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Research Article

Comparative Investigation of Engine Compartment Insulation Materials on ECE R51 Pass-By Noise Performance of M3 Category Buses

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ABSTRACT

Exterior vehicle noise regulations, particularly ECE R51, impose increasingly stringent limits on pass-by noise emissions, making acoustic insulation materials a critical design parameter in commercial vehicle development. In addition to acoustic performance, engine compartment insulation materials must also comply with fire safety requirements specified by ECE R107. This study presents a comparative investigation of two insulation materials commonly used in commercial vehicle engine compartments: closed-cell polyurethane foam and polyester nonwoven felt. A comprehensive review of commercially available insulation materials was initially conducted considering both acoustic performance and regulatory requirements. Based on this evaluation, two representative insulation solutions were selected for full-scale experimental validation. Two equivalent M3 category city buses equipped with identical 220 kW rear-mounted Mercedes diesel powertrains were tested under standardized ECE R51 pass-by noise conditions. Both insulation systems utilized a thickness of 30 mm and an aluminum-faced protective covering. The first configuration employed closed-cell polyurethane foam, while the second utilized polyester nonwoven felt. Noise measurements were performed according to ECE R51 requirements under homologation-level test conditions. A simplified acoustic prediction model based on frequency-dependent sound absorption coefficients was developed and validated through experimental testing. The results demonstrated that the polyester nonwoven insulation achieved a lower average pass-by noise level of 74.9 dB(A) compared to 79.5 dB(A) for the polyurethane foam configuration, corresponding to an overall improvement of approximately 4.6 dB. The improved performance was attributed to the superior sound absorption characteristics of the porous fibrous structure, particularly within the dominant engine noise frequency range of 1500–2000 Hz. The study provides practical guidance for acoustic insulation material selection in commercial vehicle applications and demonstrates the importance of considering both acoustic performance and regulatory compliance during engine compartment insulation design.

KEYWORDS

ECE R51, ECE R107, Pass-by Noise, Acoustic Insulation, Polyester Nonwoven Felt, Polyurethane Foam, M3 Bus

1. Introduction

Vehicle exterior noise has become an increasingly important environmental issue due to its impact on urban acoustic comfort, public health, and environmental sustainability. Road traffic noise generated by heavy commercial vehicles is one of the major contributors to environmental noise pollution, particularly in densely populated urban areas. Consequently, international regulations such as UN/ECE Regulation No. 51 impose progressively stricter limits on vehicle pass-by noise emissions in order to reduce the environmental impact of road transportation systems [1–3].

For heavy-duty M3 category buses, compliance with ECE R51 Phase 3 requirements represents a significant engineering challenge. During pass-by noise testing, vehicle exterior noise is influenced by several factors including engine power output, combustion characteristics, cooling system operation, exhaust noise, and engine compartment acoustic insulation performance [4,5]. In rear-engine diesel buses, the engine compartment is one of the dominant noise sources contributing to measured pass-by noise levels, particularly within the frequency range associated with combustion and mechanical excitation.

In addition to acoustic performance requirements, insulation materials installed within the engine compartment must satisfy fire safety requirements. According to ECE R107, flammable sound-proofing materials or materials liable to become impregnated with fuel, lubricant, or other combustible substances shall not be used in the engine compartment unless adequately protected by an impermeable covering [6]. Consequently, material selection for engine compartment applications requires a balance between acoustic absorption performance, durability, and regulatory compliance.

Various acoustic insulation materials are currently used in commercial vehicle engine compartments, including polyurethane foams, polyester nonwoven felts, melamine foams, glass fiber mats, mineral wool-based insulation systems, and recycled PET acoustic felts. These materials exhibit different sound absorption characteristics depending on their internal morphology, airflow resistivity, density, and frequency-dependent behavior [7–11].

