

Systematic Review

Noise Level Index in Transport Cabins: A Systematic Review of Measurement Methods, Passenger Impacts, and Mitigation Strategies

Jean-Paul Kapuya Bulaba Nyembwe ¹, John Omomoluwa Ogundiran ¹, Mihail Fontul ², Anderson D'Oliveira ³,
Alexandro Andrade ³ and Manuel Gameiro da Silva ^{1,*}

¹ Department of Mechanical Engineering, ADAI, University of Coimbra, Pólo II, Rua Luís Reis Santos, 3030-788 Coimbra, Portugal; kapuyanyembwe@efs.uc.pt (J.-P.K.B.N.); jogundiran@dem.uc.pt (J.O.O.)

² IBER-OLEFF Componentes Técnicos em Plástico Sa Parque Industrial Manuel da Mota, Lt 10/18, 3100-354 Pombal, Portugal; mihailfontul@gmail.com

³ Health and Sports Science Center, Laboratory of Sport and Exercise Psychology, LAPE, Santa Catarina State University, UDESC, Florianopolis 88035-901, Brazil; anderson.oliveira3@edu.udesc.br (A.D.); alexandro.andrade@udesc.br (A.A.)

* Correspondence: manuel.gameiro@dem.uc.pt

Abstract

This systematic review summarizes a 30-year body of research (1996–2025) on in-cabin noise measurement and evaluation across transport modes, including road, rail, air, hybrid and electric vehicles. Guided by the PRISMA 2020 framework, 38 included records were identified and analyzed, comprising 33 empirical and 5 standards/guideline documents to address six research questions (RQ1–RQ6): the distribution of studies by mode and context, the methods and descriptors employed, comparative strengths and weaknesses of standard and psychoacoustic metrics, the identification of dominant noise sources and mitigation strategies, the development of a hybrid integrated noise index, and the existence of electric-vehicle-specific indicators. Results show that the equivalent continuous sound level (Leq) remains the most widely used descriptor due to regulatory acceptance. In contrast, psychoacoustic parameters such as loudness and sharpness show stronger correlations with perceived comfort and annoyance. Hybrid indices VACI, NCI, NAFI, and SQI offer enhanced predictive accuracy but are mainly limited to automotive and HVAC contexts. Primary interior noise sources include powertrain, tire–road or wheel–rail interactions, and HVAC systems, with effective mitigation achieved through acoustic insulation, aerodynamic refinement, and active noise control below 300 Hz. To unify these approaches, this review proposes a Hybrid Integrated Cabin Noise Index (HCNI) that combines physical SPL metrics with perceptual psychoacoustic descriptors, all measured under standardized protocols. The HCNI framework provides a pathway toward a cross-modal, perception-driven standard for evaluating acoustic comfort in next-generation transport cabins, including electric and autonomous vehicles.

Keywords: in-cabin noise; noise comfort index; psychoacoustics; vehicle acoustics; hybrid noise index; vehicle interior noise; transport cabins; occupational exposure; passenger comfort; indoor environmental quality



Academic Editors: Gaetano Licitra, Riccardo Mastrantonio, Loreta Tobia, Mario Muselli, Matteo Vitali and Claudiu T. Lungu

Received: 8 September 2026

Revised: 28 September 2026

Accepted: 12 October 2026

Published: 20 October 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

Noise inside transport cabins is widely recognized as a critical environmental and ergonomic factor influencing passenger comfort, safety, and health. Across diverse modes

of transportation, including road vehicles, rail systems, aircraft, and maritime vessels, cabin noise arises from a complex interplay of aerodynamic forces, mechanical systems, structural vibrations, and auxiliary equipment, often interacting in ways that produce highly variable acoustic environments [1,2]. Interestingly, in developed regions such as the EU, about 100 million people are estimated to be exposed to harmful road traffic noise, necessitating various interventions (including special noise barriers) to mitigate the risk [3]; however, vehicle interior noise suggests that exposure extends to vehicle occupants both indoors and outdoors. Mitigating immediate noise and annoyance risks to vehicle passengers is also needed, providing a holistic approach to combating noise-associated risks. To quantify and characterize these environments, the Noise Level index has emerged as a standardized framework, most commonly expressed in A-weighted decibels [dB(A)] to align with the frequency sensitivity of human hearing (ISO 1996-1:2016) [4]. Typical assessments employ the equivalent continuous sound level (L_{eq}) as a primary descriptor, supplemented by maximum sound level (L_{max}) and statistical indicators such as L_{10} and L_{90} , which capture temporal variations and noise distribution over time [5].

The current review motivation hinges on the existential risks posed by suboptimal acoustic performance and the occupational hazards associated with interior vehicle noise. Notably, poor indoor environmental quality (IEQ) parameters in transport microenvironments, including noise, air quality, thermal and visual comfort, can pose elevated risks to occupants with longer exposure durations, alongside other factors such as occupancy density, pollutant concentrations, heating, ventilation, and air conditioning (HVAC) system/settings, cabin geometry, vehicle age and condition. However, vehicle interior noise is often underrepresented in these risk factors, even though the aforementioned factors, combined with elevated noise and annoyance, adversely affect health, comfort, well-being, and performance. Commuting on public transport can exceed the reported average of 4–7% of modern man's daily indoor time spent in transport microenvironments, underscoring the need to mitigate risks associated with commuting and occupational exposure [6]. Evidence from the London Underground further demonstrates that routine metro commuting can contribute substantially to cumulative daily noise exposure, highlighting the importance of assessing passenger exposure using standardized dosimetry and exposure-based acoustic metrics [7]. Moreover, besides the long-exposure tendency for passengers and drivers during long hauls, professional drivers, transport operators, delivery personnel, and other mobile workers experience prolonged exposure to vehicle-cabin noise as part of their occupational environment. Understanding and characterizing this exposure is essential for assessing potential impacts on comfort, stress, fatigue, cognitive performance, and IEQ condition in transport cabins.

Notably, a recent review of vehicle cabin climate has highlighted that noise remains one of the least integrated dimensions of the in-vehicle environment [8]. While thermal comfort and air quality are increasingly assessed using standardized indicators, the evaluation of interior noise remains fragmented, relying largely on separate physical metrics (e.g., sound pressure level (SPL)) and psychoacoustic descriptors such as loudness, sharpness, and roughness [9,10]. Recent research shows that objective noise measurements alone are insufficient to explain occupants' perceived acoustic comfort, particularly in EVs, where the absence of engine masking reveals new tonal and high-frequency sounds that significantly affect user perception [11]. Empirical investigations reveal substantial variation in cabin noise levels across transport modes and operational contexts. For instance, typical cruise noise levels in commercial aircraft range from 80 to 85 dB(A), with peaks near 88 dB(A), while high-speed trains may average 70–75 dB(A) depending on track smoothness and aerodynamic conditions [12]. Although these levels often remain below occupational hazard thresholds, research indicates that even moderate noise can impair speech intelligibility,

elevate physiological stress responses, and reduce perceived service quality, particularly with prolonged exposure [13,14]. Chronic exposure above 85 dB (A) is associated with increased risks of hearing loss and cardiovascular effects [15], underscoring the importance of precise measurement and targeted mitigation [11,16,17]. Focusing on vehicle acoustics and EVs highlights prevailing knowledge gaps regarding the integration of quantitative acoustic indicators with qualitative human-centered assessments of soundscape and comfort. Despite advances in sound-quality evaluation, no widely accepted integrated noise index exists to simultaneously capture physical exposure and subjective perception within vehicle cabins, and this gap is even more pronounced for EVs [11]. Furthermore, the rapid transition toward electrified transportation introduces new acoustic exposure profiles that require updated assessment frameworks.

International standards, such as ISO 5128:2023 [18] for Road vehicles, ISO 5129 [19] for aircrafts and ISO 3381 [20] for railway vehicles, provide guidelines for in-cabin noise assessment. These guidelines prescribe instrumentation protocols, microphone placement, and operational-phase categorization to ensure reproducibility. Despite these standards, cross-study comparability remains challenging due to differences in study design, weighting filters, sampling durations, and environmental conditions. To address these limitations, recent research has increasingly incorporated psychoacoustic metrics, such as loudness, sharpness, and fluctuation strength, which offer more profound insight into subjective comfort perceptions than physical measurements alone [21]. However, comprehensive cross-modal analyses integrating both physical and perceptual data remain scarce, despite their essential role in advancing vehicle design, refining regulatory frameworks, and guiding innovations in passive and active noise control technologies.

Within this broader context, noise and vibration harshness (NVH) performance has become a defining factor in the overall quality perception of modern vehicles, influencing both measurable comfort indices and subjective user satisfaction. Among the various in-cabin noise sources, the HVAC system is particularly significant, especially in low-engine noise conditions, such as those found in hybrid and electric vehicles [22]. Although HVAC noise is typically not the dominant sound source, its psychoacoustic attributes, loudness, sharpness, and roughness, induce annoyance, distraction, and a decline in perceived acoustic comfort [23,24]. This has prompted a shift from merely reducing SPL to actively enhancing sound quality (SQ) through psychoacoustic optimization and sound design strategies [13,14].

Traditional noise evaluation approaches, dominated by SPL and dB(A) metrics, often fail to capture the nuanced perceptual dimensions of acoustic comfort [25,26]. Studies have shown that psychoacoustic metrics such as Zwicker loudness, sharpness, roughness, and fluctuation strength correlate more strongly with human auditory perception than SPL alone [14,24]. For example, Yoon et al. [15] demonstrated that regression and neural network models combined with semantic differential methods can effectively predict “pleasantness” from objective metrics, with neural networks outperforming statistical models due to their ability to model complex perceptual relationships. Similarly, Kumar and Riyazuddin found strong correlations between statistical loudness/roughness and subjective annoyance ratings in rattle-noise evaluations of air-vent assemblies [27]. The assessment of acoustic comfort has also evolved toward soundscape approaches, satisfaction-based indices, and hybrid frameworks that integrate physical measurements with perceptual and contextual factors [26]. This shift reflects recognition that passenger comfort perception is influenced not only by measurable acoustic variables but also by cognitive, affective, and situational elements [11,26]. Notably, psychoacoustic parameters alone may account for only part of the variance in perceived comfort, underscoring the need for multimodal, context-aware evaluation methods. The transition to electric and

hybrid mobility has further reshaped NVH profiles, reducing traditional engine noise and increasing the relative prominence of auxiliary sources such as HVAC systems, tire–road interaction, and aerodynamic vents [22,28]. Comparative studies between internal combustion engine vehicles (ICEVs) and hybrid/electric vehicles (HEVs) show that HVAC noise, once masked by engine operation, now plays a more dominant role in shaping cabin acoustics, requiring more precise prediction and mitigation strategies [22]. Effective noise-refinement solutions, including structural modifications, the application of acoustic felts, and vent-geometry optimization, have demonstrated reductions in both SPL and tonal peaks, thereby improving perceived quality [25,28]. Given the diversity of transport modes, noise sources, measurement methods, and descriptors employed in the literature, a systematic review is necessary to consolidate existing evidence, identify methodological trends, highlight knowledge gaps, and propose a framework for integrated noise evaluation in transport cabins. Notably, besides the fundamental objective of enhancing the interior IEQ comfort metrics of vehicles, the proposed integrated framework, which combines physical and psychoacoustic metrics, aligns with the advancements and evolutions of soundscape science, with respect to the objectives of environmental acoustics [29]. Additionally, this SLR focuses on improving the acoustic environment of vehicle interiors; to this end, we used a fundamental and successful methodological approach: defining research questions (RQs) to be answered, following the method used in these studies [30–32]. The six RQs are as follows:

1. RQ1: What are the characteristics, transport modes, geographical contexts, and study distributions of the included records?
2. RQ2: Which sound descriptors and measurement methods are used to assess interior transport-cabin noise?
3. RQ3: What are the strengths, weaknesses, opportunities, and threats (SWOT) associated with the principal noise descriptors and indices?
4. RQ4: What are the dominant cabin-noise sources and reported mitigation strategies across transport modes?
5. RQ5: What evidence supports the development of an integrated Hybrid Integrated Cabin Noise Index (HCNI), and what should its conceptual structure contain?
6. RQ6: Does a dedicated or universally recognized electric-vehicle-specific noise index currently exist?

