR. filter was sufficient. The other digital filtering classes (600, 180, and 60) required a two-stage process that included Class 1000 prefiltering. The analog filters were designed for Class 1000 operations and performed within specifications, with the flexibility to switch to other classes using jumper selections. The coefficients underwent Fourier transform analysis, and the results were visualized in a graph plotting amplitude against frequency. For comparison purposes, the S.A.E.'s acceptable filter-class-response envelope was overlaid on the same graph. [31]. Based on Figure 9, the filtered signal effectively shows the human-perceptible frequency content while removing high-frequency noise, making it suitable for comfort-related analysis.

The analysis revealed elevated vibration levels specifically at the driver's seat compared to other vehicle locations, presenting a significant comfort concern. From an NVH (noise, vibration, and harshness) perspective, this differential in vibration levels directly impacts driver comfort perception. To address these excessive vibrations, enhanced damping mechanisms and design modifications are necessary. Survey results indicate that road-induced noise transmission through the vehicle frame and tires is a major contributor to discomfort, with 64% of participants identifying this as a primary concern. This suggests that improvements in noise reduction from these sources would significantly enhance overall vehicle comfort.

Two graphical representations display the test outcomes: Figure 10 visualizes the vibration response across different frequencies, and Figure 11 represents the acoustic spectrum analysis showing noise intensity at various frequencies. When the accelerometer and microphone data show events at frequencies of 50 Hz, 250 Hz, and 450 Hz, it is essential to interpret these frequency components based on the likely sources and their impacts on the vehicle's acoustics and vibrations. In vehicles, vibrations at lower frequencies like 50 Hz are often associated with the powertrain, suspension, or drivetrain components [32–34]. Vibrations at this frequency could also be related to wheel imbalance or road surface irregularities. For example, uneven or rough roads can induce oscillations in the tires that propagate

into the vehicle body. Vibrations at 50 Hz typically produce low-frequency rumble or vibration sensations, with the amplitude data showing a peak of approximately 0.0003, as illustrated in Figure 10. These can lead to discomfort due to the physical oscillations felt by the driver and passengers. This frequency is often transmitted through the vehicle frame and contributes to the sensation of rough ride quality. The noise measurements conducted using a microphone, as shown in Figure 11, recorded a peak amplitude value of 0.00007.

