



TECHNICAL UNIVERSITY OF CLUJ-NAPOCA

ACTA TECHNICA NAPOCENSIS

Series: Applied Mathematics, Mechanics, and Engineering
Vol. 68, Issue III, September, 2025

A THEORETICAL FRAMEWORK AND CRITICAL REVIEW OF VEHICLE NOISE CONTROL STRATEGIES

Bianca CĂȘERIU, Petruța BLAGA

Abstract: This article develops a theoretical framework and presents a critical review of contemporary vehicle noise control strategies, focusing on their classification, functional principles, and integration potential. Active, passive, hybrid, and adaptive-passive systems are systematically analyzed in terms of acoustic performance, control algorithms, and material-based attenuation. A research trend analysis based on data from Web of Science, Scopus, and Google Scholar reveals growing scientific interest in hybrid solutions and sustainable approaches. Special attention is given to acoustic comfort as a predictor of cognitive performance, health, and in-vehicle well-being. The proposed framework aims to guide the development of next-generation, energy-efficient, and high-performance noise control architectures for automotive, aerospace, and rail transport applications.

Key words: interior noise, acoustic comfort, active noise control (ANC), passive noise control, hybrid noise systems, adaptive-passive systems, vehicle acoustics, sound absorption materials.

1. VEHICLE STRUCTURES UNDER ACOUSTIC STRESS: SOURCES AND IMPLICATIONS

Vehicle structures are subject to multiple sources of vibrations and noise during operation, both when stationary (idling) and in motion [1]. Interior noise is a key factor affecting ride comfort. Similarly, vehicle vibrations are generally undesirable in operation, as they can diminish comfort and safety and may even lead to issues like increased fuel consumption. For these reasons, controlling automotive noise and vibration (the field of NVH – Noise, Vibration, and Harshness) has become a major focus [2, 3] in vehicle design and research.

According to current research [5, 6] and extensive studies conducted in 2023 by the author [7, 8], the most prominent noise sources inside a vehicle cabin have been identified and quantitatively estimated. Figure 1 presents a structured overview of the main interior noise sources and their approximate contributions to the overall in-cabin noise level. Summarized, the

typical contribution ranges of these sources are as follows [7, 8]:

- Engine: ~22% – 30% of total interior noise;
- Exhaust system: ~25% – 30%;
- Intake (air intake system): ~5% – 15%;
- HVAC (climate control) system: ~7% – 15%;
- Transmission: ~12% – 15%;
- Tires (road interaction): ~9% – 15%.

From this breakdown, one can observe that the engine and exhaust together account for roughly half of the cabin noise under many conditions, while other subsystems (intake, HVAC, transmission, tires) contribute the rest in varying proportions. These noise contributions will vary with operating mode (e.g. engine load, vehicle speed and road type), but they highlight which components are typically dominant sources of interior sound levels.

Imbalances in rotating components, engine reciprocating motions, and road irregularities can induce a spectrum of free and forced oscillations in the vehicle's structure.

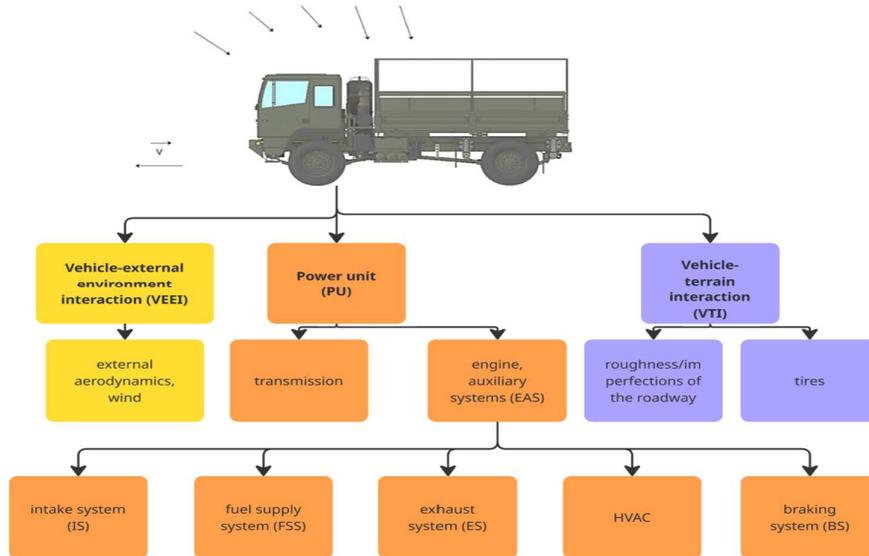


Fig. 1. The major structural noise sources contributing to vehicle interior sound levels

