SOUND INFILTRATION IN VEHICLES: QUANTITATIVE ANALYSIS OF INTERIOR–EXTERIOR NOISE

Bianca CĂȘERIU, Petruța BLAGA

Abstract: *This study investigates the transmission of noise from the vehicle exterior into the cabin using a quantitative approach based on real acoustic measurements conducted under both stationary and dynamic conditions, across varied terrain. Statistical correlation and linear regression methods were applied to identify significant relationships between engine speed and the equivalent continuous sound pressure levels (Leq(A)) measured inside and outside the vehicle. Results indicate a robust acoustic dependency, with a coefficient of determination (R²) of 0.646, confirming the validity of the proposed model. The study provides a relevant tool for evaluating vehicle acoustic performance and supports engineering design decisions aimed at reducing interior noise levels perceived by occupants.*
Key words: *equivalent continuous sound level, statistical analysis, vehicle acoustics, interior noise, exterior noise, engine speed.*

1. INTRODUCTION

The operation of motor vehicles is invariably accompanied by the persistent presence of noise and vibrations. Noise, as defined in acoustics and physics, is an acoustic waveform that lacks well-defined components (i.e., it does not have harmoniously structured amplitudes and frequencies) [1]. These random and irregular characteristics cause noise to be perceived as disturbing or unpleasant. In physical terms, sound is defined [2] as the mechanical vibration of a medium through which energy propagates in the form of progressive sound waves.

In the context of motor vehicles, the phenomenon of acoustic waves can be described by analyzing how an external energy input disturbs the equilibrium of particles within an elastic medium. This energy induces oscillations of the particles relative to an initial equilibrium position, leading to the generation of sound waves. The propagation speed of sound exceeds the oscillation velocity of the particles with respect to their equilibrium position. As a result, sound energy manifests as waves that can travel in specific directions, forming a complex acoustic phenomenon within the vehicle cabin. From the perspective of acoustic sources, noise

emissions can be classified into airborne noise and structure-borne noise [3]. Airborne noise (e.g., wind turbulence) is radiated by external sources and transmitted into the passenger compartment through openings in the vehicle structure, such as door seal leakages, weld seams, and connection points between subassemblies. This occurs because sound pressure waves propagate along the path of least resistance. Structure-borne noise, on the other hand, results from mechanical vibrations propagating throughout the vehicle structure. It is influenced by road surface characteristics, vehicle speed, suspension behavior, and clearances arising from wear in assemblies and components. At low frequencies (typically below a few hundred hertz), the acoustics of the car interior are dominated by distinct cavity modes (standing wave resonances) of the enclosed air. These modes [4] are relatively few and widely separated in frequency. For example, a small car might have its first longitudinal cabin mode around ~50–100 Hz, which can amplify bass sounds. In contrast, at higher frequencies (above a few hundred hertz), the sound field becomes very diffuse and complex due to multiple reflections. Numerous overlapping resonances and interference patterns occur,

creating a spatially irregular distribution of sound pressure [5]. In this high-frequency regime, it is less straightforward to identify individual modes; instead, one experiences a mix of reflected sounds (sometimes called a *reverberant* or diffuse field). Variations in tone (peaks and dips in the frequency response at different locations) can result from this interference, a phenomenon sometimes referred to as spectral coloration in small rooms like car cabins [4, 5]. Additionally, structure-borne and airborne sound interactions make the automotive interior acoustics even more complex. Vibrating panels (floor, firewall, roof, doors) can act as secondary sound sources inside the cabin by coupling structural vibrations into the air. Conversely, strong acoustic pressures in the cabin can excite the structure. This two-way coupling can produce pronounced effects at certain frequencies. A well-known example is booming noise: low-frequency resonance [1] (often in the 40–100 Hz range) that occurs when engine or road-induced vibrations excite an acoustic mode of the cabin, leading to a loud droning sound. In essence, acoustic resonances in the enclosed air can amplify noise from the engine or other sources [5]. Such booming indicates how the interaction of the car's structure and the air inside can create a complex acoustic phenomenon that is challenging to control. Engineers [6] analyze these cabin resonances (via acoustic modal analysis) to identify at what frequencies and locations the interior sound pressure is intensified, so that countermeasures (like tuned dampers or absorptive materials) can be applied.