2. Materials and Methods

This systematic review was planned and conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses to ensure a transparent, reproducible, and rigorous synthesis of the available evidence. A review protocol was prepared before the literature search and specified the research question, eligibility criteria, search strategy, screening procedures, and data-extraction methods. However, the protocol was not prospectively registered in a public systematic-review registry; therefore, no registration number is available. The objective of the review was to identify and synthesize empirical studies that quantitatively assessed noise levels or related acoustic parameters within transport-cabin microenvironments across different modes of transportation, including road vehicles, rail systems, aircraft, and maritime vessels.

2.1. Inclusion and Exclusion Criteria

Eligibility criteria were defined as a priority and applied consistently throughout screening. The criteria considered publication characteristics, language, study context, and methodological approach. Studies were considered eligible when they investigated noise within passenger or crew compartments and reported quantitative acoustic measurements

obtained using appropriate measurement instrumentation. Eligible studies were empirical investigations published between January 1996 and December 2025 in peer-reviewed journals, Scopus-indexed conference proceedings, book chapters, or official technical and scientific reports. Only studies published in English were included. Eligible studies were required to investigate noise within transport-cabin or passenger-compartment microenvironments and to provide quantitative acoustic measurements, including descriptors such as equivalent continuous sound level (Leq), maximum sound level (Lmax), L10, L90, sound exposure level (SEL), or other relevant acoustic or psychoacoustic parameters. Studies also had to provide sufficient methodological information to identify the measurement procedures, instrumentation, and principal operating conditions. Numerical or simulation-based studies were considered eligible only when their results were supported by experimental validation. Studies were excluded when they were review articles, non-indexed literature, unpublished drafts, books without an empirical research component, or other publications outside the predefined evidence categories. Publications not available in English were also excluded. Studies investigating external vehicle noise, environmental or ambient noise, buildings, or other non-transport environments were excluded because they did not address the target transport-cabin microenvironment. Similarly, numerical or simulation studies without experimental validation and studies focused on occupational noise in maintenance, industrial, or other contexts unrelated to passenger-cabin environments were excluded. Studies for which the available methodological information was insufficient to determine the measurement procedures, instrumentation, or principal operating conditions were also excluded because their findings could not be reliably interpreted or incorporated into the planned synthesis. The complete inclusion and exclusion criteria are presented in Table 1.

Table 1. Inclusion and Exclusion Criteria for Study Selection.

Inclusion	Exclusion
Published empirical studies between January 1996 and December 2025 in peer-reviewed journals, Scopus-indexed conference proceedings, book chapters, and official technical reports were included.	Review papers, grey reports, literature, unindexed articles, reports, conference proceedings, books, and technical drafts.
Only articles and indexed scientific reports in English	Articles and reports that were not in English
Noise assessment studies of vehicle interior and transport microenvironment	Noise assessment studies in buildings of any type, or vehicle exterior, and ambient noise
Noise studies that applied Numerical or simulation approaches with experimental validation.	Noise studies that applied Numerical and simulation approaches without experimental validation, or occupational noise in maintenance and industrial contexts unrelated to passenger cabins

2.2. Literature Search Strategy

A comprehensive literature search was conducted in Scopus, Web of Science Core Collection, ScienceDirect, and the Transportation Research Information Database (TRID). Supplementary searches were conducted in Google Scholar and ResearchGate to identify additional relevant records and potentially overlooked technical or grey-literature sources. The reference lists of relevant publications were also manually screened to identify additional eligible studies. The searches were conducted during the final literature-search phase of the review, with the publication period extending through December 2025, consistent with the predefined eligibility criteria. The database-specific search strategies combined terms describing transport-cabin noise, transportation modes, and acoustic measurement or assessment. Boolean operators, phrase searching, and truncation were used where supported by the individual databases.

The principal Scopus search strategy was structured as follows: (“cabin noise” OR “interior noise” OR “in-cabin noise” OR “noise level index” OR “Leq” OR “Lmax”) AND (“aircraft” OR “bus” OR “train” OR “railway” OR “metro” OR “ship” OR “ferry” OR “vehicle”) AND (“measurement” OR “assessment” OR “evaluation”). Equivalent database-specific adaptations were developed for Web of Science, ScienceDirect, and TRID according to their respective search interfaces, field restrictions, Boolean syntax, and truncation functions. The complete database-specific search strategies, including the searched fields, Boolean operators, truncation symbols, phrase restrictions, and publication-date limits, are provided in Supplementary Table S1 to facilitate reproducibility. The search date for each database and supplementary source is also reported in Supplementary Table S1. Google Scholar and ResearchGate were used as supplementary discovery sources rather than primary bibliographic databases. Searches in these sources were restricted to the predefined publication period and search concepts, and all identified records were subjected to the same eligibility and screening procedures as records retrieved from the primary databases. Reference-list screening of relevant publications was additionally conducted to identify potentially eligible studies not retrieved through the database searches. All retrieved records were imported into EndNote X9 for reference management and duplicate identification. Duplicate records were removed before title and abstract screening.

2.3. Study Selection Method

Following the removal of duplicate records, the retrieved records were screened in two sequential stages. First, titles and abstracts were independently assessed by two reviewers against the predefined eligibility criteria. Records considered potentially relevant by either reviewer were subsequently retrieved for full-text assessment. The full texts were independently evaluated against the inclusion and exclusion criteria, with disagreements resolved through discussion and consensus. The principal reasons for full-text exclusion were documented during the selection process. The overall study-selection process is presented in the PRISMA 2020 flow diagram.

2.4. Methodological Assessment and Data Extraction

A structured methodological reporting framework was applied to characterize the completeness of the included studies. Five domains were evaluated: instrumentation, calibration, operating and environmental conditions, measurement protocol, and data analysis/reporting. Each domain was scored from 0 to 2 (maximum score = 10). This framework was used to assess reporting transparency and guide interpretation rather than as a formal risk-of-bias instrument. The assessment was used to characterize methodological reporting and to inform the interpretation and synthesis of the evidence, rather than as a post-inclusion exclusion criterion. Data from all included studies were extracted using a standardized data-extraction form to ensure consistency across the review. The extracted information included bibliographic characteristics such as authors, publication year, and country, as well as transport mode, vehicle or cabin type, study setting, and passenger or crew compartment characteristics. Information concerning measurement methodology was extracted, including instrument type, calibration procedures, microphone placement, frequency weighting, measurement duration, sampling conditions, and applicable measurement standards. Operational conditions, such as vehicle speed, passenger or load conditions, and other relevant environmental or operational factors, were recorded where available. The reported acoustic outcomes included Leq, Lmax, L10, L90, SEL, and psychoacoustic parameters, together with information concerning compliance with relevant international measurement standards and the principal implications of the findings for passenger comfort, health, exposure, or transport-cabin design. Where reported, exposure duration, TWA, noise dose or dosimetry, and vibration measurements were also extracted

to assess cumulative exposure and the extent to which noise and vibration were jointly considered within the NVH framework. Particular attention was given to methodological characteristics that could influence the comparability of reported noise measurements, including acoustic instrumentation and calibration, microphone location, frequency weighting, measurement duration, operating and environmental conditions, and the application of recognized standards such as ISO 3381, and ISO 5129, where applicable. These characteristics, together with the methodological quality assessment, were considered during the interpretation and comparative synthesis of the evidence. The percentile noise levels L10–L90 were treated as separate acoustic descriptors throughout the review and were not combined into a single notation, as such a representation could be misinterpreted. Where both percentile levels were reported, the difference between L10–L90 was considered as a potential indicator of temporal variability in the measured cabin-noise environment. Accordingly, L10–L90 remained distinct variables during data extraction and synthesis.

2.5. Data Synthesis

The extracted data were compiled into comparative tables to facilitate the cross-modal analysis of cabin-noise levels, measurement methodologies, and reported acoustic descriptors. Particular attention was given to differences among road, rail, aviation, and maritime transport environments, as well as to differences in measurement procedures, operating conditions, and acoustic metrics. The synthesis also considered the extent to which standardized measurement procedures were applied and whether reported measurements could reasonably be compared across studies. Where measurement methods, operating conditions, study characteristics, and reported acoustic metrics were sufficiently homogeneous, quantitative synthesis or meta-analysis was considered. However, substantial methodological and contextual heterogeneity was anticipated across transport modes and study designs. Therefore, where statistical pooling was not considered appropriate, a qualitative and comparative synthesis was conducted to identify recurring patterns, methodological differences, evidence gaps, and factors influencing noise levels within transport cabins.

3. Results

3.1. Results Summary

A systematic literature search identified 1290 records, comprising 1245 publications retrieved from Scopus, Web of Science Core Collection, ScienceDirect, and the TRID, together with 45 additional records identified through searches of grey literature sources, including Google Scholar and ResearchGate. After removing 190 duplicate records and five records excluded for other reasons, 1095 unique publications remained for title and abstract screening. During this stage, 930 records were excluded because they did not meet the predefined inclusion criteria. The full texts of 165 potentially relevant publications were sought for retrieval, of which three reports could not be obtained. Consequently, 162 full-text articles were assessed for eligibility. Following detailed evaluation, 124 studies were excluded because they did not satisfy the eligibility criteria, owing to insufficient methodological reporting, failure to satisfy the predefined eligibility criteria, or duplication of previously published work. The selected studies represent a comprehensive body of evidence on transportation cabin acoustics, encompassing investigations of passenger cars, buses, coaches, heavy vehicles, commercial vehicles, railway systems, aircraft cabins, and HVAC systems. Together, they provide a robust foundation for examining noise sources, assessment methodologies, psychoacoustic descriptors, passenger comfort, and noise mitigation strategies across different transportation environments. Figure 1 illustrates the study selection process, summarizing the identification, screening, eligibility assessment,

and final inclusion of studies in accordance with the PRISMA 2020 reporting guidelines. The final evidence set comprised 38 included records, including 33 empirical studies and five standards and guideline documents. Standards and guidelines were synthesized separately from empirical studies because they provide normative methodological guidance rather than original empirical evidence.

