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Research paper

Experimental investigation on the effect of nano polyester sound insulation on the noise inside the vehicle cabin

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Abstract

Today, one of the key criteria for choosing a vehicle is the comfort inside the cabin, which is influenced by various factors, including the noise inside the vehicle. The present research investigates this issue experimentally by choosing a vehicle as a test study and using a portable sound pressure level measuring device. In the first stage, the standard insulators installed on the vehicle are evaluated. In the second stage, the standard insulators are separated from the vehicle and examined without insulation. In the last stage, the vehicle's insulation material is changed, insulation is re-evaluated by installing the new sound insulation, and the desired insulation performance is tested. For all the mentioned stages, two general tests are considered. First, the vehicle is tested under static tests at different engine speeds, including idling speed, 2000, and 3000 rpm, and then the vehicle is tested under dynamic tests at speeds of 30, 50, 70, and 100 km/h. The static test shows the performance of insulation in reducing engine noise, and the dynamic test shows the performance of insulation in reducing road and wind noise. The results indicate that vehicle insulation with nano polyester significantly affects sound penetration into the interior of the vehicle, which on average is between 5.3% to 8.03% dB in the complete insulation of the vehicle decreases. These findings highlight the effectiveness of nano polyester insulation in improving acoustic comfort inside the vehicle cabin.

1. Introduction

The sound inside the vehicle cabin is one of the critical factors directly related to the comfort of the vehicle passengers [1]. Reducing the amount of noise in the cabin is one of the essential approaches for enhancing market competitiveness. The sound inside the vehicle cabin is usually a combination of noises transmitted through different paths [2].

Various sources contribute to sound generation in a vehicle, including the engine, powertrain system, road surface, exhaust, tires, and wind collision with the body surface [3]. The sounds produced are dependent on engine speed, such as those generated by the engine, powertrain system, and exhaust. Additionally, some noise sources are related to vehicle speed, including the sound of tires and wind impact on the vehicle body [4].

At maximum engine power, the primary source of noise is the engine system, whereas at high speeds, the dominant noise source is wind collision with the body surface [5]. Vibrations and noise caused by road surface roughness are transmitted into the vehicle cabin through the suspension system and chassis [6].
Advancements in design and structural modifications to the engine and powertrain system have led to a reduction in noise generated. However, at high speeds and frequencies, wind-induced noise remains a major contributor to cabin noise levels [7]. Concerning the contemporary manufacturing of hybrid and electric vehicles, the acoustic output from the engine is notably diminished; however, in contrast, the intrusion of road and ambient noises into the cabin is exacerbated [8].
Noise control is primarily achieved through two methods: eliminating or reducing the noise source and utilizing structural solutions such as sound-absorbing or insulating materials [9]. Sound-absorbing materials are widely used in environments with high noise levels to attenuate sound waves [10]. These materials function by absorbing sound waves, converting some or all of their energy into heat, or allowing the waves to pass through without reflection [11].
Various methods exist to neutralize or mitigate vibrations responsible for noise production, one of which is the use of viscoelastic materials. These materials significantly reduce noise, particularly at low frequencies [12]. Steel and aluminum plates are commonly used in different parts of a vehicle's body, such as the roof, doors, and floor. Viscoelastic materials are typically added to these structures to enhance sound control [13].
The damping properties of viscoelastic materials improve vibration absorption, and ultimately reduce noise levels [14]. Studies indicate that drivers experience higher SPL levels across all frequency ranges, particularly in the rear passenger section. Therefore, the primary focus of sound control measures is the driver's position. Wind-induced noise in a vehicle's body can be reduced by over 6% through the use of a steel plate coated with a thin viscoelastic layer [15].
Engine noise can be mitigated using a multi-layered acoustic package composed of a porous material and a perforated plate, which results in a 5 dB reduction in engine noise, particularly at medium and high frequencies [16]. Felt, a commonly used porous material in automotive applications, is frequently employed for sound insulation. However, optimal sound insulation is achieved by combining felt with dense materials, as felt alone does not provide sufficient noise reduction. The combination of felt with heavy layers leads to approximately a 12 dB reduction in sound transmission at frequencies above 2000 Hz [17]. Another effective noise reduction approach is sound insulation, which involves separating the noise source from the intended environment. When sound waves strike an insulating surface, part of the wave is reflected while the remaining portion penetrates the material. Non-metallic materials and noise-reducing structures in vehicles are collectively referred to as sound packages. These packages minimize the transmission of external noise into the vehicle cabin through the body structure [18].
Numerous materials are employed for sound control, possessing the capacity to absorb or reflect sound waves, including felt, foam, polyester, and wool, among others. Presently, insulators are being developed utilizing polymeric materials in conjunction with various natural or synthetic fibers, yielding a reduction in weight and minimal adverse environmental impact [19]. Nanofibers are increasingly being used in the development of sound insulators due to their high surface area. Upon collision with nanofibers, sound waves experience energy loss due to the friction and viscosity. To enhance performance, nanofibers are often combined with other porous materials [20].
Adjusting parameters related to porous materials, such as density, airflow resistance, and structural coefficients, can improve sound wave absorption [21]. Recent studies highlight that incorporating nanofibers into polymer matrices significantly enhances sound absorption. Consequently, nanofibers are considered a promising solution for noise control across various industries [22]. A balance between sound insulation and absorption is