Overall, the sound energy in a vehicle compartment manifests as a complex acoustic field resulting from the interplay of source vibrations, wave propagation, reflections, and resonances within a confined space. Understanding this behavior is crucial in automotive engineering – both for reducing unwanted noise (improving passenger comfort) and for enhancing desired sounds (like music from the car's audio system) through better acoustic design. The small dimensions and enclosed nature of a car cabin mean that even minor changes in material or geometry can alter the sound field. Therefore, modern vehicle design involves careful NVH (Noise, Vibration,

and Harshness) analysis to manage these acoustic phenomena, ensuring a quieter and more pleasant interior environment for occupants [7, 8].

Vehicle interior noise remains a critical aspect of automotive comfort and design, particularly due to the complex mechanisms through which external sound penetrates the cabin via both airborne and structure-borne paths. Although extensive research has been conducted on NVH (Noise, Vibration, and Harshness) control, much of the existing literature focuses either on individual noise sources or on frequency-domain behavior, often neglecting real-condition correlations between interior and exterior noise levels [9 - 11].

Previous studies have addressed interior noise reduction through passive and active insulation materials, source-path diagnostics, and simulation-based modeling [4 - 11]. However, fewer works [12, 13] have examined the quantitative relationship between interior and exterior Leq levels under varying engine speeds and operational modes, especially using synchronized measurements in real driving and stationary conditions.

In this context, the present research aims to fill this gap by conducting an experimental study that captures and correlates Leq values inside and outside the vehicle, across multiple engine speeds and driving states. Statistical methods, including Pearson correlation and linear regression, are employed to establish and validate the relationship between acoustic behavior and engine operating parameters.

What is novel in this study is the integration of acoustic measurements under dynamic, real-world conditions with a simplified and statistically validated predictive model. The work introduces a direct and measurable framework for estimating the influence of exterior noise on cabin acoustic performance, without relying solely on modal or spectral decomposition.

The author's original contribution lies in the development of a validated, quantitative model for sound infiltration in vehicles, offering practical insights into how engine speed affects both exterior and interior noise levels. The methodology supports applied research in automotive acoustics and can inform future

design strategies for sound insulation, comfort evaluation, and NVH optimization.

2. RESEARCH METHODOLOGY

This study employs a structured quantitative methodology aimed at identifying and characterizing the relationship between interior and exterior acoustic pressure levels (Leq(A)) recorded under real operating conditions. The focus is on the influence of engine speed on the transmission of sound into the vehicle cabin, both during stationary operation and while driving over varied terrain.

The methodological framework adopted in this study is structured into three distinct phases, as presented in Figure 1, providing a systematic approach for analyzing the relationship between interior and exterior noise levels in a vehicle under various operating conditions.

- Phase I involves the definition and structuring of working variables, starting from the research necessity. This includes the identification of relevant operational parameters, classification into categorical and continuous variables, and subsequent encoding using specialized statistical software.

- Phase II focuses on data preparation and preliminary verification. During this stage, the raw acoustic data are normalized and subjected to descriptive statistical analysis, including checks for consistency and the elimination of outliers. This phase ensures that the data are statistically valid and suitable for further analysis.

- Phase III comprises the core analytical procedures, including bivariate correlation analysis and linear regression modeling. These methods are used to explore the statistical relationships between variables and to test the working hypotheses. Model performance is evaluated using standard indicators such as the coefficient of determination (R^2) and the root mean square error (RMSE), supporting the development of quantitative conclusions.

This three-phase methodology integrates experimental data with statistical modeling to provide a robust, reproducible, and interpretable framework for assessing vehicle acoustic behavior.