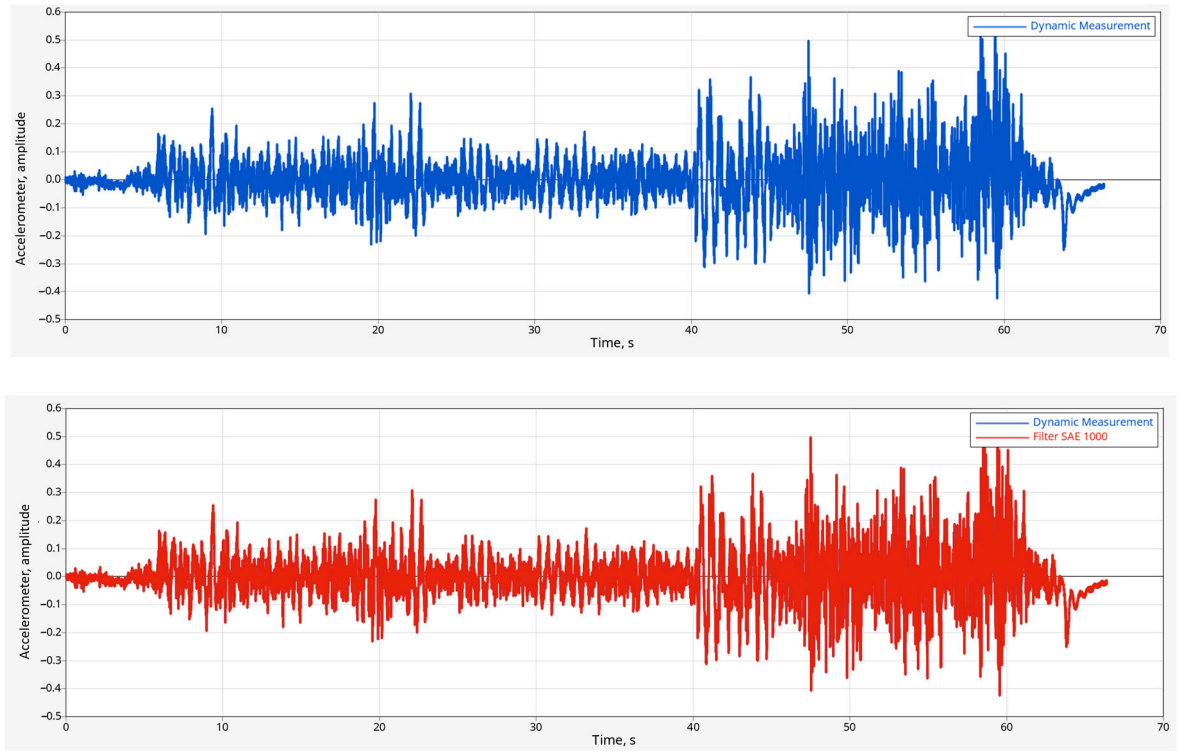


Figure 9. Dynamic measurement analyzed using SAE 1000 filter.

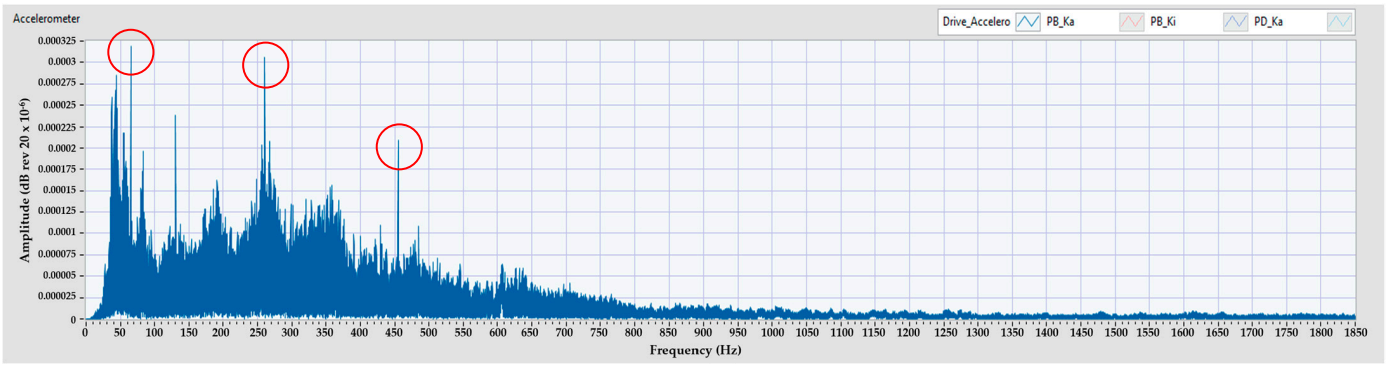


Figure 10. The frequency-dependent vibration characteristics.

Vibrations at around 250 Hz are commonly associated with the contact between tires and the road surface, particularly in EVs where tire noise is a dominant source of noise and vibration. This frequency could also point to chassis or frame resonances, where the vehicle's structure vibrates in response to external forces like bumps or road irregularities. In electric vehicles, harmonics from the electric motor's operation, especially under varying speeds, can produce tonal vibrations in this range. Vibrations at 250 Hz contribute to a mid-frequency droning noise that is noticeable inside the cabin. It is less physically felt as vibration and more experienced as sound, with the amplitude data showing a peak of approximately 0.0003 on the accelerometer measurement and 0.00004 on the microphone

measurement, as illustrated in Figures 10 and 11. If these vibrations are not properly damped, they can affect the overall acoustic comfort, making the cabin environment feel harsher or noisier.