crucial. Effective vehicle sound package design requires a comprehensive understanding of vehicle type, primary noise sources, sound transmission paths, and the properties of commercially available insulation materials.
Experimental tests and numerical simulations facilitate the development of optimized insulation solutions that are specifically tailored to distinct vehicle applications [23].
In Iran, one of the key quality assessment criteria for vehicles is the level of noise penetrating the cabin. Therefore, automotive manufacturers must assess the efficiency and effectiveness of different insulation materials in reducing noise. In experimental studies on vehicle sound insulation and SPL analysis, comprehensive investigations covering all aspects of a vehicle have been relatively limited. However, experimental investigations provide valuable insights by testing vehicles under real-world conditions, making the results more applicable and reliable.
This research utilizes experimental testing to analyze SPL values, ensuring a thorough understanding of the results and their practical implications. Moreover, no prior experimental research has specifically examined the impact of nano polyester acoustic insulation in vehicles. The primary objective of this study is to evaluate the effectiveness of nano polyester insulation in reducing noise transmission into the cabin from both engine and road sources.

2. Noise fundamental

The human can hear sounds from 20 to 20 kHz. The unit of sound measurement is in decibels (dB). The decibel unit is a logarithmic scale that expresses it in a relative form. The Sound Pressure Level (SPL) is defined according to the decibel scale, which uses a value of 2×10^{-5} pa. The SPL is described in Eq. (1):

$$\text{SPL}=10\ log_{10}[\frac{p^2}{p_o^2}] \qquad (1)$$

where p_o is the reference sound pressure (20 µPa, or 2×10^{-5} Pa) [24].
The effectiveness index of sound insulation, especially the vehicle's sound package, is evaluated under the name Noise Reduction (NR). This index shows the difference between the SPL of the external sound source compared to the SPL inside the vehicle cabin and is defined in Eq. (2) [18]:

$$\text{NR}= SPL_{out} - SPL_{in} \qquad (2)$$

Changes in the range of 1 dB are difficult to detect by the human ear, and changes in the range of 2 to 3 dB are understandable to some extent. However, the change of 5 dB can be easily felt, and the changes above 10 dB can be recognized and understood [24].
According to the characteristics of the human ear system, based on decibel and frequency, the drawn curves are known as curves A, B, C, and D. In the A-weight curve, the frequency of 1000 Hz equals the value of 0 dB. It is considered as the reference frequency [18].
Eq. (3) is used to consider the percentage error of the measured values so that the measurements do not have excessive error.

$$\text{Percentage error} = (\frac{Device\ tolerance}{SPL})\times 100 \qquad (3)$$

3. Experimental tests

This research is conducted using a case study on a 2003 Kia Rio passenger car with 220,000 kilometers of mileage. The vehicle under test is equipped with a manual transmission, and the throttle body is a mechanical type controlled by a cable. Before conducting the tests, all vehicle systems, including the suspension system, are checked and their health is ensured.
A portable sound level meter device is used to record the SPL inside the vehicle cabin. This device is called Benetech® GM1356, has a resolution of 0.1 dB, accuracy ±1.5 dB (reference sound pressure standard 94 dB at 1 KHz) and its sensor is of a type ½ inch polarization capacitance microphone. During the car test, the device is placed between the front seats and near the driver's right ear.
Nano polyester sound insulation is replaced in the specified locations, as shown in Fig. 1. In order to minimize the error in performing the tests, each part of the tests is repeated three times.

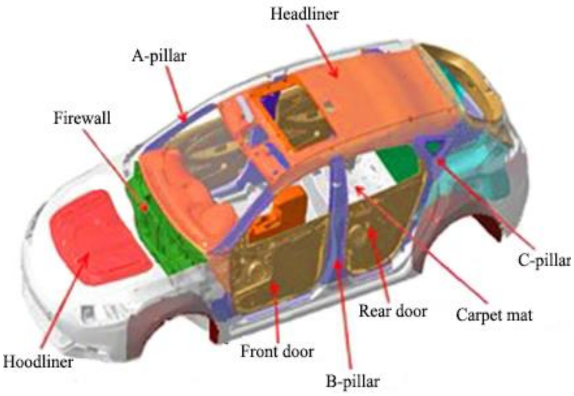

Fig. 1. Insulators examined in this research [18].

For each test, 15 s is considered, and the average SPL is recorded for three tests. The final data in dB in A-weight is considered for the research. The values recorded by the sound level meter device are analyzed by the SoundLab software. This software is designed by the manufacturer of the sound level meter device. As shown in Fig. 2, the software has the ability to display data in real time, plot it, save the data, and finally, the data can be output to Microsoft Excel.

All the test conditions, such as the idling speed of the car at around 750 rpm, the engine temperature at 85 °C, the type and place of movement path, and the length of the test time, are considered the same. Also, the air temperature during the tests varies between 38 and 41 °C.

Before conducting the tests and installing insulators, the vehicle's mass is measured (1055 kg, Fig. 3) to examine the changes in the vehicle's mass after installing insulators.

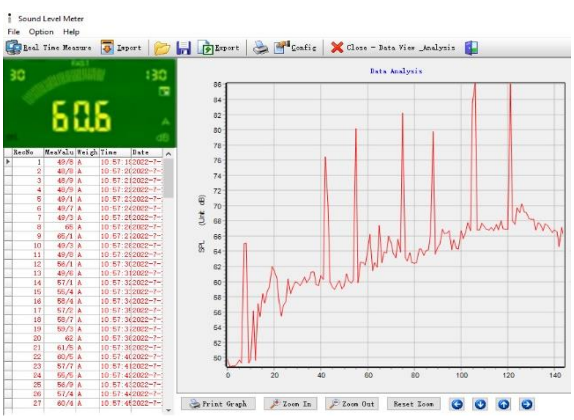

Fig. 2. SoundLab software environment.