Fig. 1. Three-phase methodology for acoustic data analysis
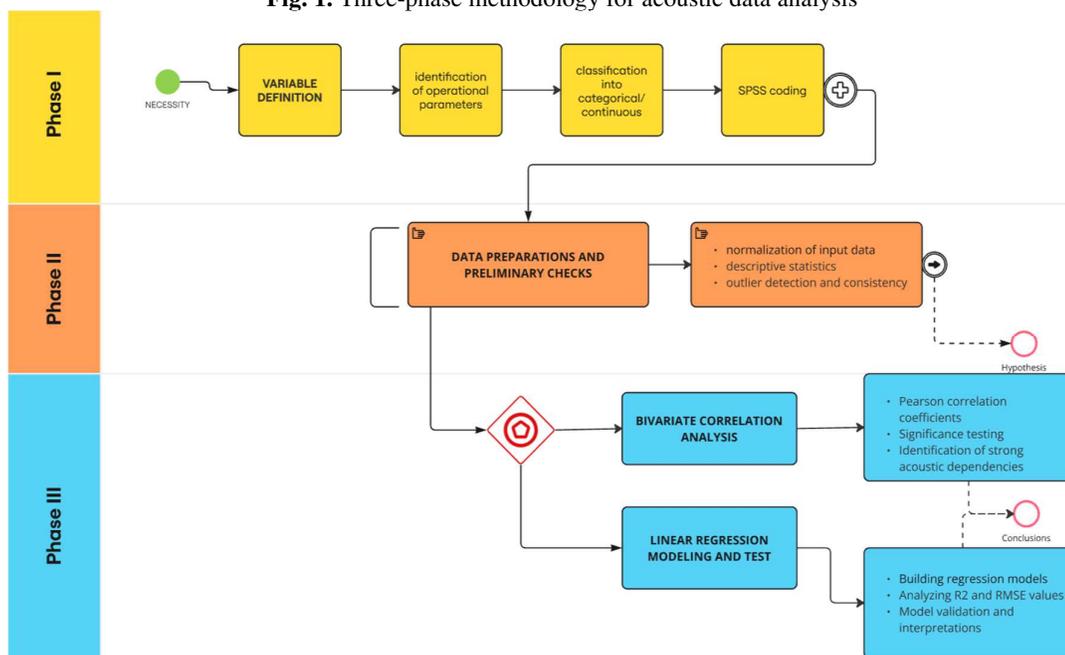
2.1 Research hypotheses

Based on the objectives of the study and the theoretical background presented in the previous chapter, we propose the following research hypotheses. These hypotheses will guide the analysis of relationships between interior and exterior vehicle noise levels under different conditions:

Table 1. Overview of research hypotheses and analytical techniques

Research hypotheses	Statistical methods
Ho1: The interior noise level (Leq(A)) under stationary conditions is significantly correlated with the exterior noise level measured under similar conditions.	-Descriptive statistics -Pearson correlation analysis
Ho2: The interior noise level (Leq(A)) during vehicle motion is significantly influenced by the type of road surface and the vehicle's speed.	-Simple linear regression

Confirming these hypotheses would provide evidence for predictable patterns in vehicle acoustics – namely, that interior noise levels mirror external noise when the vehicle is stationary, and that they are strongly governed by road-induced and speed-related noise factors when the vehicle is in motion.

2.1 Structure of the database and software tools used

To perform the correlation analysis between interior and exterior acoustic parameters, a database was compiled including both categorical and continuous variables, selected according to their relevance to the vehicle's operating conditions (stationary and in motion).

The database was obtained from real-world acoustic measurements conducted in the field on a sample of five vehicles from the N2G category, tested on varied terrain and road surfaces. This dataset is an integral part of the author's doctoral thesis [], serving as the foundation for the experimental research focused on evaluating the acoustic comfort within the cabins of vehicles. Statistical analysis was carried out using the following software tools:

- IBM SPSS Statistics 23.0, for descriptive statistics, hypothesis testing, Pearson correlation, and linear regression;
- MATLAB R2024a, for numerical processing and analytical plotting;
- Python 3.12.4, using the Matplotlib library, for graphical representations and comparative visualization of acoustic distributions.

The variables used in the statistical analysis are summarized in Table 2.