Inside the vehicle cabin, noise comprises a combination of sounds from various acoustic sources, interacting with reflections from surfaces and surrounding objects. An effective acoustic strategy requires a detailed understanding of sound reverberation phenomena [9, 10], which influence both the propagation and perception of sound. From an engineering standpoint, noise elimination and the management of sound and vibration involve a multi-stage cycle of testing, analysis, and mitigation strategies, particularly since acoustic comfort considerations are typically addressed in the final stages of production [11].

The dimension of acoustic comfort contributes significantly [12] to the overall perception of comfort. In comfort research, growing attention is given to individual preferences regarding ambient sound quality, as these are closely linked to personal well-being and productivity. Acoustic evaluation in transport systems has become a mandatory design consideration from early production stages [13]. It not only serves as an indicator of the vehicle's technical status and external acoustic environment, a standard adopted since the late 1990s and early 2000s [14], but also has a critical impact on operational competence, driver focus, and psychological well-being [15], particularly in the case of professional drivers.

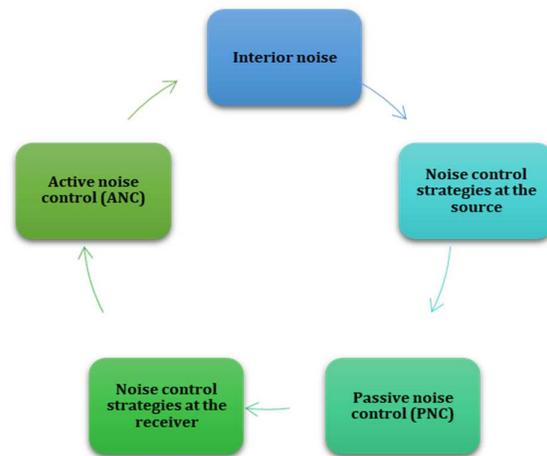


Fig. 2. Integrated noise control strategies for managing interior vehicle noise

A series of evaluations conducted by NVH (Noise, Vibration, and Harshness) engineers [16] focuses on the proactive identification of structural areas within the vehicle that are prone to elevated vibrations and the localization of unwanted noise sources. More broadly, as illustrated in Figure 2, the issue of interior noise is generally addressed through two primary approaches [17]: Passive Noise Control (PNC) and Active Noise Control (ANC).

2. RESEARCH METHODOLOGY

Although the existing literature is extensive with regard to vehicle acoustics, vibration control, and cabin comfort—each addressed

from engineering, psychoacoustic, and materials science perspectives—the integration of these domains into a unified framework for noise control strategies remains limited. The present study seeks to bridge this gap by conducting a critical synthesis of scientific findings related to active, passive, hybrid, and adaptive-passive noise control techniques, with the aim of formulating a comprehensive understanding of their application in the automotive context.

2.1 Methodological approach

The methodological approach adopted involves an exhaustive and systematic review of the scientific literature, driven by the necessity of clearly defining the research problem and identifying relevant, high-quality publications. This process ensures a solid, evidence-based foundation to support both the theoretical framework and the applied research outcomes.