Table 1: *Comparison of common engine compartment acoustic insulation materials used in commercial vehicles*

Material	Structure	Typical Sound Absorption Coefficient @1000 Hz	Effective Frequency Range (Hz)	Fire Performance	ECE R107 Suitability
Closed-cell Polyurethane Foam	Closed-cell	0.20–0.35	1000–4000	Moderate	Requires protective covering
Open-cell Polyurethane Foam	Open-cell	0.60–0.90	500–4000	Moderate	Requires protective covering
Polyester Nonwoven Felt	Open fibrous	0.75–0.95	500–3000	Good	Suitable when protected
Melamine Foam	Open-cell	0.80–1.00	500–5000	Excellent	Suitable
Glass Fiber Mat	Fibrous	0.85–1.00	250–4000	Excellent	Suitable
Mineral Wool	Fibrous	0.85–1.00	250–4000	Excellent	Suitable
Recycled PET Acoustic Felt	Open fibrous	0.70–0.95	500–3000	Good	Suitable when protected

Among these materials, polyester nonwoven structures and melamine foams generally exhibit superior acoustic absorption performance due to their open porous morphology, while closed-cell polyurethane foams provide comparatively lower acoustic absorption but offer advantages in thermal insulation and mechanical durability [8–12].

However, despite the availability of acoustic characterization data under laboratory conditions, limited studies have investigated the influence of these materials on full-scale vehicle pass-by noise performance under homologation-level ECE R51 testing conditions.

Therefore, this study focuses on two insulation solutions widely used in commercial vehicle applications and capable of meeting engine compartment installation requirements: closed-cell polyurethane foam and polyester nonwoven felt. The objective is to investigate the relationship between material acoustic properties and measured vehicle exterior noise emissions and to provide practical guidance for insulation material selection in future commercial vehicle developments targeting compliance with ECE R51 Phase 3 requirements.

2. Materials and Methods

Test Vehicle Specifications

The experimental study was conducted using two equivalent M3 category city buses developed on the same vehicle platform.

Table 2: *Vehicle Specifications*

Parameter	Value
Vehicle Category	M3 City Bus
Engine Type	Mercedes Diesel
Maximum Engine Power	220 kW
Engine Speed at Maximum Power	1800 rpm
Transmission	Automatic
Engine Compartment Volume	4 m^3
Insulation Area	8 m^2

According to ECE R51 requirements, pass-by noise measurements were performed while the engine operated within 85–89% of the engine speed at maximum power, corresponding to approximately 1530–1600 rpm during acceleration tests. Simultaneously, vehicle speed at the BB' line was maintained within 35 ± 5 km/h.

Under these operating conditions, dominant combustion, mechanical, cooling fan, and powertrain-related noise components were concentrated primarily within the 1500–2000 Hz frequency range.

Insulation Configurations

Two insulation configurations were comparatively evaluated.

Table 3: *Insulation Configurations*

Configuration	Insulation Material	Structure	Thickness
A	Polyurethane Foam	Closed-cell	30 mm
B	Polyester Nonwoven Felt	Open fibrous	30 mm

Both insulation systems employed identical aluminum-faced protective coverings in order to satisfy engine compartment durability and contamination protection requirements. Therefore, the observed acoustic performance differences can primarily be attributed to the acoustic behavior of the underlying insulation materials.

Acoustic Material Properties

The frequency-dependent sound absorption coefficients of both materials were evaluated according to representative literature and manufacturer data.

Table 4: *Frequency-Dependent Sound Absorption Coefficients*

Frequency (Hz)	Polyurethane Foam	Polyester Nonwoven Felt
500	0.15	0.57
1000	0.25	0.84
1200	0.30	0.82
1500	0.35	0.93
2000	0.40	0.84

The polyester nonwoven felt exhibits significantly higher absorption performance within the frequency range associated with dominant diesel engine noise.

ECE R51 Pass-By Noise Test Procedure

Exterior vehicle noise measurements were conducted in accordance with UN/ECE Regulation No. 51 Revision 3 under ISO 10844 compliant test track conditions. Microphones were positioned 7.5 m from the vehicle centerline and 1.2 m above ground level. Measurements were obtained separately from both sides of the vehicle and repeated four times for each configuration. Environmental conditions satisfied all ECE R51 requirements regarding wind speed, ambient temperature, and background noise levels.

Prior to the pass-by noise evaluation, reference engine noise measurements were conducted under stationary operating conditions. The engine was operated at 1800 rpm, corresponding to the engine speed at maximum power, while the engine compartment cover was kept open. The microphone position was maintained consistent with the ECE R51 measurement geometry. Under these conditions, the measured reference engine noise level was approximately 81.0 dB(A), while the direct engine noise level was measured as 81.5 dB(A). These measurements were subsequently used as reference inputs for the acoustic prediction model.