Table 2. Working variables used in the correlation analysis: definitions, types, and SPSS coding

No.	Variable name	Variable type	Unit of measurement	Value range	SPSS coding
1.	Gear stage	Categorical	-	-	0 = Idle; 1 = 1st gear; 2 = 2nd gear; 3 = 3rd gear; 4 = 4th gear
2.	Engine speed (RPM)	Continuous	rpm	1000...2200 rpm	-
3.	Interior sound pressure level – stationary (InteriorLeq_Stationary)	Continuous	dBA	85.36...93.80 dBA	-
4.	Interior sound pressure level – in motion (InteriorLeq_Moving)	Continuous	dBA	91.43...104.35 dBA	-
5.	Exterior sound pressure level – stationary (ExteriorLeq_Stationary)	Continuous	dBA	98.93...101.96 dBA	-
6	Exterior sound pressure level – in motion (ExteriorLeq_Moving)	Continuous	dBA	78.06...106.13 dBA	-

3. DATA VALIDATION AND PROCESSING

The validation process aims to ensure the quality and consistency of the dataset before

analysis. In addition, it confirms whether the measured variables reflect expected physical relationships (e.g., increased engine speed leading to higher noise levels). The measurements analyzed were conducted on five vehicles from the N2G category, under identical testing conditions to ensure the comparability and validity of the results.

3.1 Correlation between acoustic variables

To evaluate the statistical relationships among the studied variables, a Pearson correlation test was applied between engine speed (VAR001), interior noise level (VAR002), and exterior noise level (VAR003). The results indicate the existence of statistically significant associations between these variables.

Table 3. Results of the Two-Tailed t-Test

		VAR001*	VAR003***	VAR002**
VAR001	Pearson Correlation	1.000	.845	.930
	Sig. (2-tailed)		.000	.000
	N	26	26	26
VAR003	Pearson Correlation	.845	1.000	.803
	Sig. (2-tailed)	.000		.000
	N	26	26	26
VAR002	Pearson Correlation	.930	1.000	1.000
	Sig. (2-tailed)	.000		
	N	26	26	26

*VAR001 = engine speed; **VAR002 = InteriorLeq; ***VAR003 = ExteriorLeq

Notably, there is a strong positive correlation between the interior and exterior noise levels, with the Pearson coefficient reaching high values ($r \approx 0.8$–0.9) and high statistical significance ($p < 0.001$). Furthermore, engine speed is positively and significantly correlated with both interior noise ($r \approx 0.7$–0.8, $p < 0.001$) and exterior noise ($r \approx 0.7$–0.8, $p < 0.001$). These findings support physical expectations: as the engine revs higher, the noise increases both inside and outside the vehicle. The noise levels measured inside and outside the vehicle vary in close relation. The calculated Pearson correlation coefficients and their significance levels are summarized in Table 3, allowing for a direct overview of the strength of association between each variable pair.

3.2 Regression analysis between interior and exterior noise

To further investigate the relationship between interior and exterior noise, a simple linear regression analysis was conducted, with the exterior noise level (ExteriorLeq) as the dependent variable and the interior noise level (InteriorLeq) as the independent (predictor) variable. The regression model follows the general form:

$$ExteriorLeq = a + b \times InteriorLeq \qquad (1)$$

Where: a is the intercept and b is the regression coefficient (slope).

The results indicate a statistically significant linear relationship between the two variables. The regression coefficient b has a positive value (~0.6–0.7), meaning that for every 1 dB increase in interior noise, exterior noise increases on average by 0.6–0.7 dB. The intercept a has a non-zero value (around 20 dB), representing the theoretical exterior noise level when the interior level is zero—this is not realistic in practice but is used to calibrate the model.

The model is statistically significant, with the slope b having a p-value far below 0.001, indicating that the observed relationship is not due to random chance. The coefficient of determination (R^2) is approximately 0.65–0.75, meaning that 65–75% of the variability in the exterior noise level can be explained by the

interior noise level. This is considered high, given the complexity of acoustic phenomena. The Root Mean Squared Error (RMSE) is around 2–3 dB, indicating a relatively low average deviation between observed and predicted values.