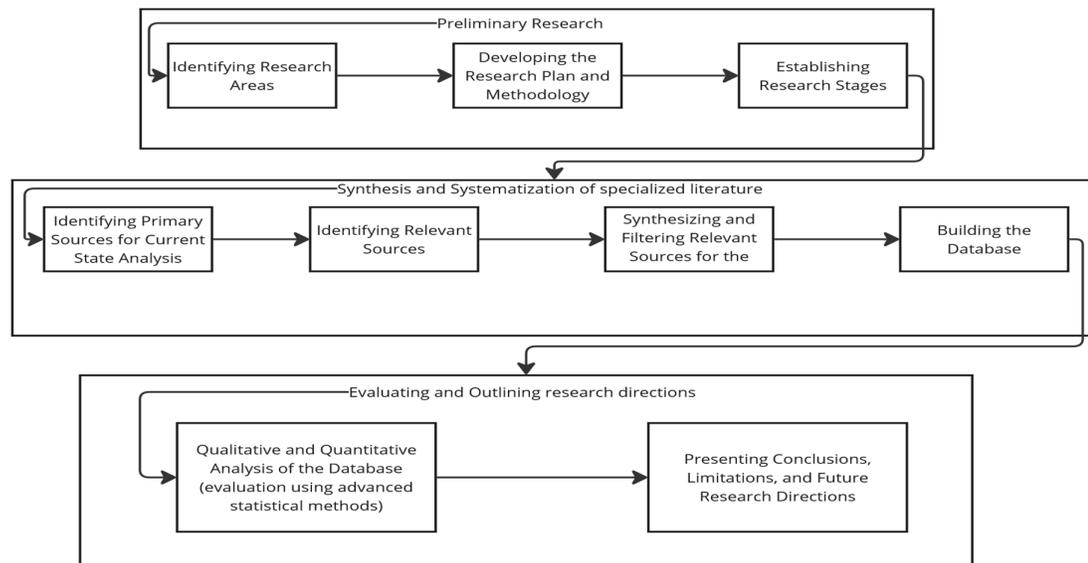


Fig. 3. Three-phase methodological approach [19] for the systematic analysis of vehicle noise control strategies
Source: realized by author

The research methodology implemented in this study is structured into three distinct phases, each supporting a rigorous and systematic investigation of vehicle noise control strategies. As illustrated in Figure 3, the process begins with a preliminary research phase, involving the identification of relevant research areas, the development of the methodological framework, and the establishment of sequential research stages. The second phase focuses on the synthesis and systematization of specialized literature, including the identification of primary and relevant scientific sources, filtering based on defined inclusion criteria, and constructing a coherent and consistent research database. In the final phase, the study engages in evaluating and

outlining research directions, which includes both qualitative and quantitative analysis of the data and the formulation of conclusions, limitations, and future research perspectives. This structured, multistage approach ensures methodological transparency, facilitates the reproducibility of the study, and supports the formulation of evidence-based conclusions for the field of vehicle noise control.

The database was limited in the preliminary stage to 20,000 publications (according to Figure 4), from which only the following types of publications with an occurrence frequency ≤ 1 were selected: articles, conference papers, books, book chapters, and review articles.