Acoustic Evaluation Approach

The acoustic performance of the investigated insulation materials was evaluated using a simplified absorption-based prediction model combined with experimental ECE R51 pass-by noise measurements. The sound absorption coefficient is defined as [8]:

$$\alpha = 1 - Ir / Ii \quad (1)$$

where Ii represents the incident sound intensity and Ir represents the reflected sound intensity. The equivalent acoustic absorption area is expressed as [13]:

$$A = \alpha S \quad (2)$$

where A is the equivalent absorption area, α is the sound absorption coefficient, and S is the insulation surface area. Noise reduction was evaluated using [14]:

$$NR = L1 - L2 \quad (3)$$

where L1 and L2 represent sound pressure levels before and after insulation application. A simplified absorption-based prediction model was employed using the measured reference engine noise level of 81.0 dB(A) as the baseline condition. The dominant operating frequency observed during the ECE R51 tests was approximately 2000 Hz. Therefore, the absorption coefficients at 2000 Hz were used for the theoretical comparison. The predicted sound pressure levels were calculated according to:

$$L2 = L1 + 10 \log10((1 - \alpha2) / (1 - \alpha1)) \quad (4)$$

where L1 = reference sound pressure level, L2 = predicted sound pressure level after insulation, α1 = absorption coefficient of the reference condition, α2 = absorption coefficient of the investigated insulation material. For the reference condition without insulation:

$$\alpha 1 = 0 \quad (5)$$

The measured reference engine noise level was L1 = 81.0 dB(A). Using the sound absorption coefficients at 2000 Hz from Table 4, the predicted sound pressure levels were calculated as follows.

Polyurethane Foam:

$$L\_PU = 81 + 10 \log10((1 - 0.40) / (1 - 0)) \quad (6)$$

$$L\_PU = 81 + 10 \log10(0.60) \quad (7)$$

$$L\_PU = 78.8 \text{ dB(A)} \quad (8)$$

Polyester Nonwoven Felt:

$$L\_PET = 81 + 10 \log10((1 - 0.84) / (1 - 0)) \quad (9)$$

$$L\_PET = 81 + 10 \log10(0.16) \quad (10)$$

$$L\_PET = 73.0 \text{ dB(A)} \quad (11)$$

Table 5: *Predicted acoustic performance based on absorption coefficients*

Configuration	Absorption Coefficient at 2000 Hz	Predicted SPL (dB(A))
Reference (No Insulation)	0.00	81.0
Polyurethane Foam	0.40	78.8
Polyester Nonwoven Felt	0.84	73.0

The calculated results indicate that polyester nonwoven felt is expected to provide significantly greater acoustic attenuation due to its higher absorption coefficient at the dominant operating frequency. These predicted values were subsequently validated through full-scale ECE R51 pass-by noise measurements presented in the following section.

Figure 1: *ECE R51 pass-by noise test setup showing the microphone position at the test track during vehicle noise measurements.*

3. Results

Pass-by noise measurements were performed under identical ECE R51 test conditions for both insulation configurations. During all measurements, the vehicle was operated in third gear with a vehicle speed of approximately 24 km/h at the AA' line and 32 km/h at the BB' line. The engine speed at the BB' line was maintained at approximately 1550 rpm for all test runs, ensuring consistent operating conditions throughout the experiments.

The results obtained for the polyurethane foam insulation configuration are presented below. Four consecutive measurements were conducted from both the left and right sides of the vehicle. The average sound pressure levels were determined as 76.3 dB(A) on the right side and 82.7 dB(A) on the left side, resulting in an overall average pass-by noise level of 79.5 dB(A).

Table 6: *Experimental ECE R51 Pass-By Noise Results — Polyurethane Foam + Aluminum Facing Insulation*

Run	Lmax right side (dB(A))	Lmax left side (dB(A))	Vaa' (km/h)	Vbb' (km/h)	Nbb' (min^{-1})
1	76.3	82.6	24	32	1550
2	76.2	83.0	24	32	1550
3	76.2	82.7	24	32	1550
4	76.3	82.6	24	32	1550
Average	76.3	82.7			
Total Average	79.5				

Table 7: *Experimental ECE R51 Pass-By Noise Results — Polyester Nonwoven Felt + Aluminum Facing Insulation*

Run	Lmax right side (dB(A))	Lmax left side (dB(A))	Vaa' (km/h)	Vbb' (km/h)	Nbb' (min^{-1})
1	73.7	76.5	24	32	1550
2	73.5	75.7	24	32	1550
3	73.9	76.0	24	32	1550
4	73.8	75.8	24	32	1550
Average	73.7	76.0			
Total Average	74.9				

The results obtained for the polyester nonwoven felt insulation configuration show that the average sound pressure levels were measured as 73.7 dB(A) on the right side and 76.0 dB(A) on the left side, resulting in an overall average pass-by noise level of 74.9 dB(A).