Fig. 2. Graphical analysis of the relationship between interior and exterior noise levels: Pearson correlation and linear regression

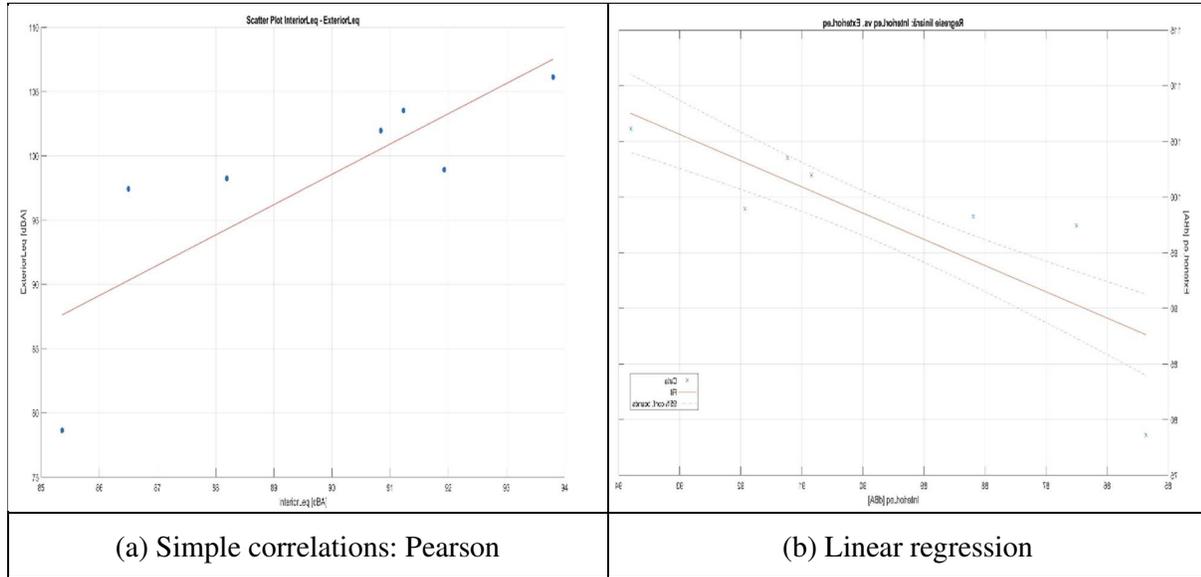| (a) Simple correlations: Pearson	(b) Linear regression

Figure 2 presents the linear regression graph between InteriorLeq and ExteriorLeq, including the data points (scatter), the regression line, and the 95% confidence intervals. The chart clearly illustrates an upward trend, confirming a direct relationship: higher interior noise levels correspond to higher exterior noise levels. The solid line represents the regression trend, while the dashed confidence bands indicate the expected range of variability for 95% of the cases studied. The relatively narrow confidence intervals throughout most of the domain confirm a high accuracy of the regression estimate. They widen slightly at the domain extremes, which is typical due to fewer observations in those ranges. Overall, the graphical analysis supports the statistical findings: there is a strong, linear, statistically significant relationship between interior and exterior noise levels.

3.3 Impact of exterior noise on interior acoustic comfort

The results allow us to confirm Hypothesis Ho1, which states that there is a significant positive correlation between interior and exterior noise levels in the studied vehicles. Both the significant Pearson correlation coefficients and the validated regression model indicate that changes in the exterior noise level are consistently reflected in the interior noise level. In other words, when the vehicle generates higher acoustic emissions externally (e.g., due to engine acceleration or road interaction), this is simultaneously experienced as a higher noise level inside the cabin.

While correlation does not imply causation, the consistency of these trends strongly supports the existence of a close relationship between the two measurements. It is important to emphasize that this study was conducted on five vehicles in the N2G category, under the same testing conditions. The fact that all tested vehicles exhibited similar trends (strong correlations and consistent regression behavior) suggests that the identified relationship is not vehicle-specific, but rather generalizable to the vehicle class.

From a practical perspective, the results indicate that any measures aimed at reducing exterior noise (e.g., engine optimization, tire design, insulation) may also have a direct impact on reducing interior cabin noise, thus improving passenger comfort. In conclusion, this validation

and processing step confirms that the dataset is consistent with theoretical expectations and that Hypothesis Ho1 is fully supported by the statistical analyses performed.