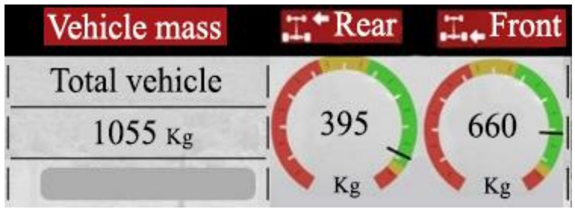

Fig. 3. Vehicle mass measurement.

The considered tests are generally divided into static and dynamic categories. In the static test, the vehicle is examined in a stationary position at different engine speeds, including three tests at Idle engine speed, 2000 rpm, and 3000 rpm.

In the dynamic test section, the vehicle moving at different speeds is evaluated, which includes four tests of the vehicle in gear two at a speed of 30 km/h, the vehicle in gear three at a speed of 50 km/h, the vehicle in gear four with a speed of 70 km/h and the vehicle is in five gears with a speed of 100 km/h.

3.1. Introduction of nano polyester insulation

The acoustic insulation used in this research, shown in Fig. 4, is nano polyester. This insulation has physical properties including a thickness of 15 mm, weight per square meter equal to 1.4 Kg, and density of 66 kg/m^3.

The desired insulation is available in thicknesses of 10, 15 and 20 mm. Given that the thicker the insulation, the greater its efficiency, the 10 mm thickness is not suitable.

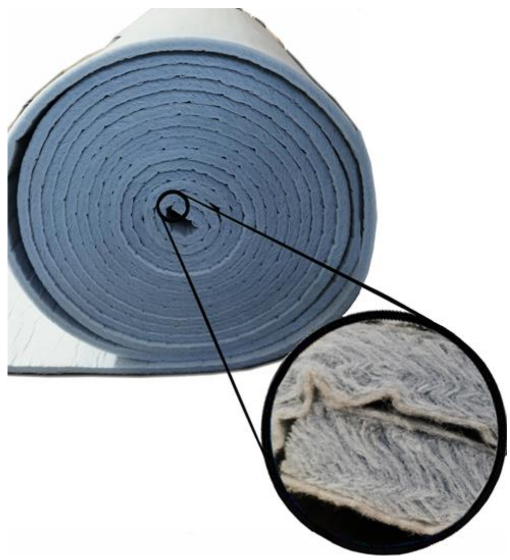

Fig. 4. Nano polyester insulation roll.

Since it is not possible to make changes in most parts of the car to use insulation with a thickness of 20 mm; therefore, insulation with a thickness of 15 mm is selected for this study, which installed the insulation without making any changes to the original factory parts.

3.2. Static test

In the first stage, the vehicle is subjected to a static test with the standard insulators installed by the manufacturer, and the SPL inside the cabin is measured at Idling speed, engine speed of 2000 rpm, and engine speed of 3000 rpm. The values recorded from these tests are used to compare with other data obtained from subsequent tests. In order to minimize the error in performing the tests, each part of the test is repeated three times.

At first, the SPL value is measured by a portable sound level meter device at the idle speed of the engine for 15 s. This device automatically calculates the value of SPL using Eq. (1), and a number of 15 data samples obtained from the SoundLab software is extracted. The average of 15 samples of the SPL of each test is shown in Table 1, and the percentage error is also calculated based on Eq. (3) for all data.

Because in the static test, the most wave sound penetration is from the engine into the cabin, the insulation in the engine compartment is examined in the static test, which includes the firewall insulation shown in Fig. 5, beauty cover engine insulation, and hood insulation. The standard insulation material of the firewall and hood is made of felt with fireproof fabric, and the insulation of the beauty cover engine is made of acoustic foam.

In the next stage of the test, the standard insulation of every part of the engine compartment is separated. As shown in Fig. 6, the main vehicle panel, which is made of steel plate remains, and the static tests are repeated.

Table 1. Average SPL inside the cabin with standard insulation.

Static test	Standard insulation (dB)	Percentage error (%)
Idle speed	43.6	3.4
2000 (rpm)	51.5	2.9
3000 (rpm)	61.9	2.42

Fig. 5. Standard firewall insulation.

Then, the values of the SPL obtained inside the cabin are recorded. So that the value of SPL for the state without insulation of the firewall, beauty cover engine, and hood was measured for 15 s at engine Idle speed, engine speed of 2000 rpm, and 3000 rpm. The average of 15 samples from each test is calculated, as shown in Table 2.

Finally, the standard insulations are replaced with nano polyester acoustic insulation in the mentioned points. According to the standard insulation pattern of each point, the desired acoustic insulation is cut in the order mentioned and installs on the vehicle, as shown in Fig. 7.

As with standard insulation, glue is unnecessary to install the replacement insulation, which is held in place by the push retainer. It should be noted that the insulation inside the car cabin is standard.

Fig. 6. Firewall without standard insulation.

Table 2. Average SPL inside the cabin without standard insulation.

Static test	Hood insulation (dB)	Beauty cover engine insulation (dB)	Firewall insulation (dB)	Percentage error (%)
Idle speed	44.3	44.6	44.8	3.3
2000 (rpm)	52	52.4	52.3	2.8
3000 (rpm)	62.6	63	62.9	2.4

Fig. 7. Replacement of firewall insulation with nano polyester.