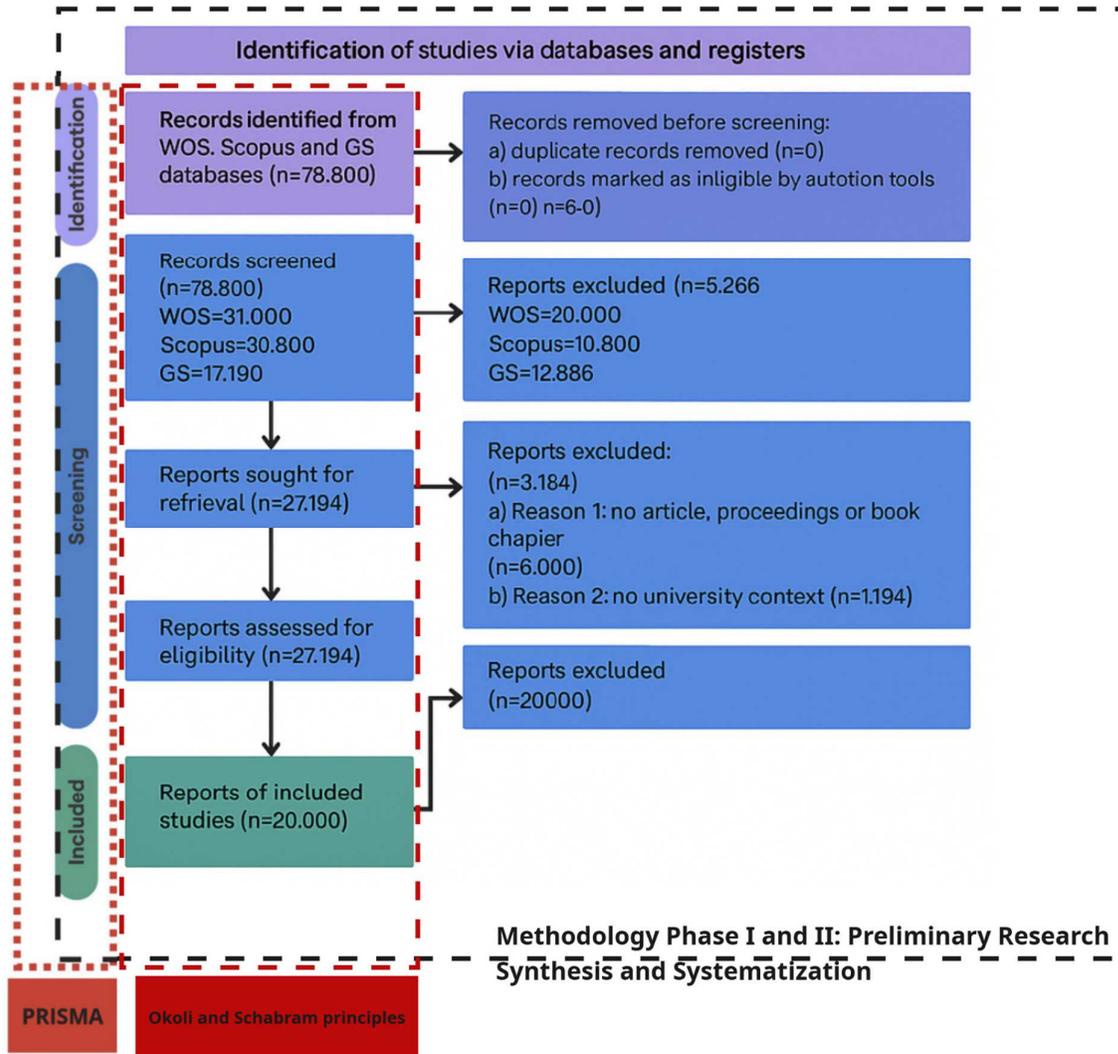


Fig. 4. Methodology Phase I and II – PRISMA flow diagram for identification, screening, and inclusion of studies on vehicle noise control

Based on the preliminary analysis of 79,890 publications, a comprehensive dataset was established, including: 11,949 review articles, 11,663 book chapters, 1,386 conference proceedings, 2,072 journal articles, and 124 books (Figure 4).

2.2 Comparative review of vehicle noise control methods

As early as 1992, at the Inter-Noise 92 conference, Bernhard et al. proposed a conceptual classification of noise and vibration control methods into four distinct categories [30]: active systems, passive systems, adaptive-passive systems, and hybrid active-passive systems [31–34].

Table 1. Review of vehicle noise control methods

No.	Description	Noise control strategy	Implementation	Effectiveness / Field of Application	Ref.
1.	Active Systems	Cancellation and control of unwanted sound waves by introducing an opposite-phase sound	Mainly uses systems such as: microphones, loudspeakers, controller/digital signal	Especially effective in the low-frequency (< 250 Hz) and mid-frequency range (250 Hz – 2000 Hz). / Used in the	[31]

		wave. Uses adaptive algorithms to continuously adjust to frequency and amplitude changes in the source wave.	processor (DSP), digital-to-analog converter (DAC), power amplifier, real-time controller, electronic control units (EMS ECU and TMS ECU).	automotive and aerospace industries.	
2.	Passive Systems	Based on absorption, blocking, and isolation of sound waves.	Use of materials and structural designs.	Effective across a wide frequency range, but efficiency depends on material characteristics; less effective and more difficult to implement at low frequencies. / Used in the automotive and aerospace industries.	[32]
3.	Hybrid Systems	Combines active and passive techniques to achieve enhanced noise reduction over a broader frequency range.	Uses passive devices for high- and mid-frequency control, and active devices for low-frequency control.	Broad frequency spectrum. / Applied in complex industrial environments.	[33]
4.	Adaptive-Passive Systems	Adjust parameters of passive devices according to changes in the operating environment.	Uses sensors and control algorithms to tune passive devices (e.g., Helmholtz resonator).	Suitable for variable-frequency environments with diverse acoustic sources, without requiring external energy for control activation. / Commonly used in: automotive, aerospace, construction, home entertainment, and IT sectors.	[34]

3. DATA VALIDATION AND PROCESSING

3.1 Evolution of publications trends

Evaluating the combined integration efforts of active and passive systems to achieve enhanced interior noise reduction performance in vehicles reveals an upward trend starting from 2001 to the present day [20-30]. Figure 5 illustrates the evolution of publication trends (articles, book chapters, review papers, conference proceedings, and books) retrieved from major databases such as Google Scholar, Scopus, and Web of Science, beginning with 2001.