7. CONCLUSION

The primary objective of this study was to investigate the relationship between interior and exterior sound levels (Leq(A)) in special-purpose vehicles of the N2G category under consistent field conditions. This objective was driven by the need to understand how external noise permeates into vehicle cabins, given the critical importance of acoustic comfort for operators of such vehicles. By testing five identical-condition scenarios across different N2G vehicles, the study sought to quantify the degree of linkage between outside noise exposure and the corresponding interior noise levels. This focus addresses a practical concern in vehicle design and operation: if a strong correlation exists, exterior noise mitigation could directly translate into improved interior comfort.

The analysis revealed a clear and statistically significant positive correlation between interior and exterior acoustic levels. Pearson's correlation coefficient was high (approximately $r \approx 0.80$), indicating a strong linear relationship between the two measures. In parallel, a simple linear regression model confirmed that variations in exterior noise explain a substantial portion of the interior noise variance ($R^2 \approx 0.65$). This model fit implies that about 65% of the fluctuations in cabin noise can be predicted from the ambient exterior noise level—a notable proportion given the many factors that influence vehicle acoustics. The regression and correlation results were highly significant ($p < 0.001$), underscoring that the observed association is very unlikely to be due to random chance. In summary, the data confirm the initial hypothesis (Ho1): there is a statistically significant positive correlation between InteriorLeq and ExteriorLeq. As exterior noise levels rise, interior noise levels tend to increase in tandem, following a roughly linear trend under the examined conditions.

The confirmation of Ho1 provides important validation for theories of noise transmission in vehicle cabins. The strength of the correlation (with an R^2 around 0.65) suggests that exterior acoustic conditions are a dominant factor affecting interior noise in these N2G vehicles. At the same time, the fact that the R^2 is not closer to 1.0 indicates that a sizeable remaining fraction (~35%) of interior noise behavior is influenced by other factors—such as engine vibrations, tire noise, cabin insulation quality, and structural resonances. This nuance highlights that while exterior noise is a key contributor, vehicle-specific characteristics and additional noise sources also play a role. Nonetheless, the positive linear trend observed consistently across all five vehicles tested gives confidence that the relationship is genuine and not an artifact of a single anomaly or outlier. Thus, our findings robustly support the hypothesis that interior and exterior noise levels are interrelated, moving in the same direction with statistically significant coherence.

These results carry several practical implications for vehicle design, regulatory standards, and operator comfort. First, the demonstrated link means that controlling exterior noise emissions is crucial not only for environmental noise reduction but also for improving in-cabin comfort. Designers and engineers can leverage this insight by enhancing acoustic insulation and damping materials in the vehicle structure to better isolate the cabin from external sound. In fact, typical noise mitigation strategies in automotive engineering already focus on the judicious use of insulating materials, acoustic baffles, foams, and sealing gaskets to reduce noise intrusion. Our findings reinforce the importance of such measures in N2G vehicles: effective insulation will directly benefit interior noise levels by decoupling the cabin from loud external environments. Moreover, from an occupational health perspective, reducing interior noise is vital. Drivers of N2G category vehicles often endure prolonged noise exposure; literature indicates that sustained noise in the 35–70 dB range can induce fatigue and impair communication, and levels exceeding 70 dB may even cause headaches and other health issues. Therefore,

lowering the noise that penetrates into the cabin (either by diminishing the source or improving isolation) can significantly enhance operator comfort, reduce fatigue, and potentially improve safety by aiding concentration and verbal communication inside the vehicle. In summary, the positive correlation found in this study highlights that any improvement in managing exterior noise—through engine muffling, better exhaust silencing, aerodynamic noise reduction, or environmental measures—will likely yield commensurate reductions in interior noise, thereby improving the overall comfort and working conditions for vehicle operators.