After installing the nano polyester insulation on the engine compartment, the static tests are repeated. The SPL value for the case where the firewall insulation, beauty cover engine, and hood are replaced with nano polyester insulation was measured at engine Idle speed, 2000 rpm, and 3000 rpm, and the average of 15 samples from each section is shown in Table 3.

3.3. Dynamic test

In this test, the car is subjected to a dynamic test with standard insulators installed by the car manufacturer. The purpose of this test is to check the SPL inside the car at speeds of 30, 50, 70, and 100 km/h. The values obtained from these tests are used as basic and primary data. So, for each of the mentioned speeds, the car is driven on the 0.65 km route shown in Fig. 8. For 15 s, the data is recorded and extracted by SoundLab software.

Fig. 8. Vehicle dynamic test route.

In order to minimize the error in performing the tests, each part of the tests is repeated three times. The vehicle speed is constant in each test, and due to the repetition of the tests and the length of the route, the vehicle speed is maintained constant throughout the test.
The average SPL of each test is measured for the standard automotive insulation and is recorded in Table 4.
In the dynamic test, the vehicle is moving, and the sound from the road, tires, suspension system, and the sound of the wind penetrates the cabin more than the sound of the engine, so the insulation inside the cabin is evaluated, which includes the headliner, carpet mat and interior decoration panel. The interior decorations panel covers the doors, side mirrors, pillars, and inner rocker panels.
The headliner is a sandwich panel whose inner surface is made of cardboard with a thin layer of aluminum foil, and its outer surface is covered with carpet. The carpet mat of the vehicle consists of two layers, which are made of felt in the places where the passengers' feet are placed on the lower side, and the outer surface of the floor mat is also decorated with carpet.
The interior decoration panels of the vehicle cabin do not have any insulation, and they are mainly made of plastic. After performing the test with standard insulation, the insulation inside the car cabin is separated and the dynamic tests are repeated only with the corresponding steel panel. The without-insulated vehicle is tested on the previous track and the average SPL of each test is calculated and listed in Table 5.
By performing dynamic tests without standard insulation, using nano polyester acoustic insulation according to the body pattern and covering of different parts, the desired insulation is cut and installed. As with the insulation used in the engine compartment, there is no need to use glue to install the replacement insulation inside the cabin, and it is placed by push retainer or insulation inside the covers.

Table 3. Average SPL inside the cabin with nano polyester insulation.

Static test	Nano polyester hood insulation (dB)	Nano polyester beauty cover engine insulation (dB)	Nano polyester firewall insulation (dB)	Percentage error (%)
Idle speed	43	43	42	3.4
2000 (rpm)	50.9	50.5	50	2.9
3000 (rpm)	61	59.9	59.8	2.5

Table 4. Average SPL inside the cabin with standard insulation.

Dynamic test	Standard insulation (dB)	Percentage error (%)
Speed 30 (km/h) gear 2	55.6	2.7
Speed 50 (km/h) gear 3	59.1	2.5
Speed 70 (km/h) gear 4	61.1	2.4
Speed 100 (km/h) gear 5	65.3	2.3

After installing the nano polyester insulation on the vehicle's interior parts, as show in Figs. 9 and 10, the dynamic tests are repeated. It should be noted that the insulation inside the engine compartment is standard. This car is tested on the same route mentioned at the speeds of 30, 50, 70, and 100 km/h, then the average data is calculated in Table 6.

3.4. Complete replacement of vehicle insulation with nano polyester

By conducting static and dynamic tests for the insulation of each point considered in this research, it is time to replace all the insulation in the vehicle with nano polyester insulation, and the vehicle is tested statically and dynamically with this type of insulation. The average results are listed in Table 7.

4. Results and discussion

As mentioned, Eq. (2) is used to calculate the effectiveness of the sound package. In the static test, the data in Table 2 is considered as SPL_{out}, and the data in Table 1 is replaced as SPL_{in}, and after calculating the amount of noise reduction, it is determined by the standard insulation of the vehicle. By examining and comparing the results obtained, it is clear that at different engine speeds, the standard vehicle insulation compared to when there is no insulation:

- Insulation of the hood is between 0.97% to 1.6% (0.5 to 0.7 dB)
- Insulation of the beauty cover engine is between 1.7% to 2.2% (0.9 to 1.1 dB)
- Insulation of the firewall is between 1.5% to 2.7% (0.8 to 1.2 dB)

Fig. 9. Replacement of carpet mat with nano polyester insulation.

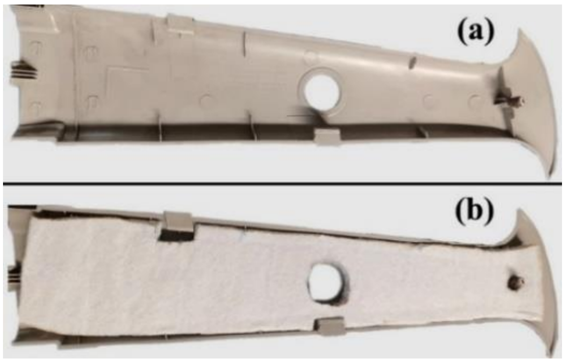

Fig. 10. (a) Pillar cover and (b) Pillar cover with nano polyester insulation.

Table 5. Average SPL inside the cabin without standard insulation.

Dynamic test	Headliner insulation (dB)	Carpet insulation (dB)	Interior decoration insulation (dB)	Percentage error (%)
Speed 30 (Km/h) gear 2	55.8	55.8	56.6	2.6
Speed 50 (Km/h) gear 3	60.5	60.6	60.6	2.4
Speed 70 (Km/h) gear 4	62.9	62.6	63.2	2.4
Speed 100 (Km/h) gear 5	67.6	67.6	69.1	2.2

Table 6. Average SPL inside the cabin with nano polyester insulation.