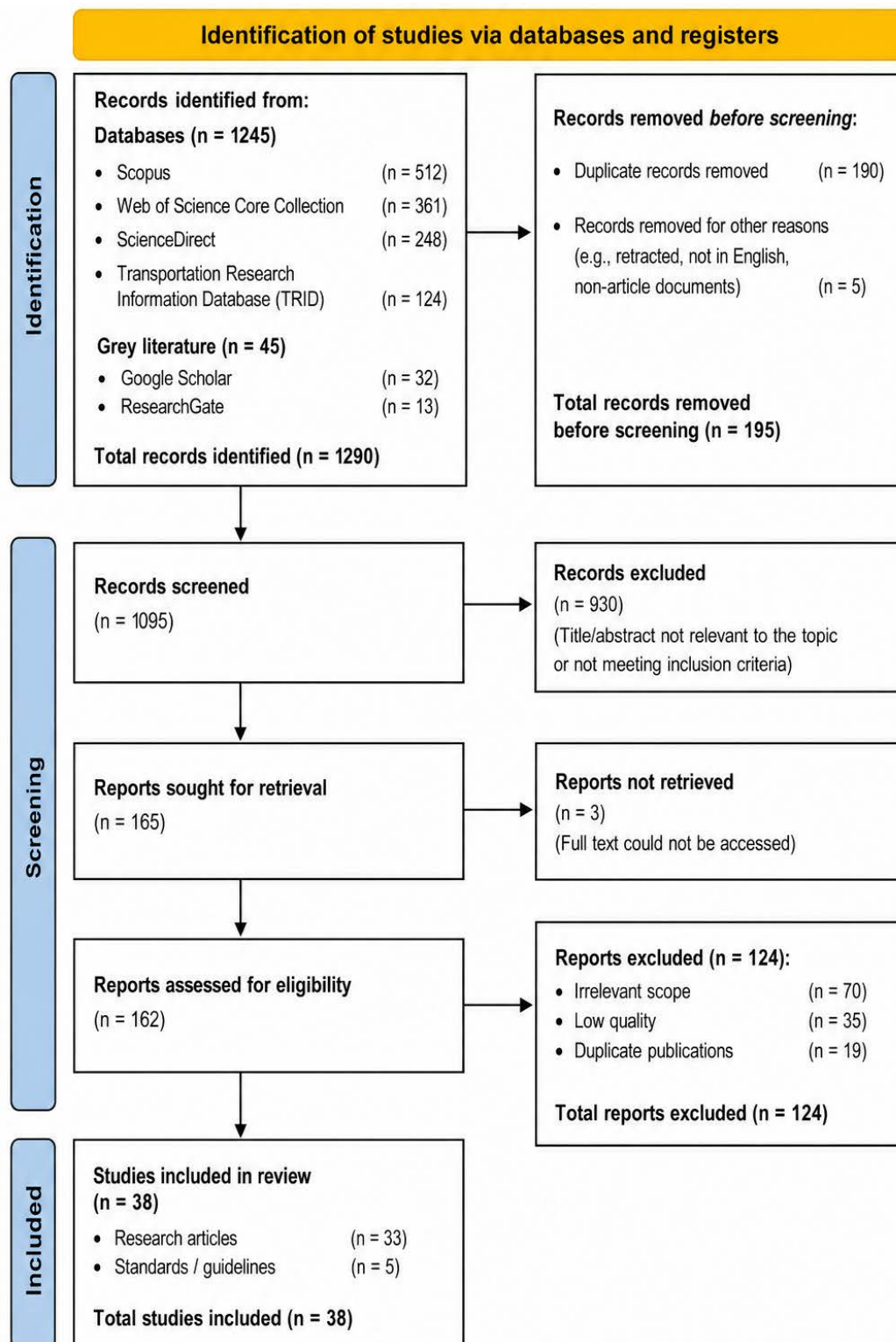


Figure 1. PRISMA flow diagram of the study selection process.

3.2. RQ1—Characteristics and Distribution of the Included Studies

Table 2 summarizes the characteristics of the 33 empirical studies and five standards included in this systematic review. The publications span the period from 1996 to 2025, demonstrating the growing research interest in transportation acoustics, IEQ, psychoacoustics, and passenger comfort. The studies represent a broad geographical distribution and encompass investigations conducted in Europe, Asia, Africa, North America, and Australia. They also cover a wide range of transportation environments, including buses, trains, passenger cars, electric and hybrid vehicles, heavy vehicles, commercial vehicles, aircraft cabins, and HVAC systems.

Table 2. Characteristics and key findings of the 33 empirical studies and five standards included in the systematic review on in-cabin noise (1996–2025).

References	Title	Year	Country	Environment	Findings
Ogundiran et al. [33]	A Field Survey on Indoor Climate in Land Transport Cabins of Buses and Trains	2024	Nigeria & Portugal	Bus & Train cabins	IEQ gaps: 83% had defective ventilation; many didn't meet standards for CO ₂ , thermal, and acoustic comfort.
Ogundiran et al. [32]	Noise Level and Indoor Air Quality Assessment of Public Transport Buses in Portugal and Nigeria	2025	Nigeria & Portugal	Bus cabins	L _{eq} ranged 59–88 dBA; many exceeded acoustic/IAQ limits under EU/WHO norms.
Ogundiran et al. [34]	Indoor Environmental Quality Assessment of Train Cabins and Passenger Waiting Areas	2023	Nigeria	Train cabins	Identified non-compliance in IAQ, thermal, and acoustic comfort.
Yoon et al. [23]	Reliability Improvement of a Sound Quality Index for a Vehicle HVAC System Using a Regression and Neural Network Model	2012	South Korea	Vehicle cabin (HVAC)	Neural network models using loudness, sharpness, and roughness predicted perceived pleasantness more accurately than regression models.
Wang & Watkins [25]	Noise Refinement Solutions for Vehicle HVAC Systems	2013	Australia	Vehicle cabin (HVAC)	Structural modifications and acoustic felts applied to HVAC systems reduced both SPL and specific frequency peaks.
Zakri et al. [16]	Modeling and Validation of Acoustic Comfort for Electric Vehicles Using a Hybrid Approach	2022	Indonesia	Electric vehicle cabin	Combined psychoacoustic parameters (loudness, roughness, sharpness) with soundscape methods for better comfort analysis.
Zhao et al. [10]	Satisfaction-Based On-board Acoustic Comfort Classification	2020	China	On-board spaces	Developed a Noise Comfort Index (NCI) correlated with user satisfaction, better than SPL alone.
Gameiro da Silva [35]	Measurements of Comfort in Vehicles	2008	Portugal	Various vehicle cabins	Identified key comfort factors—temperature, air quality, noise, vibration, light, ergonomics—and highlighted integration of physical and subjective evaluations.

Table 2. Cont.

References	Title	Year	Country	Environment	Findings
Mohd Nor et al. [14]	Index for Vehicle Acoustical Comfort Inside a Passenger Car	2010	Malaysia	Passenger car cabin	Proposed a comfort index combining Zwicker loudness, sharpness, roughness, and fluctuation strength; correlated strongly with jury test results.
Masullo et al. [22]	HVAC Noise in Car Cabin: ICEVs vs HEVs	2019	Italy/Japan	ICEV & HEV cabins	Reducing engine noise in HEVs increases the prominence of HVAC noise; psychoacoustic analysis revealed differences in perceived sound quality.
Duroyon et al. [13]	How Automotive Acousticians Talk About Sounds and Comfort in EV	2022	France	Electric vehicle cabin	Interviews identified descriptors and perceptual definitions for pleasant/unpleasant sounds; applicable for EV sound design.
Kumar & Riyazuddin [27]	Evaluation of Air-vent Rattle Noise Severity Using Sound Quality Parameters	2018	India	Vehicle air-vent	Strong correlation between statistical loudness/roughness and subjective annoyance; proposed optimized rattle testing.
Cășeriu & Blaga [36]	Assessment on the Acoustic Comfort Inside the Heavy Vehicle Cabin	2018	Romania	Heavy vehicle cabin	Found HVAC and engine noise as main contributors; assessed cumulative impact on acoustic and thermal comfort.
Guérin et al. [28]	Aeroacoustics of Automotive Vents	2004	France/UK	Vehicle HVAC vents	Interaction between the valve and grille increases noise; relocating the valve upstream reduced the SPL.
Leite et al. [24]	A Sound Quality-Based Investigation of the HVAC System Noise of an Automobile Model	2009	Brazil	Vehicle cabin (HVAC)	Loudness, tonality, and spectral composition were key in HVAC noise perception; Zwicker's loudness model predicted annoyance.
Watts [37]	A Comparison of Noise Measures for Assessing Vehicle Noisiness	1996	UK	Vehicle noise	Loudness measures are closely related to subjective noisiness; there is no advantage over A-weighted SPL when the spectra are similar.
Flor et al. [38]	Evaluation of Acoustic Noise Level and Impulsiveness in Vehicle Cabins	2022	Poland	Vehicle cabin	Found that impulsiveness impacts perceived noise harshness in cars.

Table 2. Cont.

References	Title	Year	Country	Environment	Findings
Xie et al. [39]	Characteristics of Cab Interior Noise Under Operating Conditions	2024	China	Commercial vehicle	The neural network accurately predicted noise from operational parameters.
Kandekar et al. [40]	Simulating HVAC Noise in Vehicle Cabin with Material Modeling	2022	India	Vehicle HVAC	Used CFD and Lattice–Boltzmann methods to predict airborne HVAC noise.
Grigg et al. [41]	Experimental Validation of HVAC Humming-Type Noise in Vehicles	2021	Turkey	Vehicle HVAC	Identified the compressor and AC piping as the primary humming noise sources.
Ihi et al. [42]	Acoustic Sensing and Noise Identification of an HVAC Unit	2021	UK	Vehicle HVAC	Acoustic camera & psychoacoustic metrics identified dominant HVAC noise sources.
Prakash et al. [43]	Flow-Induced Noise Prediction and Validation of a Heavy Vehicle HVAC System	2025	Japan	Heavy vehicle HVAC	Validated HVAC noise predictions using CFD and experimental data.
Sakhaei et al. [44]	Bayesian NVH Metamodels to Assess Interior Cabin Noise	2022	India	Vehicle cabin	Combined aerodynamic, rolling, and electric motor noise paths for NVH optimization.
Sineau et al. [45]	Vibration Transfer Path Analysis for NVH Optimization	2020	Iran	Vehicle interior	Ranked vibration transfer paths to diagnose structure-borne noise.
Torija & Ruiz [46]	Acoustic Factors in Railway Noise Annoyance	2025	France	Railway cabins	Linked acoustic traits with instantaneous annoyance ratings.
Fastl & Zwicker [21]	Using Psychoacoustics to Assess Urban and Transport Noise	2015	Spain	Transport environments	Loudness & sharpness predicted annoyance better than SPL alone.
Schulte-Fortkamp & Fiebig [47]	Interior noise characteristics, source identification, and its quantification contribution of a 400 km/h high-speed train in different operating environments	2021	China	High-speed train	Average Leq 70–75 dB(A); influenced by track smoothness & aerodynamics.
Tang et al. [2]	Soundscape Analysis in High-Speed Rail	2006	Germany	High-speed train	Applied the soundscape framework to railway passenger comfort.
Przydatek et al. [48]	Influence of Aerodynamic Noise on Train Cabin Comfort	2019	China	High-speed train	Aerodynamic noise dominates above 300 km/h; a fairing design mitigates it.
Jiang et al. [5]	Analysis of Noise Levels in Typical Passenger Cars	2022	South Korea	Passenger car	HVAC, tire–road, and aerodynamic noises interact non-linearly.

Table 2. Cont.