Starting in 2010, which marked only 2% of total publications, a consistent annual increase of approximately 1% was observed until 2023, which recorded the peak number of publications, reaching a total of 6,232 entries. Among the contributing countries, Romania is also represented, with a total of 19 publications related to this topic.

This hybrid approach combines the advantages of both strategies, demonstrating effectiveness by utilizing passive materials to attenuate mid- and high-frequency noise, while applying active noise control (ANC) systems to cancel out specific low-frequency sources, such as engine-related noise.

3.2 Strategic directions in acoustic comfort and noise mitigation

A systematic and in-depth review of the specialized literature reveals several ongoing trends:

- The combined integration of active and passive noise control systems;
- The optimization of algorithms for active noise control (ANC) within vehicle interiors;
- The enhancement of in-cabin comfort through noise control techniques;
- The use and development of advanced materials for vehicle acoustics;

- The advancement of structural analysis methods for vehicle components, vibration, and acoustic performance;
- An increasing focus on sustainability and energy efficiency in noise control solutions.

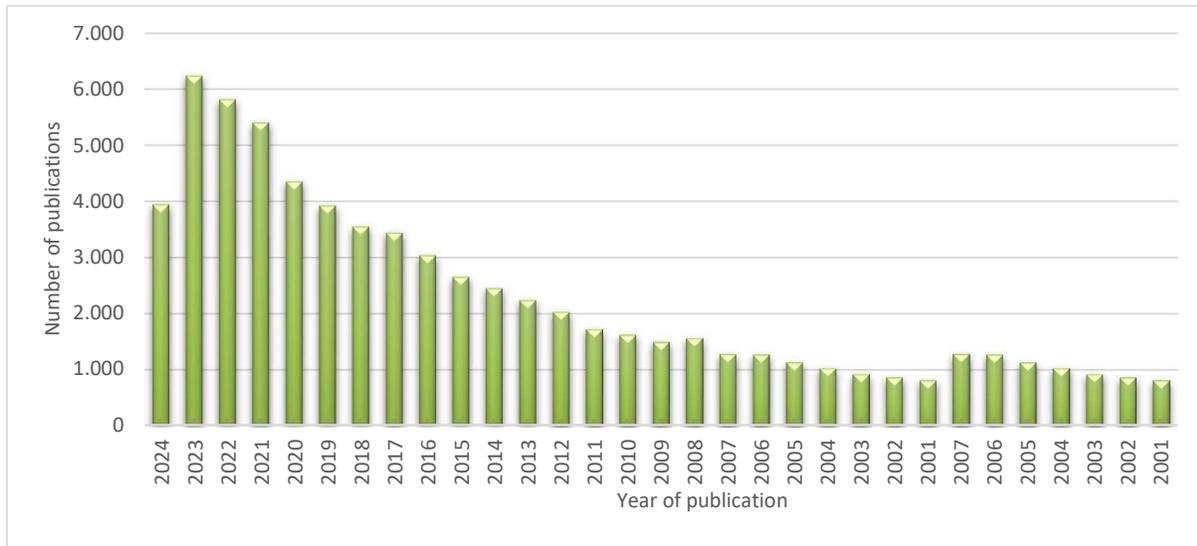


Fig. 5. Integrated approaches to cabin noise reduction: active and passive control trends

Source: Scopus, Web of Science și Google Scholar

Another emerging trend is the optimization of algorithms for active noise control (ANC) within vehicle cabins [35–37]. Based on the analysis of specialized literature [38, 39], two primary ANC methods have been identified: feedforward control and feedback control.

Feedforward ANC uses a reference signal detected before it reaches the secondary source. It is considered more robust because it isolates the reference input from the secondary anti-noise output. Many research efforts have focused on enhancing the performance and adaptability of this approach.