Dynamic test	Nano polyester headliner insulation (dB)	Nano polyester carpet insulation (dB)	Nano polyester interior decoration insulation	Percentage error (%)
Speed 30 (Km/h) gear 2	55.1	55	54.9	2.7
Speed 50 (Km/h) gear 3	57.6	57.7	57.8	2.6
Speed 70 (Km/h) gear 4	59.6	59	58.7	2.5
Speed 100 (Km/h) gear	63.1	63	61.6	2.3

It can reduce engine noise.
For case study vehicle, 10 m^2 of insulation is used. Considering the area used and not considering the discarded parts of the insulation during cutting, the overall net mass of the insulation used is 10.28 kg, and ultimately the mass of the vehicle after installing all the insulation reaches 1065.28 kg.
To calculate the effect of car nano polyester insulation, Eq. (2) is used again to calculate it, and the data in Table 1 as SPL_{out} and the data in Table 3 as SPL_{in} are entered into the equation.
By replacing the car's insulation with 15 mm thick nano polyester material, the noise inside the cabin reduces at different engine speeds compared to standard insulation, and the results are as follows:

- Insulation of the hood is between 1.1% to 1.4% (0.6 to 0.8 dB)
- Insulation of the beauty cover engine is between 1.3% to 3.3% (0.6 to 2 dB)
- Insulation the firewall is between 3% to 3.8% (1.5 to 2.1 dB).

The SPL analysis values in the cabin of all static tests are shown in Figs. 11-13.
While in the same case by Zhang *et al.* [25], a three-layer firewall acoustic package was used, combining a light layer of felt with a density of 1000 g/m^2, a middle layer of PE, and a final layer of felt with a density of 1500 g/m^2. The thickness of this package is 35 mm and an average of 2.5 dB of engine noise is reduced. In another case by Mao *et al.* [26], a two-layer firewall acoustic package with a felt and EVA (Ethylene vinyl acetate) structure with a total thickness of 30 mm was used, which reduced the SPL level on the engine side by 2.1 dB on average.

Table 7. Average SPL inside the cabin, complete insulation with nano polyester.

Test type	Inside the cabin (dB)	Percentage error (%)
Idle speed	39.8	3.7
2000 (rpm)	48.8	3
3000 (rpm)	56.7	2.6
Speed 30 (Km/h) gear 2	52.8	2.8
Speed 50 (Km/h) gear 3	56	2.6
Speed 70 (Km/h) gear 4	57.9	2.5
Speed 100 (Km/h) gear 5	62.2	2.4

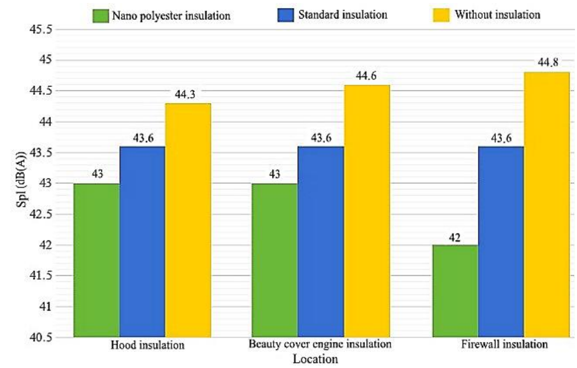

Fig. 11. SPL inside the vehicle cabin at idling speed.

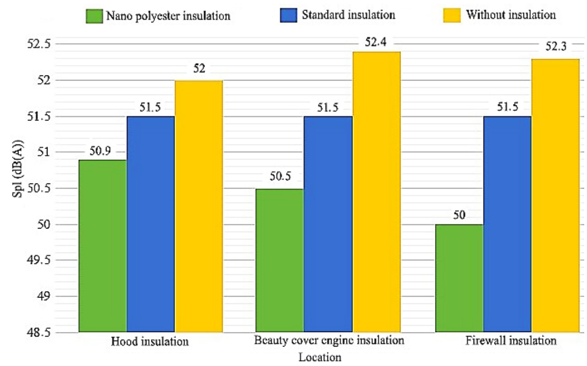

Fig. 12. SPL inside the vehicle cabin at 2000 rpm.

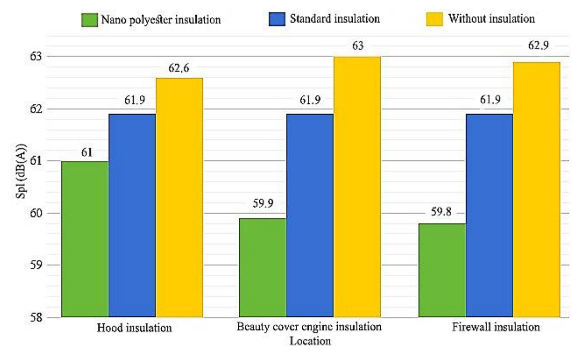

Fig. 13. SPL inside the vehicle cabin at 3000 rpm.

According to the analysis of the results, it is clear that replacing the insulation of the hood with nano polyester insulation does not have a noticeable effect on reducing engine noise transmission into the cabin. Replacing the beauty cover engine insulation has a favorable effect in reducing engine noise, especially at middle and high engine speeds, because this insulation is installed directly on the surface of the engine valve cover.