A comparison of the two insulation systems indicates that the polyester nonwoven felt configuration achieved the lowest overall exterior noise level. Relative to the polyurethane foam configuration, the measured pass-by noise level decreased from 79.5 dB(A) to 74.9 dB(A).

Table 8: *Predicted and Measured Pass-By Noise Levels*

Configuration	Predicted SPL (dB(A))	Measured SPL (dB(A))	Deviation (dB)
Polyurethane Foam	78.8	79.5	0.7
Polyester Nonwoven Felt	73.0	74.9	1.9

The simplified absorption-based prediction model showed good agreement with the experimental measurements. The maximum deviation between predicted and measured pass-by noise levels remained below 2 dB, indicating that frequency-dependent sound absorption coefficients can provide a useful first-order indicator for evaluating engine compartment acoustic insulation performance.

An additional observation was the difference between the left and right side measurements. The polyurethane foam configuration exhibited a side-to-side difference of approximately 6.4 dB, whereas the polyester nonwoven felt configuration reduced this difference to approximately 2.3

dB. This behavior suggests a more homogeneous acoustic energy dissipation mechanism within the engine compartment when porous fibrous insulation materials are utilized.

4. Discussion and Conclusion

The results clearly demonstrate that insulation material selection significantly affects exterior vehicle noise performance under ECE R51 pass-by testing conditions.

Although both configurations employed identical aluminum-faced protective coverings, the polyester nonwoven insulation provided substantially improved acoustic performance compared with the closed-cell polyurethane foam. This improvement is attributed to the porous fibrous morphology of polyester nonwoven materials, which enables enhanced viscous and thermal dissipation of acoustic energy.

The higher sound absorption coefficients observed within the 1500–2000 Hz frequency range correspond closely with the dominant noise frequencies generated by diesel engine combustion, mechanical operation, and cooling systems during ECE R51 acceleration tests. Consequently, the superior absorption behavior of polyester nonwoven felt translated directly into reduced exterior noise emissions.

From a regulatory perspective, the investigated materials must satisfy both acoustic performance requirements specified by ECE R51 and engine compartment safety requirements specified by ECE R107. The use of aluminum-faced coverings provides protection against contamination by fuel, lubricant, and other combustible substances while maintaining acoustic functionality.

Relative to the reference engine noise level of 81.0 dB(A), the polyurethane foam configuration achieved a reduction of approximately 1.5 dB, whereas the polyester nonwoven felt configuration achieved a reduction of approximately 6.1 dB. The measured improvement is consistent with the significantly higher absorption coefficient of polyester felt at the dominant operating frequency of approximately 2000 Hz.

The measured reduction of approximately 4.6 dB between the two insulation configurations represents a significant improvement in pass-by noise performance and may contribute substantially toward compliance with future ECE R51 Phase 3 limits.

In conclusion, polyester nonwoven felt demonstrated superior acoustic performance compared with closed-cell polyurethane foam under homologation-level ECE R51 testing conditions. The measured pass-by noise level was reduced from 79.5 dB(A) to 74.9 dB(A), corresponding to an improvement of approximately 4.6 dB. Furthermore, the simplified prediction model showed good agreement with experimental measurements, with deviations remaining below 2 dB. The findings highlight the importance of porous acoustic material selection in commercial vehicle development and provide practical guidance for future engine compartment insulation optimization targeting compliance with both ECE R51 and ECE R107 requirements.

STATEMENTS AND DECLARATIONS

Supplementary Material

No supplementary material accompanies this article.

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Author Contributions

E. Turhan Er: Conceptualization, Methodology, Investigation, Formal Analysis, Writing – Original Draft, Writing – Review & Editing. S. O. Emir: Methodology, Investigation, Homologation Testing, Writing – Review & Editing.

Conflicts of Interest

The authors declare that there is no conflict of interest. The authors are affiliated with Güleryüz Karoseri Otomotiv Sanayi ve Ticaret A.Ş., whose vehicles and test facilities were used in this study.

Data, Code & Protocol Availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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