References	Title	Year	Country	Environment	Findings
Meng et al. [49]	Evaluating the Impact of Metro Interior Noise on Passenger Annoyance: An Experimental Study	2021	China	Metro train	L10 and L90 capture fluctuations better than Leq, which is linked to annoyance.
Mohd Nor et al. [7]	The Role of Noise in Passenger Perceived Quality in Public Transport	2014	UK	Bus & rail cabins	Noise above 70 dB(A) reduced service quality perception.
Grigg et al. [41]	Passenger Car Interior Noise Evaluation Using Psychoacoustics	2011	Malaysia	Passenger car cabin	Loudness & sharpness are most critical for perceived comfort.
Garbala & Gomez-Agustina [7]	Passenger Noise Exposure in London Underground	2015	UK	London Underground (metro)	Personal noise dosimetry showed that underground passengers experience substantial cumulative noise exposure; LAeq, LCpeak and LEX,8 h were used following standardized occupational exposure methods.
ISO 3381 [20]	Psychoacoustics: Facts and Models	2007	Germany	Various environments	Defined loudness, sharpness, roughness, and fluctuation strength for comfort studies.
ISO 5129 [19]	Railway Applications—Measurement of Noise Inside Rail Vehicles	2019	International	Rail cabins	Standard methodology for in-cabin noise measurements.
WHO 2018 [50]	Acoustics—Measurement of Noise Inside Aircraft	2019	International	Aircraft cabins	Standardized cabin noise measurement procedures.
OSHA [15]	Environmental Noise Guidelines for the European Region	2018	International	Transport noise	Recommended limits for exposure to transport noise to protect health.
ISO 5128:2023 [18]	Acoustics—Measurement of interior vehicle noise	2013	International	Road vehicles	Provides methods for measuring interior vehicle noise.

The 38 included records selected through the PRISMA screening process represent a diverse body of research investigating in-cabin noise and related IEQ factors across multiple transportation modes, geographical regions, and methodological approaches. The reviewed literature encompasses public transport systems, including buses, coaches, trains, and passenger waiting areas [6,30], passenger cars [14,37], electric and hybrid vehicles [13,22], heavy and commercial vehicles [36,39,43], railway systems [2,46–48], vehicle HVAC systems [41,42,44], and internationally recognized standards and guidelines [15,19,20,50]. Collectively, these studies provide a comprehensive overview of the principal noise sources, assessment methodologies, passenger perception, and mitigation strategies employed in transportation acoustics. Studies conducted in public transportation environments frequently combined acoustic measurements with assessments of thermal comfort, indoor air quality, and ventilation performance, revealing widespread exceedance of WHO and European recommendations for acoustic and environmental comfort and identifying defective HVAC and ventilation systems as major contributors to passenger discomfort [22,33,34,44]. Research

on passenger cars, hybrid vehicles, electric vehicles, heavy vehicles, and commercial vehicles primarily focused on engine, tire–road interaction, aerodynamic turbulence, structural vibration, and HVAC noise, demonstrating that psychoacoustic descriptors, particularly loudness, sharpness, roughness, and fluctuation strength, provide more accurate predictions of passenger comfort than conventional sound pressure level measurements alone [13,14,22,26,36–39,41–44]. A substantial proportion of the reviewed literature investigated vehicle HVAC systems, identifying blowers, ducts, compressors, valve–grille interactions, and airflow-induced noise as the dominant contributors to cabin noise. These studies demonstrated that acoustic insulation materials, optimized ventilation geometries, Computational Fluid Dynamics (CFD), machine learning, and neural network models can significantly improve both noise prediction and mitigation [21,27,39,47,48]. Similarly, studies on railway and high-speed rail environments identified wheel–rail interaction, aerodynamic turbulence, and traction systems as the primary noise sources, with psychoacoustic metrics and soundscape approaches providing stronger correlations with passenger annoyance than conventional A-weighted sound pressure levels [2,46–48].

Several cross-modal investigations proposed integrated acoustic comfort indices, including the Noise Comfort Index (NCI) and the Vehicle Acoustical Comfort Index (VACI), demonstrating that hybrid approaches combining conventional acoustic descriptors with psychoacoustic parameters provide more reliable predictions of passenger comfort and perceived sound quality than physical metrics alone [14,26]. International standards and guidelines, including ISO standards, the World Health Organization (WHO), and the Occupational Safety and Health Administration (OSHA), provide standardized measurement procedures and exposure limits that serve as essential references for evaluating transportation cabin noise and ensuring consistency across studies [15,19,20,50]. The reviewed studies reveal a clear transition from traditional sound pressure level-based assessments toward integrated evaluation frameworks that combine objective acoustic measurements, psychoacoustic descriptors, subjective passenger responses, and advanced computational modeling. These findings provide the scientific foundation for the development of the proposed Hybrid Cabin Noise Index (HCNI).

3.2.1. Comparative Synthesis of the Included Studies

To facilitate comparison across transportation modes, the included studies were further synthesized by dominant noise sources, assessment objectives, acoustic descriptors, and principal findings. This comparative synthesis highlights the common characteristics and methodological differences across transportation environments while identifying emerging research trends and remaining knowledge gaps. The results of this synthesis are presented in Table 3.

As shown in Table 3, engine operation, tire–road interaction, aerodynamic turbulence, HVAC systems, structural vibration, compressors, and wheel–rail interaction were consistently identified as the principal contributors to transportation cabin noise. Although L_{eq} , L_{max} , L_{10} , and L_{90} remain the most frequently reported descriptors, researchers increasingly incorporated psychoacoustic parameters, including loudness, sharpness, roughness, tonality, and fluctuation strength, to better explain passenger perceptions of acoustic comfort. The synthesis also demonstrates the growing application of CFD, machine learning, neural networks, and transfer path analysis to predict and mitigate cabin noise. Collectively, these findings indicate a clear transition from conventional sound pressure level assessment toward integrated, perception-based acoustic comfort evaluation.

Table 3. Summary of in-cabin noise studies (1996–2025) by transport mode, sources, objectives, metrics, and key findings.

Transport Mode	Representative Studies	Dominant Noise Sources	Typical Objectives	Descriptors/Metrics Used	Key Findings
Buses/Coaches	Ogundiran et al. [33], Torija et al. [46]	Engine, tyre–road interaction, HVAC blower, structural vibration	IEQ and comfort assessment; compliance checks; multimodal comfort analysis	Leq, Lmax, L10 and L90, loudness, sharpness; CO ₂ and thermal parameters in IEQ context	Leq ranged 59–88 dB(A); many exceeded EU/WHO limits; noise > 70 dB(A) reduced service quality; ventilation defects in >80% of surveyed buses
Trains–High-speed/intercity	Schulte-Fortkamp & Fiebig [47,51]	Wheel–rail interaction, aerodynamic turbulence (>300 km/h), traction motors	SPL profiling; aerodynamic mitigation; soundscape comfort analysis	Leq, Lmax, L10 and L90, SEL, loudness, sharpness	Average Leq 70–75 dB(A); smoother track & fairings reduce aerodynamic noise; sharpness correlates with annoyance
Trains–Metro/commuter	Jiang et al. [5]; Torija et al. [46]	Wheel–rail roughness, curve squeal, traction motors	Noise fluctuation analysis; passenger comfort evaluation	Leq, L10, L90, loudness	L10/L90 captured fluctuation better than Leq; noise > 70 dB(A) lowered perceived service quality
Passenger cars (ICE)	Mohd Nor et al. [14]; Watts [37]; Lee et al. [1]	Engine, tyre–road, aerodynamic noise	Development of comfort indices: multi-source interaction analysis	Leq, loudness, sharpness, roughness, fluctuation strength	Comfort index using psychoacoustics correlated strongly with jury ratings; HVAC–tyre–aero noise interacts non-linearly
Electric/Hybrid cars	Masullo et al. [22]; Zakri et al. [16]; Duroyon et al. [13]	Tyre–road, HVAC blower, aero vents	Characterizing new NVH profile; psychoacoustic comfort analysis	Leq, loudness, sharpness, roughness, soundscape methods	Engine noise drops increased HVAC prominence; psychoacoustics outperforms SPL in predicting comfort
Heavy vehicles	Cășeriu & Blaga [36]; Ihi et al. [42]	Engine, HVAC blower, hydraulics	Acoustic/thermal comfort assessment; HVAC noise validation	Leq, Lmax, loudness	HVAC + engine main contributors; CFD & experiments validated HVAC noise predictions
HVAC-specific studies	Yoon et al. [23]; Wang & Watkins [25]; Leite et al. [24]; Guérin et al. [28]; Kandekar et al. [40]; Satar et al. [52]; Grigg et al. [41]	Blower, ducts, vents, compressor, valve–grille interactions	Noise source identification; mitigation design; simulation validation	Loudness, sharpness, roughness, tonality, SPL	Neural networks & psychoacoustics predicted comfort better than SPL; acoustic felts & design changes reduced SPL and tonal peaks.

Table 3. Cont.

Transport Mode	Representative Studies	Dominant Noise Sources	Typical Objectives	Descriptors/Metrics Used	Key Findings
Commercial vehicles	Xie et al. [39]; Prakash et al. [43]; Sakhaei et al. [44]	Aerodynamic, rolling, electric motor noise; vibration paths	Predictive NVH modelling; transfer path ranking	SPL metrics, loudness, vibration levels	Neural networks predicted SPL from operational data; ranked vibration paths to target structure-borne noise.
Railway annoyance studies	Sineau et al. [45]	Multiple interior noise sources	Link acoustic traits to annoyance	Loudness, sharpness, SPL	Loudness/sharpness are better predictors of annoyance than SPL alone
Standards & guidelines	ISO 3381: [20]; ISO 5129: [19]; WHO [53]	—	Provide measurement & exposure frameworks.	SPL, SEL, psychoacoustic metrics (optional)	Define instrumentation, mic placement, and operating states; set health-protective limits.

3.2.2. Classification of Transport and Noise Study Contexts

To illustrate the distribution of the reviewed literature across transportation modes, the included studies were classified according to their principal research context. The classification distinguishes investigations of buses and coaches, railway systems, passenger cars, electric and hybrid vehicles, heavy vehicles, commercial vehicles, HVAC-specific studies, and international standards and guidelines, as shown in Figure 2.

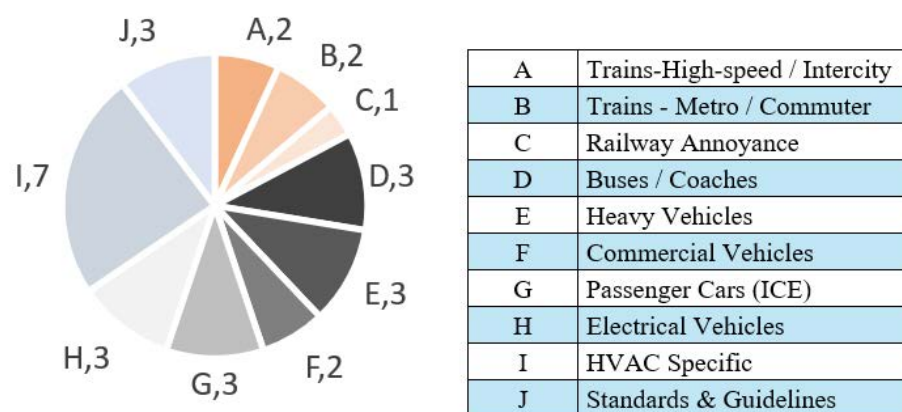


Figure 2. Classification of Transport and Noise Study Contexts.

Figure 2 shows that passenger cars, HVAC systems, and railway applications constitute the largest proportion of the reviewed literature, reflecting the increasing emphasis on passenger acoustic comfort in these transportation modes. In contrast, relatively fewer studies have focused on heavy vehicles, commercial vehicles, and integrated indoor environmental quality assessments. This distribution highlights important opportunities for future research, particularly in developing standardized methodologies capable of evaluating acoustic comfort consistently across different transportation systems.