In contrast, feedback ANC [39] operates independently of prior information by using an error microphone that detects acoustic feedback to attenuate unwanted noise. This method is generally more cost-effective, offers stability

across multiple noise sources, and is particularly suitable for application in vehicle cabins. However, it presents limitations in terms of stability and is subject to the "waterbed effect"—a theoretical limitation indicating the inability to cancel noise uniformly across all frequencies simultaneously. Within the systematic review conducted, several studies have emerged as the most frequently cited contributions in the field of Active Noise Control (ANC). These works have had a significant impact on the development of adaptive ANC algorithms, proposing innovative control strategies and improving implementation efficiency across diverse acoustic environments. The most cited articles, summarized in Table 3, provide a solid theoretical and technical foundation for current and future research in vehicle noise mitigation.

Table 3. Key Research contributions on adaptive algorithms for active noise control (ANC) systems

Author	Year	Innovations and research in active noise control (ANC) systems	Ref.
Wu, L.	2014	Introduction of a simplified adaptive feedback ANC system, which uses the error signal as a reference in an adaptive feedforward control structure to reduce computational load and programming requirements.	[41]
Luo, L.	2017	Proposal of a novel approach using the WPFXLMS (Wavelet Packet FXLMS) algorithm to decompose and independently control predictable components of broadband noise, demonstrating superior noise cancellation performance.	[42]
Wu, L.	2018	Development of an adaptive algorithm for eliminating noise amplification in feedback systems by replacing the scalar leakage factor with a real symmetric Toeplitz matrix.	[43]

Schumacher, T.	2011	Introduction of a new approach for broadband feedback ANC, combining adaptive and non-adaptive techniques to attenuate various aspects of environmental noise.	[44]
Miyazaki, N.	2013	Exploration of improvements in headset-mounted ANC systems through the implementation of a virtual sensing technique to achieve greater noise attenuation.	[45]
Roy, T.K.	2013	Presentation of FxLMS and feedback ANC algorithms, introducing a new structure aimed at improving noise reduction performance.	[46]

The basic functional architecture of a narrowband ANC system is shown in Figure 6, based on the concept developed by Kuo et al. in 2008 [40]. This system generates a cancellation

signal that is out of phase with the primary noise, using a digital filter dynamically adjusted by an adaptive algorithm based on real-time feedback from a microphone.

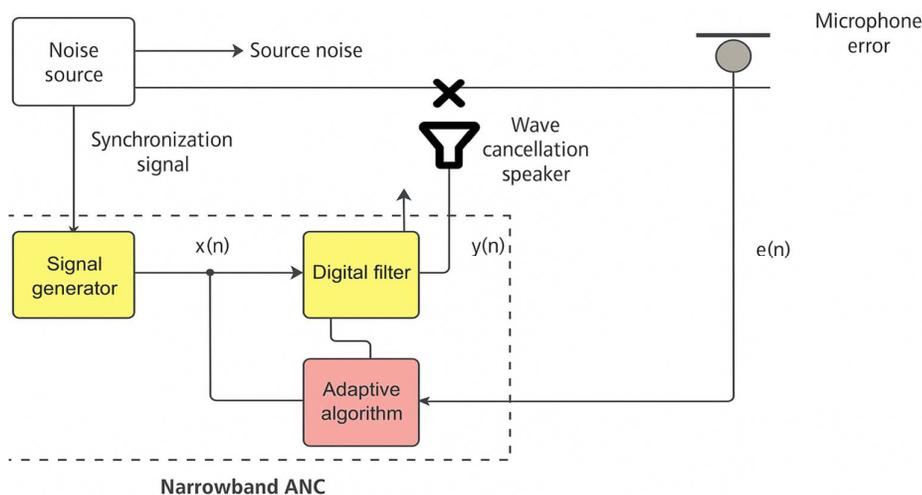


Fig. 6. Basic concept [40] behind active noise cancellation technologies

3.3 Multidimensional approaches in vehicle noise control

An exhaustive review of the specialized literature [34–40] indicates that noise control systems are increasingly used to improve the interior sound quality of vehicles, primarily by reducing noise generated by sources such as the engine and tire–road interactions.

Another recent direction in noise and vibration research [40–44] focuses on advanced analytical methods, including structural intensity analysis, noise source identification, and the evaluation of predominant structural components contributing to interior noise. These approaches are leading to new strategies for noise mitigation, especially at critical frequency ranges.

A significant emphasis in noise control strategies and comfort assurance has also been placed on sustainability and energy efficiency [34–46]. Current research aims to reduce interior

noise and enhance cabin comfort while maintaining a low vehicle weight, a key factor in achieving fuel efficiency and minimizing environmental impact. Noise control systems are thus required to contribute to these sustainability objectives without adding substantial mass to the vehicle.