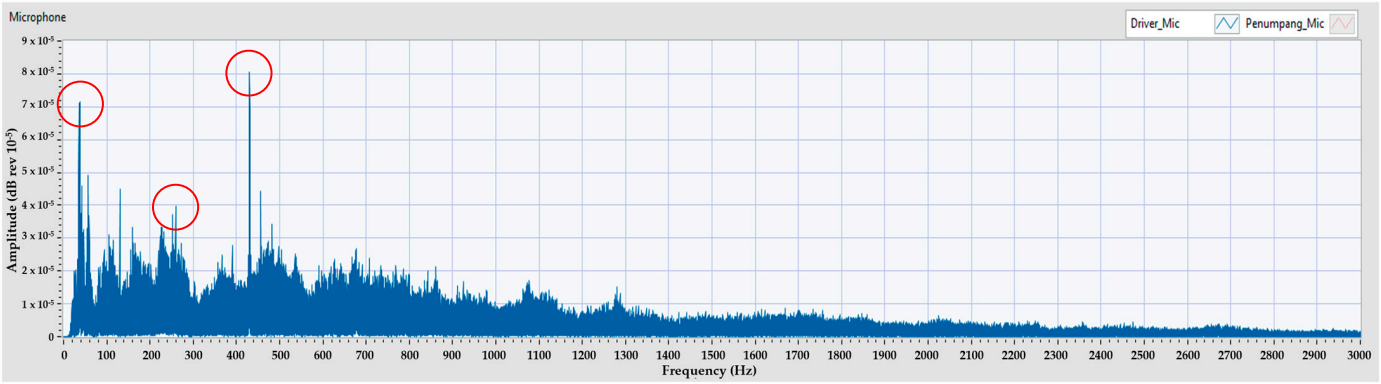


Figure 11. The spectral distribution of noise measurements across the frequency range.

One of the most common sources of vibrations in this range, especially in EVs, is the electric motor, which can produce a tonal sound at around 450–500 Hz. This is typically a dominant frequency in electric motors due to pulse width modulation (PWM) control or other operating characteristics of the motor [35,36]. This could also result from high-speed tire-road interaction, especially at higher vehicle speeds. Vibrations at 450 Hz are usually experienced as a high-pitched whine or tonal noise inside the cabin. These higher frequencies can be annoying and create discomfort, particularly because they are more easily transmitted through the air as sound waves. They can also cause a vibration sensation in the driver's seat or steering wheel, affecting comfort during acceleration or at high speeds.

4. Conclusions

Research comparing subjective comfort assessments with measurable parameters revealed several noise sources needing enhancement, specifically in body acoustics, wheel-generated noise, and acceleration noise. Research participants rated vehicle comfort, safety, and satisfaction with a score of 3, indicating that vehicle acoustic environment design requires further refinement to achieve optimal comfort levels. The comfort model analysis revealed varying relationships between perceptual dimensions (comfort and dynamics) and psychoacoustic parameters. The correlation analysis between comfort perception and acoustic measurements demonstrated diverse relationships: a weak correlation with loudness (0.0411), a strong correlation with roughness (2.3452), and a notable correlation with sharpness (0.9821). With an overall correlation coefficient of 0.5, the findings suggest that additional factors beyond sound color and character influence comfort perception. This demonstrates that psychoacoustic parameters alone are insufficient to fully characterize human perception of vehicle comfort.

The sound propagation analysis identified higher vibration levels in the driver's seat region compared to other vehicle locations, establishing specific areas for enhancement. The study detected notable acoustic events at three distinct frequencies (50 Hz, 250 Hz, and 450 Hz), necessitating detailed analysis to understand their origins and impact on the vehicle's NVH (noise, vibration, and harshness) performance. These findings provide essential guidance for optimizing EV acoustic design to better meet user comfort requirements. The study's hypothesis was confirmed, showing that integrating both psychoacoustic and soundscape parameters creates a more thorough understanding of how passengers perceive vehicle acoustics. This comprehensive approach successfully pinpointed specific areas

requiring acoustic improvement, including frame vibration noise on rough road surfaces, tire noise, and sounds generated during acceleration.

Author Contributions: Conceptualization, K.W.Z.; Data curation, K.W.Z.; Formal analysis, K.W.Z.; Funding acquisition, K.W.Z.; Investigation, K.W.Z.; Methodology, K.W.Z.; Project administration, K.W.Z.; Resources, K.W.Z.; Software, K.W.Z.; Supervision, R.S.J.S., S.P.S. and F.X.N.S.; Validation, K.W.Z.; Visualization, K.W.Z.; Writing—original draft, K.W.Z.; Writing—review and editing, K.W.Z., R.S.J.S., S.P.S. and F.X.N.S. All authors have read and agreed to the published version of the manuscript.

Funding: This study received no external funding.

Data Availability Statement: The original contributions presented in this study are included in the article; further inquiries can be directed to the corresponding author.