3.3. RQ2—Sound Descriptors and Measurement Methods

In a review on the evaluation of comfort in vehicles, Gameiro da Silva [19] discussed the relevant noise descriptors for evaluating acoustic comfort in vehicles, such as SPL, sound power level (PWL), sound intensity level (SIL), loudness, composite rate of preference (CRP), equivalent sound level (Leq), Articulation Index (AI), predicted speech interference level (PSIL) [35], Speech Transmission Index (STI), and Sound Insulation Index (DnT,w). The aforementioned noise descriptors primarily apply to physical acoustic metrics, including maximum sound level (L_{max}), background noise level (L₉₀), and Reverberation Time (RT₆₀). However, vehicle interior noise is evaluated alongside vibration and harshness. NVH collectively impacts passenger comfort in vehicles. Another class of noise descriptors, referred to as psychoacoustic descriptors, includes loudness (N), sharpness (S), tonality (T), fluctuation strength (FS), roughness (R), impulsiveness (I), and oppressiveness penalty (OP) [54]. These psychoacoustic descriptors are particularly relevant for assessing the impact of noise on exposed human occupants [55]. In Table 4, the most used sound descriptors and noise indices are presented.

Table 4. Categories of Sound Descriptors and Noise Indices.

SN	Physical Acoustic	Psychoacoustic	Noise Indices
1	Maximum sound level (L _{max})	Loudness (N)	Noise Annoyance Fuzzy Index (NAFI)
2	Background noise level (L ₉₀)	Sharpness (S)	Noise Comfort Index (NCI)
3	Composite rate of preference	Fluctuation strength	Vehicle Acoustical Comfort Index
4	Equivalent sound level (Leq)	Roughness (R)	Sound Quality Index (SQI)
5	Articulation Index (AI)	Impulsiveness (I)	
6	Predicted speech interference level	Oppressiveness penalty	
7	Speech Transmission Index		
8	Sound power level (PWL)		
9	Sound intensity level (SIL)		
10	Insulation Index (DnT,w)		
11	Reverberation Time (RT ₆₀)		
12	Noise Equivalent Power		

Moreover, other kinds of descriptors may be explored in the context of the activity that occupants are experiencing, including effects on comfort, privacy, control perception, or suitability for such activities, reinforcing the notion that noise is highly subjective, though it can be objectively evaluated; hence the need for an integrated index that accounts for acoustic comfort regarding indoor spaces, including transport microenvironments.

Notably, most studies assessed interior vehicle noise together with NVH, recognizing their combined influence on passenger acoustic comfort. Based on the studies included in this systematic review, Figure 3 presents the quantitative distribution of the acoustic descriptors applied in field investigations. Loudness was the most frequently used descriptor (9 studies), followed by sharpness (7 studies) and Leq/LAeq (7 studies), confirming the continued importance of equivalent continuous sound level for regulatory and comparative assessments. Roughness, SPL, and composite noise indices (including VACI, NAFI, NII, and NCI) were each reported in four studies, whereas L_{max} and L₁₀-L₉₀ appeared in three studies. SEL, fluctuation strength, tonality, LC_{Peak}, and LEX_{8 h} were used less frequently, appearing in only one or two studies. Garbala and Gomez-Agustina further expanded conventional cabin-noise assessment by applying personal noise dosimetry and

cumulative exposure descriptors (LAeq, LCPeak, and LEX, 8 h) throughout complete passenger journeys in the London Underground rather than during vehicle operation alone, demonstrating the value of exposure-based measurements for evaluating commuter noise in metro systems [7]. Overall, the distribution highlights the growing importance of psychoacoustic descriptors, particularly loudness and sharpness, while emphasizing the continued relevance of Leq for standardized assessment and the limited adoption of cumulative exposure and advanced temporal descriptors in transport-cabin acoustics. Exposure duration and cumulative exposure were less consistently reported than conventional acoustic descriptors. SEL, TWA, noise dose, and personal dosimetry were not systematically applied, indicating an important gap in the assessment of cumulative cabin-noise exposure. Future studies should report both instantaneous sound levels and exposure duration to improve comparability across transport modes.

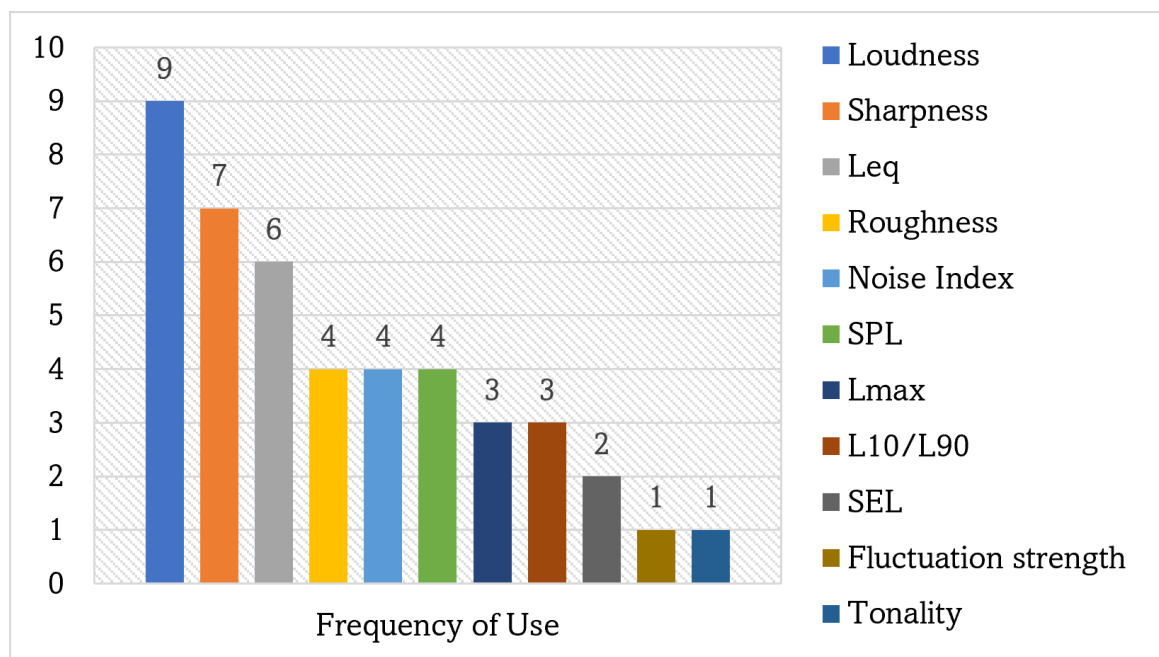


Figure 3. Frequency of Use of Descriptors in Cabin Noise Studies (1996–2025).

3.4. RQ3—SWOT Analysis of Noise Descriptors and Indices

RQ3 evaluates the strengths, weaknesses, opportunities, and threats of A-weighted, psychoacoustic, and hybrid descriptors, and this analysis was conducted to assess the performance and practical applicability of the main categories of in-cabin noise descriptors identified in the reviewed literature: A-weighted SPL metrics, psychoacoustic descriptors, and hybrid or composite indices. This analysis aimed to determine how each descriptor type contributes to understanding, predicting, and managing interior noise in transport environments. A-weighted SPL descriptors such as Leq, Lmax, L10, and L90, and SEL remain the most frequently used measures due to their simplicity, repeatability, and recognition in international regulatory frameworks such as the WHO [25], ISO 3381 [20], ISO 5129 [19] and OSHA [15]. Their key advantage is that they enable cross-study comparability and compliance with acoustic standards. However, these descriptors compress spectral and temporal characteristics into single-number values, limiting their ability to capture perceptually essential aspects of sound such as tonal sharpness or modulation depth [25,26]. In contrast, psychoacoustic descriptors, including loudness, sharpness, roughness, and fluctuation strength, provide insight into how passengers perceive sound rather than how it is physically measured [14,22,23]. These perceptual descriptors have shown stronger

correlations with comfort and annoyance, especially in EV and HVAC environments where tonal or high-frequency noise dominates [22]. Finally, hybrid indices such as the VACI [14], NCI [26], NAFI [26], and SQI [23] integrate physical and psychoacoustic parameters to produce single, perceptually weighted comfort scores. Despite their superior predictive performance ($R^2 > 0.85$ with subjective ratings), they remain limited to automotive and HVAC research contexts. The following table summarizes the strengths, weaknesses, opportunities, and threats identified for each descriptor category. Table 5 presents a SWOT analysis of the cabin noise assessment metrics.

Table 5. SWOT Analysis of Cabin Noise Assessment Metrics.

Category	Strengths	Weaknesses	Opportunities	Threats
A-weighted SPL Metrics (L_{eq} , L_{max} , L10 and L90, SEL)	Universally recognized by WHO, EU, and OSHA Enables regulatory compliance and cross-study comparability	Cannot represent spectral or temporal variability Weak correlation with perceptual comfort	Can serve as a baseline within hybrid indices Compatibility with ISO standards for cabin noise	Risk of overreliance leading to outdated methodologies Poor perceptual accuracy in low-noise EV/HEV environments
Psychoacoustic Descriptors (Loudness, Sharpness, Roughness, Fluctuation Strength, Tonality)	Directly linked to human perception Strong predictor of comfort and annoyance Captures tonal and modulation effects	Requires advanced analysis tools Lacks global standardization Higher measurement complexity	Core foundation for perceptual noise indices Applicable to EV/HEV and AI-based sound modeling	Inconsistent methods may limit comparability Absence of reference values across modes
Hybrid Indices (VACI, NCI, NAFI, SQI, Proposed HCNI)	Integrate physical and perceptual parameters High correlation ($R^2 > 0.85$) with subjective comfort Facilitate design optimization and benchmarking	Currently limited to automotive/HVAC studies Absence of a universal weighting framework	Basis for standardized, cross-modal HCNI development Potential for regulatory adoption and comfort certification	Methodological fragmentation may delay acceptance Lack of validation in public transport and aircraft cabins

The table shows that A-weighted SPL descriptors, although indispensable for compliance and benchmarking, offer only a limited representation of the passenger acoustic experience. Their standardization through WHO [50], ISO 33 [6], and ISO 5129 [5] ensures regulatory consistency but restricts perceptual insight, as these measures cannot account for frequency distribution, prominence, or amplitude modulation, all crucial to perceived annoyance and comfort [25,26]. In contrast, psychoacoustic descriptors such as loudness, sharpness, and roughness better capture the human auditory response to cabin noise by representing subjective sound qualities [14,21,23]. Research by Yoon et al. [23], Leite et al. [24], and Masullo et al. [22] demonstrate that psychoacoustic parameters outperform traditional SPL metrics in predicting perceived comfort, especially under the quiet operating conditions of EVs and HEVs, where HVAC and aerodynamic tonalities become dominant [22]. Nonetheless, adoption slowed because standardized computational methods and reference scales across modes were lacking. Hybrid indices, such as the VACI, NCI, and SQI, address this gap by integrating physical SPL and psychoacoustic parameters into unified frameworks that better correlate with subjective comfort ($R^2 > 0.85$) [14,26]. However, these indices are primarily confined to automotive and HVAC studies, limiting their broader applicability. The synthesis underscores the need for a Hybrid Integrated Cabin Noise

Index (HCNI) that harmonizes regulatory SPL descriptors with perceptually grounded psychoacoustic metrics, enabling a standardized, human-centered evaluation of in-cabin noise across all transport modes. Such a framework would not only enhance cross-study comparability but also align future acoustic comfort research with the perceptual realities of passengers in modern, low-noise transport systems.

Comparative Assessment of Standard A-Weighted Indices to Psychoacoustic Metrics

The review reveals that standard A-weighted SPL descriptors, including L_{eq} , L_{max} , L_{10} , L_{90} , and SEL , are the most consistently applied tools for quantifying interior noise across all transport modes. Their popularity stems from regulatory recognition (e.g., WHO, EU directives, OSHA), straightforward instrumentation, and cross-study comparability. L_{eq} is the primary indicator of continuous exposure; L_{max} captures instantaneous peaks; L_{10} and L_{90} describe the statistical distribution and temporal stability; and SEL quantifies the total energy of transient events such as train pass-bys, aircraft take-offs, or door slams. In public transport research [8]. These metrics are usually used to assess compliance with health-based limits and capture operational variability. Notably, in metro systems, L_{10} and L_{90} were more effective than L_{eq} at reflecting fluctuations during curve squeal events, improving predictions of passenger discomfort.