Changing the firewall insulation material to nano polyester, because the insulation is located between the engine and the cabin space, has a noticeable effect in reducing noise, especially at high engine speeds. The insulation of this area is one of the primary and most effective insulations used in vehicles.

To calculate the effect of standard car insulation compared to the without insulated state, as well as the effect of nano polyester insulation compared to standard insulation at different speeds the same method as above is used and the data of Tables 4 and 6 are used in Eq. (2).

At different speeds, standard insulation reduces wind and road noise transmission into the cabin as follows, compared to the uninsulated state:

- Headliner between 0.3% to 3.5% (0.2 to 2.3 dB)
- Standard interior decoration panel between 1.7% to 5.8% (1 to 3.8 dB)
- Carpet between 0.3% to 3.5% (0.2 to 2.3 dB)

The results below show that nano polyester insulation reduces road and wind noise at various speeds compared to standard car insulation. The results are as follows:

- Headliner insulation between 0.9% to 3.4% (0.5 to 2.2 dB)
- Interior decoration insulation between 1.2% to 6% (0.7 to 3.7 dB)
- Carpet insulation between 1% to 3.6% (0.6 to 2.3 dB)

The SPL analysis values inside the cabin of all dynamic tests are shown in Figs. 14-17.

In a similar study to reduce noise from the floor of a vehicle by Guellec *et al*. [27], using a combination of porous absorbent and damping materials, as well as modifying the appearance of the vehicle floor panel, an average of 2.8 dB of radiated noise from the floor area of the vehicle was reduced.

The insulation of the headliner has a favorable effect on reducing wind noise in the cabin. However, this issue is directly related to the structure of the roof panel, whether the roof panel has a strong or weak structure, and how much it can prevent the roof panel from vibrating.

Replacing the carpet mat with nano polyester insulation because the vehicle floor has a wide surface and is connected to the suspension system, especially at speeds above 70 km/h; it absorbs the sound of the road and tires and the sounds from the shocks of the suspension system.

In most vehicles, the cover of the pillars and rocker panels are not insulated; in some vehicles, the door covers are also not insulated.

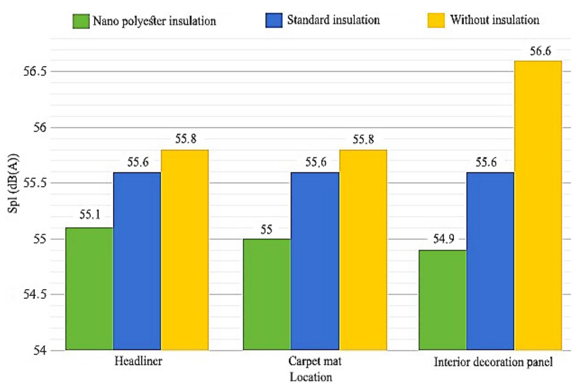

Fig. 14. SPL inside the vehicle cabin at a speed of 30 Km/h.

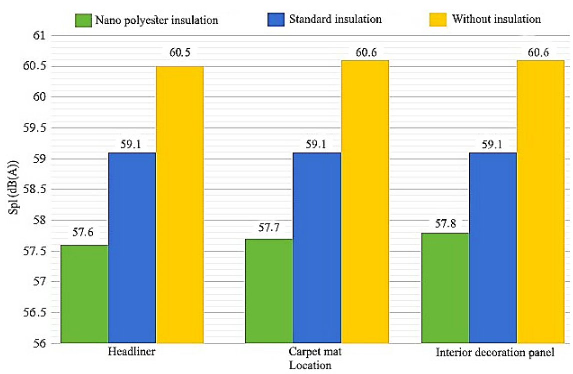

Fig. 15. SPL inside the vehicle cabin at a speed of 50 Km/h.

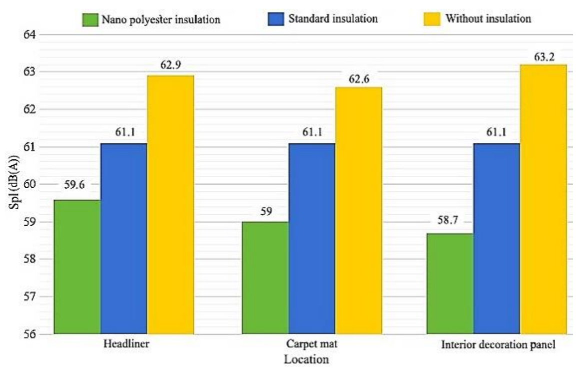

Fig. 16. SPL inside the vehicle cabin at a speed of 70 Km/h.

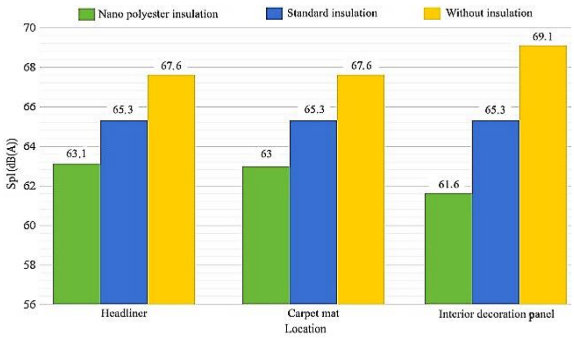

Fig. 17. SPL inside the vehicle cabin at a speed of 100 Km/h.