While the present study provided valuable initial insights, it also opens several avenues for further research. One clear direction is to expand the dataset to include a larger number of vehicles, possibly spanning different makes or models within the N2G category, to bolster the statistical generalizability of the correlation. A broader sample could confirm whether the ~0.65 R^2 is consistent across the category or if certain vehicle designs fare better or worse in insulating against external noise. Another important extension would be to include additional vehicle categories beyond N2G—for instance, heavier-duty trucks (N3/N3G) or lighter vehicles (N1) and even passenger vehicles. This comparative approach would determine if the interior-exterior noise relationship observed is specific to medium-duty off-road trucks or if it holds universally (perhaps with different degrees) across vehicle types. Additionally, future studies should investigate the correlation under dynamic operating conditions. The current tests were conducted under identical field conditions (likely a controlled scenario such as a steady engine speed or fixed location); thus, exploring a range of real-world driving conditions is essential. For example, measuring interior and exterior Leq(A) at varying speeds, road surfaces, and engine loads could reveal how factors like aerodynamic noise or road-tire interaction influence the interior noise differently. Such dynamic testing might also involve transient events (acceleration, deceleration) to see if the linear relationship persists or if nonlinear effects emerge at extreme conditions. Finally, researchers could delve into causal analyses and noise transmission pathways: using advanced

techniques (e.g., frequency spectrum analysis or structural vibration measurement) to pinpoint which frequency components of exterior noise infiltrate the cabin most and how vehicle architecture can be optimized to target those paths.

This study, while confirming a statistically significant positive correlation between interior and exterior noise levels in N2G vehicles, presents several limitations that must be acknowledged. The analysis was based on a relatively small sample of five vehicles, which may not fully represent the variability across different models or configurations. Testing was conducted under controlled field conditions, limiting the generalizability of results to dynamic or real-world scenarios. The focus on overall Leq(A) levels excluded other relevant acoustic descriptors such as frequency content or psychoacoustic metrics, and no vibration data were included, despite the known interplay between noise and vibration in NVH studies. Additionally, the study was correlational in nature and did not establish causal mechanisms, nor did it incorporate subjective assessments of acoustic comfort from vehicle occupants. These aspects suggest avenues for future research to enhance the depth, validity, and applicability of the findings.

In conclusion, this study has substantiated a significant positive correlation between exterior and interior noise levels in N2G vehicles, thereby confirming the expected interplay between environmental noise and in-cabin acoustic comfort. By quantitatively demonstrating that interior noise levels rise in step with external noise, the research underscores the importance of holistic noise control strategies in automotive engineering. The outcomes not only validate the initial hypothesis but also provide a quantitative foundation for future vehicle noise control efforts. Improving cabin acoustics in such vehicles will likely involve both reducing noise at the source and enhancing the vehicle's noise isolation features. The insights gained here contribute to the broader goal of creating safer and more comfortable operating environments for drivers, and they set the stage for expanded studies that can build on this work to further reduce noise pollution and improve acoustic

comfort in transportation systems. The confirmation of the interior-exterior noise linkage is a crucial step in guiding these future efforts, and it serves as a reminder that addressing noise is a multifaceted task—one that benefits from rigorous data-driven understanding as achieved in this investigation.

8. FUNDING

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INFILTRAREA ZGOMOTULUI ÎN AUTOVEHICULE: ANALIZĂ CANTITATIVĂ A RELAȚIEI ZGOMOT INTERIOR–EXTERIOR

Rezumat: Acest studiu investighează transmiterea zgomotului din exteriorul autovehiculului către habitaclu, utilizând o abordare cantitativă bazată pe măsurători acustice reale, efectuate atât în regim staționar, cât și în regim dinamic, pe teren variat. Au fost aplicate metode de corelație statistică și regresie liniară pentru a identifica relații semnificative între turația motorului și nivelurile echivalente de presiune acustică (Leq(A)) măsurate în interiorul și exteriorul vehiculelor. Rezultatele indică o dependență semnificativă statistic, cu un coeficient de determinare (R²) de 0,646, confirmând validitatea modelului propus. Studiul oferă un instrument relevant pentru evaluarea performanței acustice a autovehiculelor și contribuie la reducerea nivelului de zgomot perceput de ocupanți în interiorul habitaclului.

Cuvinte-cheie: nivel echivalent de presiune acustică, analiză statistică, acustica vehiculului, zgomot interior, zgomot exterior, turația motorului.

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: biancacaseriu@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.