While valuable, A-weighted metrics compress complex spectral and temporal characteristics into single-number values, limiting their ability to account for spectral distribution, tonal prominence, and modulation patterns that strongly influence perception. Although A-weighting partially compensates for the ear's frequency sensitivity, it can overlook perceptually essential features. For example, two sounds with identical L_{eq} can elicit very different comfort ratings if one has high-frequency tonal peaks or pronounced low-frequency modulation. Psychoacoustic descriptors, including Zwicker loudness, sharpness, roughness, and fluctuation strength, quantify specific perceptual attributes and offer richer insight into passenger response. Loudness reflects perceived intensity across the spectrum and is influenced by both level and spectral shape; sharpness captures the proportion of high-frequency content; roughness measures rapid amplitude modulations (15–300 Hz); and fluctuation strength quantifies slower modulations (<20 Hz) associated with “wobbling” or “pulsating” impressions. In the reviewed studies, loudness and sharpness were the most predictive single indicators of annoyance, especially in automotive and HVAC contexts [14,22,23]. In EV cabins, the reduced broadband engine noise exposed high-frequency HVAC and aerodynamic tones, making sharpness a critical measure of discomfort [13]. Roughness and fluctuation strength, though less frequently used, were particularly relevant for identifying annoyance from tonal modulations caused by compressors and from propeller-blade passage in turboprops.

Studies that combined A-weighted and psychoacoustic measures consistently produced the most accurate models of passenger comfort. For example, [26] developed an NCI integrating L_{eq} , loudness, and sharpness, achieving correlations above $R^2 = 0.85$ with satisfaction ratings, substantially outperforming SPL-only approaches. Similarly, [13] employed a hybrid framework that combined loudness, sharpness, and soundscape analysis with L_{eq} , achieving higher predictive accuracy for EV comfort than either method alone. Although psychoacoustic analysis requires more advanced measurement and processing tools, its inclusion bridges the gap between physical sound characterization and human perception. The evidence supports a dual-layer evaluation framework: retaining A-weighted SPL metrics for compliance, baseline assessment, and regulatory alignment, while systematically incorporating psychoacoustic descriptors to enhance perceptual relevance and predictive accuracy.

3.5. RQ4—Cabin-Noise Sources and Mitigation Strategies

RQ4 identifies dominant noise sources and effective mitigation strategies reported across transport modes. In road vehicles with internal combustion engines, engine and powertrain noise, tire–road interaction, and aerodynamic noise at higher speeds are predominant [14,48], while in electric and hybrid vehicles, the reduction of engine noise makes tire–road, HVAC blower, and aero-ventilation leakage more perceptible [13]. Buses and coaches are typically affected by engine bay noise, tire–road vibration, HVAC blower operation, and structural resonance [8], whereas rail systems are dominated by wheel–rail interaction (including roughness, corrugation, and curve squeal), traction motor noise, and aerodynamic turbulence at high speeds [12]. Aircraft cabins are primarily influenced by aeroacoustic excitation of the fuselage and windows, turbofan or propeller noise, and environmental control system (ECS) duct noise [19]. In contrast, maritime cabins are affected mainly by propulsion machinery, auxiliary equipment, and hydrodynamic hull flow [36]. Transmission pathways encompass a combination of structure-borne noise propagated through the chassis, bogies, suspension systems, or fuselage panels, and airborne noise entering via glazing, door and window seals, ventilation ducts, and body shell openings [43,44]. Effective mitigation strategies reported in the literature include improved sealing of doors and windows to reduce airborne leakage [25,28]; acoustic insulation and damping using multi-layer floors, laminated glazing, and acoustic felts [23,24] structural optimisation such as resilient rail pads and tuned mass dampers [12]; aerodynamic refinements through fairing design and smooth exterior surfaces [2]; HVAC noise control via blower isolation, grille geometry optimization, and acoustic lining [40,41], use of low-noise components such as optimized tyres and redesigned propeller blades; and active noise control (ANC) for low-frequency attenuation, particularly below 300 Hz [26].

3.6. RQ5—Evidence and Conceptual Structure of the Hybrid Cabin Noise Index

RQ5 addresses the design and development of an HCNI that unites physical and perceptual measures. The HCNI presented in this review is a proposed conceptual framework rather than a validated or standardized acoustic index. Its mathematical formulation, normalization procedure, weighting coefficients, thresholds, and scoring equation remain to be established through future empirical validation. At the first layer, the index should incorporate L_{eq} , L_{max} , and percentile measures (L_{10} , L_{90}), and SEL for transient events, measured in accordance with relevant ISO standards (e.g., ISO 3381 [20] for rail, ISO 5129 [19] for aircraft, ISO 362 [4] adaptations for road interiors) using IEC 61672 Class 1 instrumentation with traceable calibration. These descriptors ensure alignment with compliance requirements, enable comparison with existing exposure limits (WHO, EU, OSHA), and capture the overall level, peak events, and temporal variability. The second layer should integrate Zwicker loudness, sharpness, roughness, and fluctuation strength, which quantify perceptual attributes critical to passenger comfort and annoyance. Loudness provides a measure of perceived intensity; sharpness reflects the prominence of high-frequency content; roughness quantifies rapid amplitude modulations (15–300 Hz); and fluctuation strength captures slower modulations (<20 Hz), often associated with HVAC or aerodynamic “pulsation” effects. The hybrid index would output both a physical score (dB-based) and a perceptual score (psychoacoustic-based), weighted according to the relative predictive power of each descriptor for passenger comfort, as demonstrated [14,26].

To enhance cross-study comparability, future research should adopt standardized protocols for reporting operational conditions, including vehicle type and configuration, speed, road/track quality, HVAC settings, and environmental parameters such as temperature, humidity, and wind speed. Microphone placement should follow the relevant ISO standard for the mode studied, and studies should document both calibration traceability

and measurement uncertainty. Reporting should include both steady-state and transient analyses, with time histories or spectral plots to allow secondary analysis. Importantly, studies should utilize both layers of the HCNI framework to ensure that both regulatory and perceptual dimensions are addressed, thereby enabling meta-analyses across modes and geographies. Finally, integrating subjective evaluations (e.g., comfort or annoyance ratings) alongside objective field surveys is strongly recommended, as it provides essential data to refine weighting factors in the hybrid index.

The HCNI presented here is a proposed conceptual framework, not a validated standardized index. The present review does not establish normalization constants, weighting coefficients, decision thresholds, or a validated scoring equation. Future studies should derive these parameters from sufficiently large datasets linking synchronized physical and psychoacoustic measurements with standardized passenger comfort or annoyance responses. Candidate weighting coefficients should then be estimated using transparent statistical or machine-learning models, followed by independent validation across transport modes, vehicle types, operating conditions, and passenger populations. Ongoing monitoring and evaluation of multimodal transport options, including emerging technologies such as EVs, autonomous shuttles, and high-speed rail, should be prioritized to ensure the HCNI remains relevant within rapidly evolving transportation systems.

3.7. RQ6—Electric-Vehicle-Specific Noise Indices

RQ6 investigates whether an EV-specific noise index currently exists and identifies research gaps for future development. The review found that, despite the rapid transition toward electric mobility, no dedicated or universally recognized noise index currently exists for electric vehicles (EVs) or hybrid electric vehicles (HEVs). While several studies have examined the acoustic characteristics of EV interiors, most have relied on existing physical or psychoacoustic descriptors rather than developing bespoke indices tailored to the unique noise profile of these vehicles. In traditional internal combustion engine vehicles (ICEVs), engine and powertrain noise dominate cabin acoustics, often masking other sound sources. However, in EVs and HEVs, the reduction of engine masking reveals new dominant noise contributors such as HVAC blower noise, tyre–road interaction, aero-ventilation leaks, and high-frequency tonal components from electric drivetrains and inverters [13,22,25]. These sound characteristics are more perceptually intrusive at moderate sound pressure levels, as they exhibit tonal sharpness and fluctuation patterns not adequately captured by A-weighted SPL descriptors. Studies by Masullo et al. and Zakri et al. confirmed that the acoustic environment in EVs is strongly influenced by the psychoacoustic properties of tonal and broadband components rather than overall sound level, emphasizing the need for a perceptually sensitive evaluation framework [22]. Similarly, Masullo et al. [22] and Zakri et al. [18] reported that loudness and sharpness remain the most influential predictors of comfort and annoyance in low-noise EV interiors, outperforming standard SPL-based measurements that correlate with passenger satisfaction [13,23,25]. However, the indices applied in these studies, such as the NCI, VACI, and SQI, were adapted from combustion-engine or HVAC contexts and were not explicitly formulated for EV-specific sound signatures. Consequently, there is a clear methodological gap in existing literature. While psychoacoustic analysis has advanced the understanding of EV interior noise perception, a dedicated EV Noise Comfort Index (EV-NCI) or equivalent framework has not yet been developed or validated. This gap underscores the need to extend hybrid frameworks, such as the proposed HCNI, to incorporate weighting factors that account for the tonal, high-frequency, and low-level noise features characteristic of EVs. The development of an EV-specific extension to HCNI would enable accurate comfort prediction, standardize acoustic design targets, and improve cross-modal comparability, providing the

foundation for perception-driven acoustic optimization in the next generation of electric and autonomous vehicles.

4. Discussion

This review highlights the evolution of in-cabin noise assessment methods in vehicles over the period 1996–2025, demonstrating a gradual shift from reliance on standard A-weighted SPL metrics to incorporating psychoacoustic parameters and composite Noise Indices. Traditional descriptors, such as L_{eq} , L_{max} , L_{10} , L_{90} , and SEL, remain necessary for regulatory compliance and comparison (WHO, 2018; OSHA, 2020; ISO 3381, 2019; ISO 5129, 2019), but their predictive ability for passenger comfort is limited. They do not provide direct information about spectral content, tonal prominence, or modulation characteristics, all of which are crucial in human perception [37].

The emergence of Noise Indices in automotive research addresses this gap. Notable examples include VACI [12], NAFI [12], Noise Isolation Index (NII) [35], NCI [26], and SQI [20]. These indices combine psychoacoustic metrics—loudness, sharpness, roughness, and fluctuation strength with physical SPL measurements to produce a single comfort score. Studies consistently show that such hybrid indices better align with subjective annoyance or satisfaction ratings than SPL alone, particularly in identifying discomfort associated with tonal HVAC noise, aerodynamic whistles, or interactions between vibration noise and other sources [22]. Mode-specific results further reinforce the value of hybrid metrics. In ICE passenger cars, engine and powertrain noise dominate, whereas in EVs and HEVs, tire–road interaction, HVAC blower noise, and aero-ventilation leaks are more perceptible due to the absence of masking engine noise [13]. Noise Indices have been effective in these contexts, capturing perceptual effects that conventional SPL measurements fail to capture. For HVAC-specific assessments, the SQI framework has proven effective in isolating and mitigating blower and duct noise using targeted design interventions [25,40]. Exposure duration and cumulative noise exposure were not reported consistently across the reviewed literature. Sound Exposure Level (SEL) was used in a limited subset of studies, whereas time-weighted average (TWA), personal noise dose, and other cumulative exposure indicators were not consistently available for cross-modal synthesis. Evidence from London Underground passenger measurements illustrates the value of explicitly considering journey duration and cumulative exposure in addition to instantaneous sound levels [50]. This limited reporting represents an important research gap, particularly for frequent commuters and transport workers whose risk depends on repeated or prolonged exposure. Similarly, although vibration is frequently discussed within the NVH framework, integrated noise–vibration exposure assessment remains insufficiently developed in the reviewed evidence. Future studies should therefore report synchronized acoustic and vibration measurements, exposure duration, and cumulative dose where relevant.