Another important trend observed in the literature [34–46] is the development and application of materials in the automotive industry. A predominant technique for reducing unwanted cabin noise involves the integration of acoustic absorbing materials and vibro-elastic damping layers within the structural frame. For many researchers [40–46], a critical performance criterion for acoustic comfort is achieving a specific sound absorption coefficient under random incidence conditions. As a result, the absorption coefficient of production-ready materials is increasingly

considered a fundamental benchmark in automotive acoustic design.

7. CONCLUSION

This review has provided a comprehensive analysis of vehicle noise control strategies by integrating findings from a large-scale literature survey (over 79,000 publications) and recent research on Active Noise Control (ANC) systems. The results reveal clear trends in the hybridization of passive and active methods, with growing emphasis on algorithmic adaptability, lightweight acoustic materials, and sustainable engineering solutions.

Passive control remains essential for mid- and high-frequency noise, while ANC has proven most effective in the low-frequency range. The scientific literature increasingly supports combined active–passive approaches, which offer broader frequency coverage and more effective sound reduction. In particular, hybrid systems that integrate adaptive ANC algorithms with structural or material-based solutions represent a promising direction for the future of in-cabin acoustic comfort.

In the area of ANC, recent advancements in algorithm optimization—especially filtered-x LMS, wavelet-based methods, and adaptive feedback structures—have significantly improved noise attenuation capabilities. Emerging trends include the integration of AI-assisted adaptive control, real-time self-tuning systems, and predictive modeling based on driving or environmental conditions. These approaches enable more intelligent, robust, and user-centric noise management.

Parallel to algorithmic advances, the field is also being shaped by material innovation. Acoustic metamaterials, vibro-elastic layers, and recycled composites are now commonly explored for their ability to deliver high noise absorption with minimal added mass. This aligns with broader industry goals around fuel efficiency, battery range, and environmental sustainability.

However, several limitations remain. The lack of standardization in test conditions and evaluation metrics makes it difficult to compare results across studies. Many solutions are vehicle-specific, requiring recalibration for

different cabin geometries or noise profiles. Moreover, long-term validation in real driving conditions is rarely reported, and the integration of ANC in lower-cost vehicles remains limited by complexity and implementation costs.

Looking forward, this critical review points to several promising directions for future research that could address the above limitations and push vehicle noise control technology to new heights:

-Real-time ANC in autonomous and next-generation vehicles: As vehicles become increasingly autonomous, connected, and multifunctional, the demands on interior noise control will grow. Future research should focus on seamlessly integrating ANC with autonomous vehicle systems to maintain calm cabins in the absence of engine masking noise and during autonomous operations. This includes developing ANC that can adapt to new noise scenarios in electric and self-driving vehicles – for example, handling more prominent road and wind noise in nearly silent electric drivetrains. The trend towards autonomy thus presents an opportunity: noise control can be elevated from a purely comfort feature to an integral part of the vehicle’s human-centric design, ensuring quiet environments that improve safety (by reducing fatigue) and passenger well-being.

-Enhanced material modeling for vibro-acoustic performance: To maximize the impact of new noise control materials (e.g. metamaterials, acoustic foams, laminated panels), future studies should invest in more sophisticated vibro-acoustic modeling and simulation tools. This involves multi-disciplinary approaches combining finite element modeling of vehicle structures with acoustic simulations to predict how novel materials or damping treatments will perform in situ. By developing high-fidelity models, researchers can optimize material placement and properties before physical prototyping, saving time and cost. In particular, modeling of lightweight and metamaterial treatments needs to be refined to capture their frequency-dependent behavior and interactions with vehicle structures. Better models will also enable the design of smart materials (for instance, tunable or adaptive absorbers) that

could change properties on demand to target different noise conditions.