Placing insulation in the mentioned parts can have a noticeable effect on reducing the sound entering the cabin.
Because the pillars, inner rocker panels, and doors are produced with a two-panel structure, this hollow space is a factor for sound transmission.
Finally, by examining the results obtained when all parts of the vehicle are covered with nano polyester insulation, it is clear that the SPL inside the cabin is significantly reduced compared to standard vehicle insulation, the results of which are as follows:

- Idling speed 9.5% SPL reduction (3.8 dB)
- 2000 rpm 5.5% SPL reduction (2.7 dB)
- 3000 rpm 9.1% SPL reduction (5.2 dB)
- Speed of 30 km/h 5.3% SPL reduction (2.8 dB)
- Speed of 50 km/h 5.5% SPL reduction (3.1 dB)
- Speed of 70 km/h 5.5% SPL reduction (3.2 dB)
- Speed of 100 km/h 4.9% SPL reduction (3.1 dB)

These results are shown in Fig. 18.

5. Conclusions

Given that the main objective of the research is to use nano polyester insulation to reduce the sound entering the car cabin compared to standard insulation, this 15 mm thick insulation is able to significantly reduce the sound inside the cabin in both static and dynamic tests. Overall, the average SPL reduction is 8.03% (3.9 dB) in static tests and 5.3% (3.05 dB) in dynamic tests. In the local case, the performance of sound insulation can be expressed as follows:
Hood insulation has the least effect, while firewall insulation has the most effect in reducing engine sound transmission into the cabin. Headliner insulation has the least effect, whereas interior decoration insulation has the most effect in reducing road and wind sound transmission into the cabin.

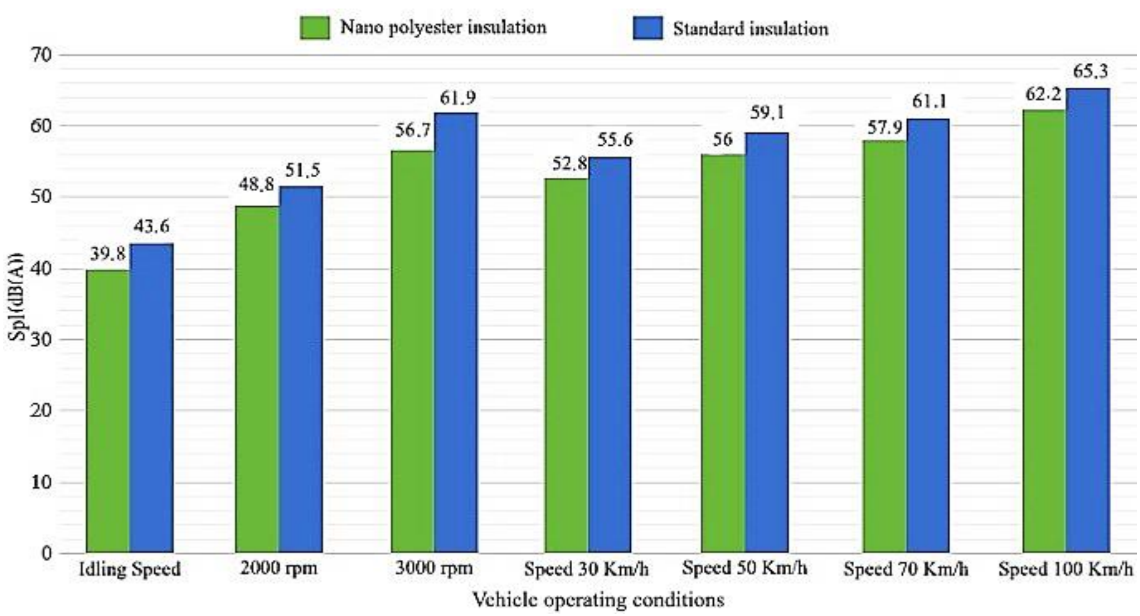

Fig. 18. SPL of complete vehicle insulation with nano Polyester.

If the car is completely insulated, it will increase the mass of the car by 0.97% (10.28 kg), which has a negligible impact on the overall vehicle performance and can be counterbalanced by reducing the mass of other components. This insulation exhibits multiple advantages such as easy installation without the need for special tools, high flexibility, and the ability to be cut into any desired size. Moreover, it is non-toxic, hypoallergenic, resistant to decay, and fully recyclable, making it an environmentally friendly alternative to conventional insulation materials. From a user experience perspective, implementing nano polyester insulation in vehicles can enhance passenger comfort by reducing fatigue and improving concentration levels, particularly during long-distance travel. Future studies could investigate long-term durability in different weather conditions or combine it with other soundproofing materials, which would lead to further improvements in car cabin acoustics.

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References

[1] S. Dhandole and S. V. Modak, "Review of vibro-acoustics analysis procedures for prediction of low frequency noise inside a cavity", *Conf. Proc. of the "Society for Experimental Mechanics Series"*, Florida, US, (2007).

[2] M. Rao, "Recent applications of viscoelastic damping for noise control in automobiles and commercial airplanes", *J. Sound Vib.*, Vol. 262, No. 3, pp. 457-474, (2003).

[3] E. T. Fernandez, *The influence of tyre air cavities on vehicle acoustics*, PhD thesis, University of KTH, Stockholm, Sweden, (2006).

[4] Z. Mohamed, X. Wang, and R. Jazar, "Structural-acoustic coupling study of tyre-cavity resonance", *J. Vib. Control*, Vol. 22, No. 2, pp. 513-529, (2014).

[5] A. R. George, "Automobile aerodynamic noise", *SAE Trans.*, Vol. 99, No. 6, pp. 434-457, (1990).