Despite these advances, notable gaps remain. Most Noise Indices have been developed for passenger car cabins or HVAC systems, with limited application to other vehicle categories such as heavy trucks, buses, trains, or aircraft. Cross-modal validation is rare, and even within automotive studies, indices are often tested under narrow operating conditions without accounting for variability in road surfaces, driving styles, passenger loads, or climate control settings. Moreover, no unified Noise Index standard exists, leading to fragmented methodologies that hinder comparability across studies and limit the translation of findings into industry-wide comfort benchmarks.

This fragmentation supports the case for an HCNI applicable across vehicle types and transport modes. Such a framework would retain regulated SPL measures (L_{eq} , L_{max} , L_{10} , L_{90} , SEL) to ensure compliance, while integrating psychoacoustic descriptors loudness, sharpness, roughness, and fluctuation strength to capture perceptual relevance. Incorporation

rating ISO-compliant measurement protocols, detailed operational state reporting, and subjective passenger feedback would ensure reproducibility, comparability, and practical value. Adopting a standardized HCNI could shift in-cabin noise evaluation from merely meeting regulations to a comprehensive measure of passenger experience, enabling targeted strategies that enhance both objective performance and perceived comfort. The proposed HCNI should therefore be interpreted as a conceptual framework derived from the reviewed evidence rather than a validated standardized index. Future studies should derive and validate its weighting coefficients using synchronized physical and psychoacoustic measurements together with standardized passenger comfort responses. This change is significant as the industry shifts to EVs and autonomous vehicles, where the noise profile is evolving, and previously masked tonal and high-frequency sounds are becoming more noticeable.

5. Conclusions

This systematic review synthesized 38 included records (1996–2025), comprising 33 empirical studies and 5 standards documents on in-cabin noise across road, rail, and aircraft environments, with targeted coverage of HVAC-specific research. Five integrative conclusions emerge. (i) Descriptors: A-weighted SPL metrics (Leq, Lmax, L10, L90, SEL) remain indispensable for regulation and comparability, yet they under-represent perceptually salient attributes such as tonality and temporal modulation. (ii) Psychoacoustics: Loudness and sharpness, followed by roughness and fluctuation strength, consistently exhibit stronger associations with passenger comfort/annoyance than SPL alone, especially in EV/HEV and HVAC contexts where tonal/high-frequency content is prominent. (iii) Hybrid indices: Composite approaches (e.g., VACI, NCI, NAFI, SQI) outperform single-metric evaluations by fusing physical and perceptual information, but their validation is primarily confined to passenger cars and HVAC subsystems. (iv) Sources & mitigation: Dominant sources are mode-dependent (engine/powertrain and tire–road for ICE, HVAC and aero-ventilation for EV/HEV, wheel–rail and aero-turbulence for rail, ECS/aeroacoustics for aircraft). Effective strategies include sealing and insulation upgrades, aerodynamic refinements, HVAC component optimization, transfer-path and structural treatments, and low-frequency ANC. (v) Field gap: No widely accepted, cross-modal EV-specific noise index exists; consequently, there is no standard benchmark for the perceptual qualities that define acoustic comfort in modern low-noise vehicles. To address these gaps, the review proposes an HCNI that preserves regulatory SPL descriptors while systematically incorporating psychoacoustic parameters, implemented under ISO-aligned measurement and reporting protocols and paired with standardized subjective evaluations. Collectively, these findings provide an evidence-based pathway from compliance-oriented measurement toward human-centered acoustic comfort in transport cabins.

6. Future Work

Future research should focus on standardizing the HCNI by developing an open, ISO-aligned protocol covering Class-1 instrumentation, calibration, microphone layout, and standardized operating states. Large cross-modal datasets linking SPL, psychoacoustic metrics, and subjective ratings should be created to derive reliable perceptual weightings using transparent and data-driven models. A dedicated EV-specific extension (EV-HCNI) is needed to account for tonal prominence, sharpness, and modulation characteristics typical of electric drivetrains and HVAC systems and to be validated across diverse vehicle types and environments. Broader modal coverage is essential, extending studies to buses, rail, aircraft, and heavy vehicles to confirm the transferability of HCNI. Future work should also integrate multiple IEQ factors, such as vibration, thermal comfort, air quality, and lighting,

to understand their combined influence on acoustic perception. Research into mitigation strategies such as low-frequency active noise control, HVAC design optimization, and structural damping should quantify improvements using pre- and post-HCNI comparisons. Real-time HCNI assessment tools and open datasets should be developed to enhance reproducibility. Finally, studies should address inclusivity and accessibility, ensuring that the next generation of acoustic comfort models reflects diverse passenger needs and use contexts.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/environments13100569/s1> [56].

Author Contributions: Conceptualization, Conceptualization, J.-P.K.B.N., J.O.O. and M.G.d.S.; methodology, J.-P.K.B.N.; validation, J.-P.K.B.N., J.O.O., A.D. and M.G.d.S.; formal analysis, J.-P.K.B.N. and J.O.O. investigation, J.-P.K.B.N.; A.A. resources, M.G.d.S.; data curation, J.-P.K.B.N.; writing—original draft preparation, J.-P.K.B.N., J.O.O.; writing—review and editing, J.-P.K.B.N., J.O.O., M.F., A.D., A.A. and M.G.d.S.; visualization, J.-P.K.B.N.; A.D., A.A. supervision, M.G.d.S.; project administration, M.G.d.S. and M.F.; funding acquisition, M.G.d.S. and M.F. All authors have read and agreed to the published version of the manuscript.

Funding: The authors acknowledge the support of the Portuguese; Fundação para a Ciência e a Tecnologia, I.P. (FCT) (ROR: <https://ror.org/00snfq58> (accessed on 14 June 2026)) through the projects UID/50022/2025 (DOI: <https://doi.org/10.54499/UID/50022/2025>), LA/P/0079/2020 (DOI: <https://doi.org/10.54499/LA/P/0079/2020>), (ADAI, <https://ror.org/05gh16g69> (accessed on 14 June 2026)), within the Associate Laboratory of Energy, Transports, and Aerospace (LAETA). The research was also funded by the AVEMOBI Project, which is part of the DRIVOLUTION Agenda, with the Grant Number: C644913740-00000022 of IAPMEI-PRR.

Data Availability Statement: Data are available on request.

Acknowledgments: The authors gratefully acknowledge IBER-OLEFF Componentes Técnicos em Plástico, S.A., Parque Industrial Manuel da Mota, Pombal, Portugal, for their support and collaboration.

Conflicts of Interest: Mihail Fontul was employed by the company IBER-OLEFF Componentes Técnicos em Plástico Sa Parque Industrial Manuel da Mota, Lt. The authors declare that this study received funding from Fundação para a Ciência e Tecnologia. The funder was not involved in the study design, collection, analysis, interpretation of data, the writing of this article, or the decision to submit it for publication.

Abbreviations

Abbreviation	Full Term
AI	Articulation index
dB	Decibel
dB(A)	A-weighted decibel
ANC	Active Noise Control
CFD	Computational Fluid Dynamics
ECS	Environmental Control System
EV	Electric Vehicle
HEV	Hybrid Electric Vehicle
HCNI	Hybrid Integrated Cabin Noise Index
HVAC	Heating, Ventilation, and Air Conditioning
IAQ	Indoor Air Quality
ICE	Internal Combustion Engine
ICEV	Internal Combustion Engine Vehicle
IEQ	Indoor Environmental Quality

ISO	International Organization for Standardization
Leq	Equivalent Continuous Sound Level
L _{max}	Maximum Sound Level
L10-L90	Statistical Noise Levels
NCI	Noise Comfort Index
NII	Noise Isolation Index
NAFI	Noise Annoyance Fuzzy Index
NVH	Noise, Vibration, and Harshness
OSHA	Occupational Safety and Health Administration
SEL	Sound Exposure Level
SPL	Sound Pressure Level
SPI	Speech intelligibility index
SQ	Sound Quality
SQI	Sound Quality Index
VACI	Vehicle Acoustical Comfort Index
WHO	World Health Organization

References

1. Lee, H.P.; Kumar, S.; Garg, S.; Lim, K.M. Assessment of in-cabin noise of wide-body aircrafts. *Appl. Acoust.* **2022**, *194*, 108809. [CrossRef] [PubMed]
2. Tang, T.; Gu, Z.; Yang, Y.; Sun, H.; Chen, S.; Chen, Y. A data-driven framework for natural feature profile of public transport ridership: Insights from Suzhou and Lianyungang, China. *Transp. Res. Part A Policy Pract.* **2024**, *183*, 104049. [CrossRef]
3. Fredianelli, L.; Del Pizzo, A.; Licitra, G. Recent Developments in Sonic Crystals as Barriers for Road Traffic Noise Mitigation. *Environments* **2019**, *6*, 14. [CrossRef]
4. ISO 1996-1:2016; Acoustics-Description, Measurement and Assessment of Environmental Noise-Part 1: Basic Quantities and Assessment Procedures. International Standards Organisation: Geneva, Switzerland, 2016.
5. Jiang, L.; Nellthorp, J. Valuing transport noise impacts in public urban spaces in the UK: Gaps, opportunities and challenges. *Appl. Acoust.* **2020**, *166*, 107376. [CrossRef]
6. Ogundiran, J.O.; Nyembwe, J.-P.K.B.; Ogundiran, J.; Gandhi, V.C.; Ribeiro, A.; da Silva, M.G. Cabin management and ventilation strategies for improved indoor environmental quality in passenger vehicles of developing tropics. *Results Eng.* **2025**, *27*, 106129. [CrossRef]
7. Garbala, M. Passenger Noise Exposure In London Underground. *Proc. Inst. Acoust.* **2015**, *37*, 203–212. [CrossRef] [PubMed]
8. Ogundiran, J.O.; Nyembwe, J.-P.K.B.; Ogundiran, J.; Ribeiro, A.S.N.; da Silva, M.G. A Systematic Review of Indoor Environmental Quality in Passenger Transport Vehicles of Tropical and Subtropical Regions. *Atmosphere* **2025**, *16*, 140. [CrossRef]
9. Schjøtt, A.; Bengtsson, M. De- and recoding algorithmic systems: The case of fact checkers and fact checked users. *Converg. Int. J. Res. New Media Technol.* **2024**, *30*, 1919–1938. [CrossRef]
10. He, Z.; Guo, H.; Liu, H.; Zhao, Y.; Zhang, Z.; Yang, S. A Sound Quality Evaluation Method for Vehicle Interior Noise Based on Auditory Loudness Model. *Sound Vib.* **2024**, *58*, 47–58. [CrossRef]
11. Münder, M.; Carbon, C.-C. A literature review [2000–2022] on vehicle acoustics: Investigations on perceptual parameters of interior soundscapes in electrified vehicles. *Front. Mech. Eng.* **2022**, *8*, 974464. [CrossRef]
12. Lan, X.; Han, J.; Zhang, J.; Xiao, X.; Peng, L.; Zhao, Y. Interior noise characteristics, source identification and its quantification contribution of 400 km/h high-speed train in different operating environments. *Appl. Acoust.* **2025**, *228*, 110321. [CrossRef]
13. Duroyon, M.; Misdariis, N.; Susini, P.; Dauchez, N.; Pardo, L.-F.; Vialatte, E. How do Automotive Acousticians talk about Sounds and Comfort in Electric Vehicle? In Proceedings of the 10th Convention of the European Acoustics Association, Turin, Italy, 11–15 September 2023.
14. Nor, M.J.M.; Fouladi, M.H.; Nahvi, H.; Ariffin, A.K. Index for vehicle acoustical comfort inside a passenger car. *Appl. Acoust.* **2008**, *69*, 343–353. [CrossRef]
15. OSHA. Exposure and Hearing Conservation, Temporary Worker Initiative Noise Bulletin N° 9, Occupational Safety and Health Administration, U.S Department of Labor, OSHA 3953-06 2018. Available online: <https://www.osha.gov/sites/default/files/publications/OSHA3953.pdf> (accessed on 25 May 2026).
16. 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. [CrossRef]
17. Qian, K.; Hou, Z.; Liang, J.; Liu, R.; Sun, D. Interior sound quality prediction of pure electric vehicles based on transfer path synthesis. *Appl. Sci.* **2021**, *11*, 4385. [CrossRef]