-AI-assisted adaptive noise control: Building on the initial forays of machine learning in ANC, future research should pursue artificial intelligence techniques to create self-optimizing noise control systems. By applying algorithms from deep learning and adaptive AI, ANC controllers could move beyond classical adaptive filters to become predictive and context-aware. For example, AI models could continuously analyze incoming noise and predict upcoming disturbances (such as identifying road texture or driver behavior that leads to certain noise patterns), allowing the ANC system to proactively adjust its countermeasures. Additionally, reinforcement learning could enable ANC algorithms to self-tune in real time, improving their performance with experience. Recent market analyses confirm that integrating AI can dramatically improve ANC effectiveness by allowing real-time adaptation to changing noise conditions. Future studies may explore neural network-based controllers that handle nonlinear noise dynamics better than linear filters, or hybrid AI approaches that switch between multiple control strategies depending on the scenario. The use of AI also opens the possibility of personalized noise control – systems that learn individual passengers' preferences for sound (for instance, some may prefer a completely silent cabin, while others might accept a bit of ambient noise for situational awareness). By incorporating AI, the next generation of ANC could become more adaptive, intelligent, and user-centric, representing a significant leap in noise control capability.

-Standardization and long-term validation: Finally, to truly mature the field, the community should work towards standardized testing methodologies and long-term experimental validation of noise control strategies.

In conclusion, this work has synthesized extensive literature and current practices to illuminate the state-of-the-art in vehicle noise control, from passive materials to active algorithms. The key contribution lies in framing an integrated active–passive control paradigm and highlighting how adaptive, intelligent ANC

systems can complement advanced materials to achieve superior acoustic comfort in vehicles. We have also drawn attention to the importance of emerging themes such as sustainability (lightweight, green materials) and the role of new vehicle trends (electrification and autonomy) in shaping noise control requirements. By critically examining limitations, the study provides a realistic assessment of what gaps remain. Ultimately, the research community is encouraged to pursue the outlined future directions. Doing so will not only address those gaps (through better standardization, modeling, and validation) but also unlock novel capabilities (through AI and new hybrid designs), driving the field toward quieter, more comfortable, and more energy-efficient vehicles for years to come. The authors believe that the framework and insights presented in this review will serve as a valuable foundation for future innovations in automotive noise and vibration control, fostering vehicles that are not only transportation devices but also serene mobile sanctuaries for their occupants.

8. FUNDING

“This work was partially supported by the University of Medicine, Pharmacy, Science and Technology “George Emil Palade” of Târgu Mures Research Grant number 163/1/10.01.2023.”

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UN CADRU TEORETIC ȘI O ANALIZĂ CRITICĂ A STRATEGIILOR DE CONTROL AL ZGOMOTULUI ÎN VEHICULE

Rezumat: Acest articol propune un cadru teoretic și realizează o analiză activă a strategiilor actuale de control ale zgomotului în vehicule, concentrându-se asupra clasificării acestora, principiilor funcționale și potențialului de integrare. Sistemele de control activ, pasiv, hibrid și adaptiv-pasiv sunt analizate sistematic din perspectiva performanței acustice, a algoritmilor de control și a metodelor de atenuare bazate pe materiale. Analiza tendințelor de cercetare, realizată pe baza datelor din bazele Web of Science, Scopus și Google Scholar, relevă un interes științific tot mai crescut pentru soluțiile hibride și abordările sustenabile. O atenție deosebită este acordată confortului acustic, considerat un indicator relevant al performanței cognitive, al sănătății și al stării de bine în mediul interior al vehiculului. Cadru propus are ca obiectiv orientarea dezvoltării unor tehnici de control al zgomotului de nouă generație, eficiente din punct de vedere energetic și cu performanțe acustice ridicate, aplicabile în domeniile auto, aerospațial și feroviar.

Cuvinte-cheie: zgomot interior; confort acustic; control activ al zgomotului (ANC); control pasiv al zgomotului; sisteme hibride de reducere a zgomotului; sisteme adaptiv-pasive; acustica vehiculului; materiale fonoabsorbante.

Bianca CĂȘERIU, Doctor of Engineering and Management, George Emil Palade University of Medicine, Pharmacy, Science and Technology of Targu Mures, IOSUD, Department of Industrial Engineering and Management, 0756849344, Address: Str. Gh. Marinescu, nr. 38, Târgu Mureș, Mureș, România, 540142, email: biancacasariu@yahoo.com

Petruța BLAGA, Professor, George Emil Palade University of Medicine, Pharmacy, Science and Technology of Targu Mures, IOSUD, Department of Industrial Engineering and Management, 0770195200, Address: Str. Gh. Marinescu, nr. 38, Târgu Mureș, Mureș, România, 540142, email: petruta.blaga@umfst.ro.