Conflicts of Interest: Keysha Wellviestu Zakri and Sigit Puji Santosa is an employee of PT Pindad, Bandung, Indonesia. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. Central Bureau of Statistics. Development of the Number of Motor Vehicles by Type (Unit), 2017–2019. Available online: https://www.bps.go.id/indicator/17/57/1/perkembangan-jumlah-kendaraan-bermotor-menurut-jenis.html (accessed on 6 June 2021).
2. Setyoko, A.T.; Nurcahyo, R.; Gabriel, D.S.; Habiburrahman, M. Policy, Supporting Infrastructure and Market of Electric Cars in Indonesia. In Proceedings of the International Conference on Industrial Engineering and Operations Management, Istanbul, Turkey, 7–10 March 2022.
3. United Nations Climate Change. Enhanced Nationally Determined Contribution Republic of Indonesia 2022. Available online: https://unfccc.int/NDCREG (accessed on 15 June 2024).
4. Instruction of The President Republic of Indonesia Number 7 in 2022. The Usage of Battery-Based Electric Motor Vehicles (Battery Electric Vehicle) as Operational Service Vehicle And/Or Individual Vehicle for Service of Central Government and Regional Government Ministry of Industry of the Republic of Indonesia. 13 September 2022. Available online: https://peraturan.bpk.go.id/Details/225262/inpres-no-7-tahun-2022 (accessed on 15 June 2024).
5. Ivanov, N.I.; Boiko, I.S.; dan Shashurin, A.E. The problem of high-speed railway noise prediction and reduction. *Procedia Eng.* **2017**, *189*, 539–546. [CrossRef]
6. Son, C.; Dong, J.; Bauer, P. Acoustic noise analysis of interior permanent magnet synchronous machine for electric vehicle application. In Proceedings of the 2020 IEEE Transportation Electrification Conference and Expo, ITEC 2020, Chicago, IL, USA, 23–26 June 2020. [CrossRef]
7. Gonzalez, A.; Ferrer, M.; Diego, M.d.; Piñero, G.; Garcia-Bonito, J.J. Sound quality of low-frequency and car engine noises after active noise control. *J. Sound. Vib.* **2003**, *265*, 663–679. [CrossRef]
8. Kosuru, V.S.R.; Venkitaraman, A.K. Trends and challenges in electric vehicle motor drivelines—A review. *Int. J. Electr. Comput. Eng. Syst.* **2023**, *14*, 485–495.
9. NAGASE. The Science of Noise, Vibration and Harshness Control in Electric Vehicle. Available online: https://www.nagase.com/content/dam/nagase-www/en/resources/nvh-reduction/NAM%20NVH%20Reduction%20in%20EVs%20WP%200323.pdf (accessed on 3 September 2024).
10. *Automotive NVH Technology*, 1st ed.; Fuchs, A., Nijman, E., Priebsch, H.-H., Eds.; Springer: Cham, Switzerland, 2015; Volume XVIII.
11. James, B.M.; Hofmann, A. Simulating and reducing noise excited in an EV powertrain by a switched reluctance machine. In Proceedings of the 8th International Styrian Noise, Vibration & Harshness Congress: The European Automotive Noise Conference, Graz, Austria, 2–4 July 2014.
12. Millán-Castillo, R.S.; Latorre-Iglesias, E.; Glesser, M.; Wanty, S.; Jiménez-Caminero, D.; Álvarez-Jimeno, J.M. MOSQITO: An open-source and free toolbox for sound quality metrics in the industry and education. In *INTER-NOISE and NOISE-CON Congress and Conference Proceedings*; Institute of Noise Control Engineering: Washington, DC, USA, 2021.
13. Virtanen, P.; Gommers, R.; Oliphant, T.E.; Haberland, M.; Reddy, T.; Cournapeau, D.; Burovski, E.; Peterson, P.; Weckesser, W.; Bright, J.; et al. SciPy 1.0: Fundamental algorithms for scientific computing in Python. *Nat. Methods* **2020**, *17*, 261–272. [CrossRef] [PubMed]
14. Oliphant, T.E. *A Guide to NumPy*; Trelgol Publishing: USA, 2006; Volume 1, Available online: https://web.mit.edu/dvp/Public/numpybook.pdf (accessed on 12 January 2025).