18. IOS 5128:2023; Acoustics—Measurement of Interior Vehicle Noise. International Organization for Standardization: Geneva, Switzerland, 2023.
19. ISO 5129; Acoustics-Measurement of Sound Pressure Levels in the Interior of Aircraft During Flight AMendMent 1. International Standards Organisation: Geneva, Switzerland, 2001.
20. ISO 3381; Railway Applications-Acoustics-Noise Measurement Inside Railbound Vehicles Applications Ferroviaires-Acoustique-Mesurage du bruit à l'intérieur des véhicules Circulant Sur Rails. International Standards Organisation: Geneva, Switzerland, 2021.
21. Zwicker, E.; Fastl, H. *Psychoacoustics: Facts and Models*; Springer: Berlin/Heidelberg, Germany, 2007.
22. Masullo, M.; Yamauchi, K.; Nakatani, Y.; Maffei, L. HVAC noise in car cabin: A preliminary comparison between ICEVs and HEVs. In Proceedings of the 23rd International Congress on Acoustics, Aachen, Germany, 9–13 September 2019.
23. Yoon, J.-H.; Yang, I.-H.; Jeong, J.-E.; Park, S.-G.; Oh, J.-E. Reliability improvement of a sound quality index for a vehicle HVAC system using a regression and neural network model. *Appl. Acoust.* **2012**, *73*, 1099–1103. [\[CrossRef\]](#)
24. Leite, R.P.; Paul, S.; Gerges, S.N. A sound quality-based investigation of the HVAC system noise of an automobile model. *Appl. Acoust.* **2009**, *70*, 636–645. [\[CrossRef\]](#)
25. Wang, X.; Watkins, S. Noise refinement solutions for vehicle HVAC systems. In *SAE Technical Papers*; SAE International: Warrendale, PA, USA, 2007. [\[CrossRef\]](#)
26. Zhao, H.; Chen, K.; Li, H.; Luo, J.; Dang, J. Method of satisfaction based on-board acoustic comfort classification and its applications. *Acta Acust.* **2025**, *9*, 22. [\[CrossRef\]](#) [\[PubMed\]](#)
27. Amit, K.; Mohammad, R. Evaluation of Air-vent Rattle Noise Severity Using Sound Quality Parameters. In *Proceedings of the INTER-NOISE and NOISE-CON Congress and Conference Proceedings, InterNoise19*; Institute of Noise Control Engineering: Madrid, Spain, 2018.
28. Guérin, S.; Thomy, E.; Wright, M. Aeroacoustics of automotive vents. *J. Sound Vib.* **2005**, *285*, 859–875. [\[CrossRef\]](#)
29. Kang, J.; Aletta, F. The Impact and Outreach of Soundscape Research. *Environments* **2018**, *5*, 58. [\[CrossRef\]](#)
30. Dominski, F.H.; Lorenzetti Branco, J.H.; Buonanno, G.; Stabile, L.; Gameiro da Silva, M.; Andrade, A. Effects of air pollution on health: A mapping review of systematic reviews and meta-analyses. *Environ. Res.* **2021**, *201*, 111487. [\[CrossRef\]](#) [\[PubMed\]](#)
31. Truppel, R.; D'oliveira, A.; Canale, L.; Stabile, L.; Buonanno, G.; Andrade, A. Do Environmental Education Programs Reduce Pollution and Improve Air Quality? Impacts on Knowledge and Behavior Based on Evidence from a Mapping Review. *Atmosphere* **2025**, *16*, 1229. [\[CrossRef\]](#)
32. Andrade, A.; D'oliveira, A.; De Souza, L.C.; Bastos, A.C.R.d.F.; Dominski, F.H.; Stabile, L.; Buonanno, G. Effects of Air Pollution on the Health of Older Adults during Physical Activities: Mapping Review. *Int. J. Environ. Res. Public Health* **2023**, *20*, 3506. [\[CrossRef\]](#) [\[PubMed\]](#)
33. Ogundiran, J.O.; Nyembwe, J.-P.K.B.; Ribeiro, A.S.N.; da Silva, M.G. A Field Survey on Indoor Climate in Land Transport Cabins of Buses and Trains. *Atmosphere* **2024**, *15*, 589. [\[CrossRef\]](#)
34. Ogundiran, J.O.; Nyembwe, J.-P.K.B.; Ribeiro, A.S.N.; da Silva, M.G. Indoor Environmental Quality Assessment of Train Cabins and Passenger Waiting Areas: A Case Study of Nigeria. *Sustainability* **2023**, *15*, 16533. [\[CrossRef\]](#)
35. da Silva, M.C.G. Measurements of comfort in vehicles. *Meas. Sci. Technol.* **2002**, *13*, R41–R60. [\[CrossRef\]](#)
36. Cășeriu, B.; Blaga, P. Assessment on the Acoustic Comfort Inside the Heavy Vehicle Cabin. *Acta Marisiensis. Ser. Technol.* **2023**, *20*, 13–17. [\[CrossRef\]](#)
37. Watts, G.R. A comparison of noise measures for assessing vehicle noisiness. *J. Sound Vib.* **1995**, *180*, 493–512. [\[CrossRef\]](#)
38. Flor, D.; Pena, D.; Oliveira, H.L.; Pena, L.; de Sousa, V.A.; Martins, A. Evaluation of Acoustic Noise Level and Impulsiveness Inside Vehicles in Different Traffic Conditions. *Sensors* **2022**, *22*, 1946. [\[CrossRef\]](#) [\[PubMed\]](#)
39. Xie, P.; Yin, Z.; Bin, S.; Shi, J.; Wang, W.; Wei, S. Research on Characteristics of Cab Interior noise under Different Conditions by Neural Network Algorithm. *Fundam. Res.* **2024**, *6*, 1736–1744. [\[CrossRef\]](#) [\[PubMed\]](#)
40. Kandekar, A.; Kakade, A.; Duppati, D.; Luzzato, C.; Mann, A.; Titave, U.; Kim, M. Simulating HVAC Noise in Vehicle Cabin with Material Absorption Modelling. In *Proceedings of the WCX SAE World Congress Experience*; SAE International: Detroit, MI, USA, 2022. [\[CrossRef\]](#)
41. Grigg, S.; Al-Shibaany, Z.Y.A.; Pearson, M.R.; Pullin, R.; Calderbank, P. Acoustic sensing and noise identification of a heating, ventilation and air conditioning unit: Industrial case study. *Appl. Sci.* **2021**, *11*, 9811. [\[CrossRef\]](#)
42. Ihi, R.; Fougere, N.; Passador, S.; Woo, S.; Kim, J.; Desouky, M. Flow-Induced Noise Prediction and Validation of a Heavy-Duty Electric Vehicle's HVAC System Using the Lattice Boltzmann Method. In *Proceedings of the Noise & Vibration Conference & Exhibition*; SAE International: Grand Rapids, MI, USA, 2025. [\[CrossRef\]](#)
43. Prakash, V.; Sauvage, O.; Antoni, J.; Gagliardini, L. Bayesian NVH metamodels to assess interior cabin noise using measurement databases. *arXiv* **2022**, arXiv:2207.02120. [\[CrossRef\]](#)
44. Sakhaei, B.; Durali, M. Vibration transfer path analysis and path ranking for NVH optimization of a vehicle interior. *Shock. Vib.* **2014**, *2014*, 697450. [\[CrossRef\]](#)

45. Sinneau, M.; Mietlicki, F.; Bernfeld, D.; Cherfan, S.; Motio-Betato, L.; Hellot, M.; Evrard, A.-S.; Regairaz, J.-P.; Rosin, C. Improve knowledge of acoustic factors involved in railway noise annoyance. *arXiv* **2025**, arXiv:2502.01175.
46. Torija, A.J.; Flindell, I.H. Listening laboratory study of low height roadside noise barrier performance compared against in-situ field data. *Build. Environ.* **2014**, *81*, 216–225. [[CrossRef](#)]
47. Brigitte, S.-F. The sound of an electrical vehicle—Its contribution to a new urban soundscape. In *Proceedings of the INTER-NOISE and NOISE-CON Congress and Conference Proceedings, InterNoise19*; Institute of Noise Control Engineering: Madrid, Spain, 2006.
48. Przydatek, G.; Ryniewicz, A.; Irimia, O.; Tomozei, C.; Mosnegutu, E.; Bodziony, M. Analysis of Noise Levels in Typical Passenger Cars. *Sustainability* **2023**, *15*, 7910. [[CrossRef](#)]
49. Ma, M.; Ran, W.; Wu, J.; Li, M.; Qu, X. Evaluating the Impact of Metro Interior Noise on Passenger Annoyance: An Experimental Study. *Int. J. Environ. Res. Public Health* **2022**, *19*, 5041. [[CrossRef](#)] [[PubMed](#)]
50. WHO. *Environmental Noise Guidelines*; WHO: Geneva, Switzerland, 2018.
51. Satar, M.; Mazlan, A.Z.A.; Hamdan, M.; Isa, M.; Paiman, M.; Ghapar, M. Experimental validation of the HVAC humming-type noise and vibration in model and vehicle system levels. *Arch. Acoust.* **2021**, *46*, 375–385. [[CrossRef](#)]
52. Fiebig, A.; Schulte-Fortkamp, B.; Genuit, K. New options for the determination of environmental noise quality. In *INTER-NOISE and NOISE-CON Congress and Conference Proceedings*; Institute of Noise Control Engineering: Washington, DC, USA, 2006; pp. 1141–1150.
53. Berglund, B.; Lindvall, T.; Schwela, D.H. New Who Guidelines for Community Noise. *Noise Vib. Worldw.* **2000**, *31*, 24–29. [[CrossRef](#)]
54. Hossain, R.; Manohare, M.; A. King, E. Systematic review of indoor soundscape assessments: Activity-based psycho-acoustics analysis. *Build. Acoust.* **2025**, *32*, 123–141. [[CrossRef](#)]
55. Torresin, S.; Albatici, R.; Aletta, F.; Babich, F.; Kang, J. Assessment methods and factors determining positive indoor soundscapes in residential buildings: A systematic Review. *Sustainability* **2019**, *11*, 5290. [[CrossRef](#)]
56. Page, M.J.; McKenzie, J.E.; Bossuyt, P.M.; Boutron, I.; Hoffmann, T.C.; Mulrow, C.D.; Shamseer, L.; Tetzlaff, J.M.; Akl, E.A.; Brennan, S.E.; et al. The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ* **2021**, *372*, n71. [[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.