[6] A. Karimyan and S. Ebrahimi-Nejad Rafsanjani, "Vibro-acoustic analysis of tire and rim finite element model coupled with fluid acoustic cavity", *Modares Mech. Eng.*, Vol. 17, No. 4, pp. 381-392, (2017).

[7] R. Buchheim, W. Dobrzynski, H. Mankau, and D. Schwabe, "Vehicle interior noise related to external aerodynamics", *Int. J. Veh. Des.*, Vol. 3, No. 4, pp. 398-410, (1982).

[8] B.-M. Căşeriu, M.-R. Gabor, P. Blaga, and C. Veres, "Quantitative Analysis of Predictors of Acoustic Materials for Noise Reduction as Sustainable Strategies for Materials in the Automotive Industry", *Appl. Sci.*, Vol. 14, No. 22, pp. 1-29, (2024).

[9] G. Thilagavathi, S. Neela Krishnan, N. Muthukumar, and S. Krishnan, "Investigations on sound absorption properties of luffa fibrous mats", *J. Nat. Fibers*, Vol. 15, No. 3, pp. 445-451, (2018).

[10] M. Aliabadi, R. Golmohammadi, and M. Mansoorizadeh, "Objective approach for analysis of noise source characteristics and acoustic conditions in noisy computerized embroidery workrooms", *Environ. Monit. Assess.*, Vol. 186, No. 3, pp. 1855-1864, (2014).

[11] T. Ulrich and J. Arenas, "Role of porosity on nanofibrous membrane sound absorption properties", *16th Int. Congr. on "Sound and Vibration"*, Krakow, Poland, (2009).

[12] D. Lee and W. Hwang, "Layout optimization of unconstrained viscoelastic layer on beams using fractional derivative model", *AIAA J.*, Vol. 42, No. 10, pp. 2167-2170, (2004).

[13] M. Alvelid and M. Enelund, "Modelling of constrained thin rubber layer with emphasis on damping", *J. Sound Vib.*, Vol. 300, No. 3-5, pp. 662-675, (2007).

[14] X. Q. Zhou, D. Y. Yu, X. Y. Shao, S. Q. Zhang, and S. Wang, "Research and

applications of viscoelastic vibration damping materials: A review", *Compos. Struct.*, Vol. 136, No. 20, pp. 460-480, (2016).

[15] J. Marzbanrad, M. Hafezian, and M. Mozaffarikhah, "Automotive interior cabin noise analysis and optimization using SEA and RSM", *Automotive. Sci. Eng.*, Vol. 9, No. 1, pp. 2887-2894, (2019).

[16] S. H. Tabatabaei, S. Moradi Haghighi, A. Kiani, and K. Ghasemian, "A new optimized sound package for the vehicle dash panel", *Automotive. Sci. Eng.*, Vol. 11, No. 2, pp. 3626-3636, (2021).

[17] H. Salmani, A. Khalkhali, and A. Mohsenifar, "A practical procedure for vehicle sound package design using statistical energy analysis", *Proc. Inst. Mech. Eng., Part D: J. Automob. Eng.*, Vol. 237, No. 13, pp. 3054-3069, (2023).

[18] J. Pang, *Noise and Vibration Control in Automotive Bodies*, John Wiley & Sons, Beijing, China, pp. 201-271, (2018).

[19] F. Sosa-Castillo, D. Palma-Ramírez, and D. S. García-Zaleta, "Design of a soundproof painting based on microcellulose for potential automotive applications", *MRS Adv.*, Vol. 9, No. 22, pp. 1754-1758, (2024).

[20] L. Cao, Q. Fu, Y. Si, B. Ding, and J. Yu, "Porous materials for sound absorption", *Compos. Commun.*, Vol. 10, No. 2, pp. 25-35, (2018).

[21] R. Talebi, M. H. Shojaeefard, R. Ahmadi, and B. Ranjbar, "Power sound transmission through double-walled laminated composite panel with intermediate porous layer considering different boundary conditions", *Modares Mech. Eng.*, Vol. 14, No. 6, pp. 11-21, (2014).

[22] A. Ghajarieh, A. Talebian, and S. Habibi, "A review on application of nanofibers in sound insulation", *12th Natio. Conf. on* "*Textile Engineering*", Yazd, Iran, (2020).

[23] X. Wang, *Vehicle Noise and Vibration Refinement*, Elsevier, Amsterdam, Netherlands, p.10-80, (2010).

[24] A.-M. O. Mohamed, E. K. Paleologos, and F. M. Howari, "Chapter 19 - noise pollution and its impact on human health and the environment", *Pollution Assessment for Sustainable Practices in Applied Sciences and Engineering*, Eds. A.-M. O. Mohamed, E. K. Paleologos and F. M. Howari, Butterworth-Heinemann, pp. 975-1026, (2021).

[25] J. Zhang, G. Zhu, X. Zhang, H. Liu, and C. Liu, "The vehicle nvh development and engineering application of the lightweight sound package", *Proc. of* "*SAE-China*", Shanghai, China, (2015).

[26] Z. Mao, M. Feng, and Y. Lin, "Application of sound package material in noise reduction of motor", *Vibroeng. Procedia*, Vol. 36, No. 4, pp. 66-71, (2021).

[27] A. Guellec, M. Cabrol, J. Jacqmot, and B. Van den Nieuwenhof, "Optimization of trim component and reduction of the road noise transmission based on finite element methods", *10th Int.* "*Noise, Vibration & Harshness Congr.: The European*", Graz, Austria, (2018).