15. Hunter, J.D. Matplotlib: A 2d graphics environment. *IEEE Ann. Hist. Comput.* **2007**, *9*, 90–95. [CrossRef]
16. Swart, J.; Bekker, A. The Psychoacoustics of Electric Vehicle Signature Sound. 2018. Available online: https://scholar.sun.ac.za/items/216df5a7-c21f-4ece-befb-060f951a3df3 (accessed on 15 June 2024).
17. Fastl, H.; Zwicker, E. *Psychoacoustics—Facts and Models*; Springer: Berlin/Heidelberg, Germany, 2007.
18. Qian, K.; Hou, Z.; Sun, D. Sound quality estimation of electric vehicles based on GA-BP artificial neural networks. *Appl. Sci.* **2020**, *10*, 5567. [CrossRef]
19. Astha, A.; Sarwono, R.S.J.; Sudarsono, A.S.; Nitidara, N.P.A. Exploring the Potential of Virtual Environment for Electric Vehicle: Study Case and Sound Quality Performance. In Proceedings of the Inter-Noise, Tokyo, Japan, 20–23 August 2023.
20. Genuit, K.; Schulte-Fortkamp, B.; Fiebig, A. Psychoacoustics in Soundscape Research. In *Soundscapes: Humans and Their Acoustic Environment*; Schulte-Fortkamp, B., Fiebig, A., Sisneros, J.A., Popper, A.N., Fay, R.R., Eds.; Springer Handbook of Auditory Research; Springer: Cham, Switzerland, 2023; Volume 76. [CrossRef]
21. Engel, M.; Fiebig, A.; Pfaffenbach, C.; Fels, J. A Review of the Use of Psychoacoustic Indicators on Soundscape Studies. *Curr. Pollut. Rep.* **2021**, *7*, 359–378. [CrossRef]
22. Chen, S.M.; Wang, D.F.; Zan, J.M. Interior Noise Prediction of the Automobile Based on Hybrid FE-SEA Method. *Math. Probl. Eng.* **2011**, *2011*, 327170. [CrossRef]
23. Genuit, K. The sound quality of vehicle interior noise: A challenge for the NVH-engineers. *Int. J. Veh. Noise Vib.* **2004**, *1*, 004079. [CrossRef]
24. Graff, E.d.; Blokland, G.V. Stimulation of low noise road vehicles in the Netherlands. In Proceedings of the Inter-Noise, Osaka, Japan, 4–7 September 2011.
25. Dudenhöffer, M.; Hause, L. Sound Perception Of Electric Vehicles. *Auto Tech. Rev.* **2013**, *2*, 44–49. [CrossRef]
26. Jabben, J.; Verheijen, E.; Potma, C.J.M. Noise reduction by electric vehicles in the Netherlands. In Proceedings of the Inter-Noise, New York, NY, USA, 19–22 August 2012.
27. Rakhim, R.F.; Sarwono, R.S.J.; Sudarsono, A.S.; Nitidara, N.P.A.; Zakri, K.W. The Sound Characteristic Of Armored Electric And Internal Combustion Engine SUV. In Proceedings of the Inter-Noise, Tokyo, Japan, 20–23 August 2023.
28. Danko, J.; Milesich, T.; Bucha, J.; Magdolen, L.; Kevicky, I.; Minarik, M.; Miskovic, Z.; Mitrovic, R. Dynamic Properties Modelling Analysis of the Rubber-Metal Elements for Electric Drive. *Stroj. Časopis—J. Mech. Eng.* **2021**, *71*, 19–26.
29. Alves, J.A.; Paiva, F.N.; Silva, L.T.; Remoaldo, P. Low-Frequency Noise and Its Main Effects on Human Health—A Review of the Literature between 2016 and 2019. *Appl. Sci.* **2020**, *10*, 5205. [CrossRef]
30. Purnomo, O.; Talita, C.; Sarwono, R.S.J.; Sudarsono, A.S. Sound quality objective evaluation of electric and combustion engine cars. In Proceedings of the Euronoise, Madeira, Portugal, 25–27 October 2021.
31. Reichert, J.K.; Landolt, J.P. *Digital and Analog Filters for Processing Impact Test Data*; SAE Technical Paper 810813; SAE: Warrendale, PA, USA, 1981.
32. Azadi, S.; Azadi, M.; Zahedi, F. NVH analysis and improvement of a vehicle body structure using DOE method. *J. Mech. Sci. Technol.* **2010**, *23*, 2980–2989. [CrossRef]
33. Li, L.; Wang, Z. Research on simulation method of low-frequency road noise based on modal tires. In Proceedings of the Annual Meeting of China Automotive Engineering Society, Shanghai, China, 5–7 June 2014; pp. 1328–1331.
34. Yu, Z.; Cheng, D.; Huang, X. Low-Frequency Road Noise of Electric Vehicles Based on Measured Road Surface Morphology. *World Electr. Veh. J.* **2019**, *10*, 33. [CrossRef]
35. O'Boy, D.; Tuplin, S.; Ebrahimi, K. Experimental Outdoor Vehicle Acoustic Testing Based on ISO-362 Pass-by-Noise and Tyre Noise Contribution for Electric Vehicles. *World Electr. Veh. J.* **2024**, *15*, 485. [CrossRef]
36. Horváth, K.; Zelei, A. Simulating Noise, Vibration, and Harshness Advances in Electric Vehicle Powertrains: Strategies and Challenges. *World Electr. Veh. J.* **2024**, *15*, 367. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.