Keywords: noise spectrum analysis; GV; HEV; BEV

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OCTAVE BAND ANALYSIS OF CAR NOISE EMISSIONS AT DIFFERENT SPEEDS AND ON DIFFERENT PAVEMENTS

Summary. Noise from cars is one of the main sources of harmful pollution. In the presented paper, an octave frequency band analysis is conducted according to standard methods of external and internal noise measurement. Experiments at different speeds, with three types of cars—conventional gasoline (GV), hybrid (HEV) and pure electric (BEV)—were carried out on two types of pavement—damaged coarse-grained and smooth fine-grained asphalt. The results show variations in external and internal noise levels vs. speed in different octave bands. At each speed, a spectral analysis was done. The diagrams with results show changes in noise level vs. speed and the positions of noise maximums. Regression models for the octave spectrum at different speeds and pavements are developed.

1. INTRODUCTION

The noise generated by transport is one of the biggest environmental problems in urban areas. It is harmful to human health and has a negative influence on people's lives. Noise pollution is one of the environmental problems of modern times [1-4]. Noise has a negative impact on people and can be regarded in two aspects: internal noise in the car where the driver and passenger are situated and external noise from the vehicle, which affects all residents of the modern city [5, 6].

Due to the importance of reducing noise levels, many standards and methods [2-4, 11, 17, 18] for its measurement have been developed. Research and projects [5, 8, 10] have focused on comparing and enhancing the methods of noise estimation.

There are direct links among dynamic loads, vibrations, and noise in car body panels. It has been experimentally established that the sound pressure in the cabin is proportional to the rate of oscillation of the panel surfaces [7].

As stated above noise from a car can be divided into two main parts: noise in the car body, where the driver and passengers are (internal noise), and external noise from the car. The emitted noise depends on the size, profile and material of the tire, the vehicle's speed, and the condition of the road surface [8, 9].

The causes of tire noise are:

- The vibration of the tire sides due to periodic deformations during rolling.
- The periodic expulsion and suction of air in the profile channels during movement (air-pumping).
- The vibration of the profile teeth when separated from the roadway. This phenomenon is due to the deformation of the tread pattern blocks in contact with the road. Free damping oscillations of the tread pattern blocks begin.

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- The largest share of the sound energy of the noise emitted during rolling is caused by the tread pattern blocs when they come into contact with the roadway.

Based on the above, it can be argued that the type of tire profile and ground pavement make major contributions to the level of airborne noise emitted.

In [8], an analysis of noise using measurement methods was done. The relations between measurements of noise indicators from the road surfaces were determined using the methods of Statistical Pass-By (SPB) method (ISO 11819-1) and Close-proximity (CPX) method (ISO/DIS 11819-2). A study of correlations, advantages and disadvantages, problems, and their influence on non-standard pavement was conducted.

The influence of the temperature on noise measurement results was studied, and a correction procedure was proposed.

The risk of hazardous noise exposure has evaluated on highways for commuters in [10]. Twelve vehicles were included in on-road tests on State Highway 288 in Houston to collect real-time internal noise levels. The results show that commuters are exposed to noise emissions between 75 dB(A) and 85 dB(A). At speeds over 70 km/h, the internal noise level exceeds the 8 h safe level of 75 dB(A).

The simulated pass-by is an alternative to the real test track that is more convenient and independent of environmental conditions [12]. Work shows that the modifications and additional measurement tasks can be added easily to minimize possible sources of external disturbances. An assessment of the contribution of the common sources, such as intake, engine, exhaust, and tires, was added to the standard measurements. The experiments show that the indoor pass-by method is an acceptable alternative for outdoor testing and can speed up the testing process while providing similar results.

The authors of [7] conducted experiments to divide the sources of internal noise in a car. They determined the contributions of different parts, such as the windshield and doors. The article identified and ranked the dominant sound sources perceived from the perspective of the driver of an EV car.

The main purpose of this study is to analyze the external and internal noise in octave frequency bands for cars using three types of driving systems during their motion on two types of pavements.

2. METHOD AND EQUIPMENT

An assessment of the noise level of cars during their movement was performed. The measurements were taken while the vehicles were moving according to standards [4,11]. The schemes of disposition of the microphone are shown in Figs. 1 and 2. The tested vehicles met the technical requirements of the producer, the tire wear did not exceed 10%, and the pressure was in accordance with the manufacturer's instructions.

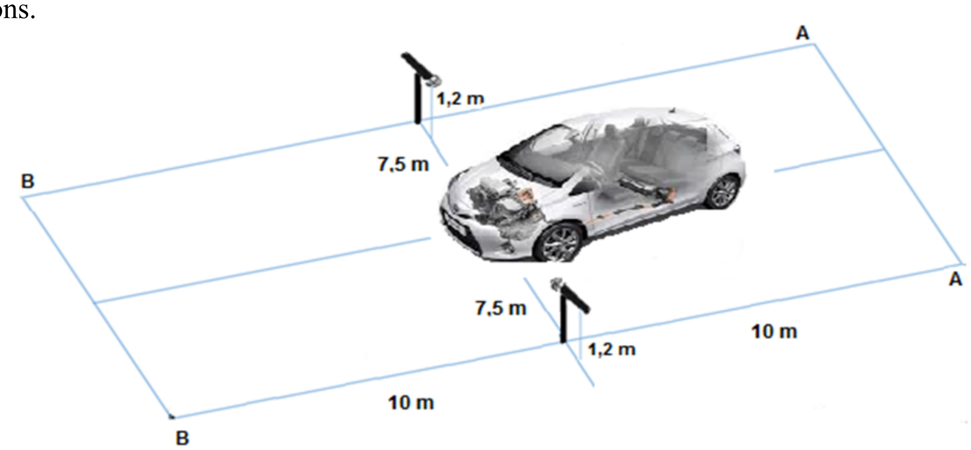

Fig. 1. A diagram illustrating the experimental methodology for studying external noise

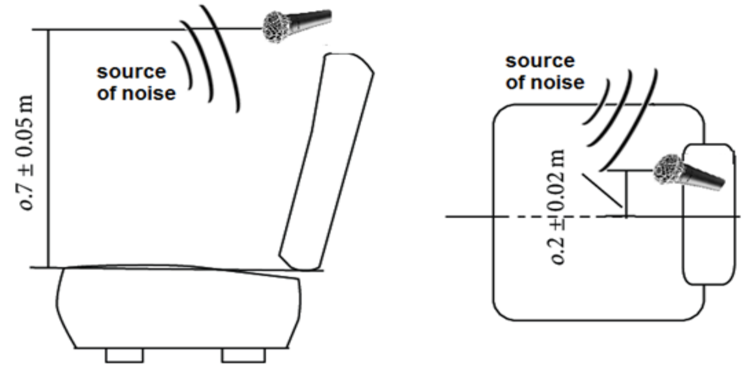

Fig. 2. Location of the microphone for measuring internal noise

Experiments were carried out to measure the noise level of cars when driving under certain conditions. The noise of the three cars with different traction systems on different road surfaces was measured.

The experiments were done on damaged coarse-grained and smooth fine-grained asphalt pavement (shown in Figs. 3 and 4). The experiment was realized at speeds of 20, 30, 40, 50, 60, 70, 80, 90, and 120 km/h. For each speed value in this range, the sound levels were recorded for no less than 5 s.

During the test, the accelerator pedal needed to be in a position to maintain between lines AA 'and BB' (Fig.1). A constant speed was defined in [11, 12]. According to the standards used, all measurements were made with a temporary "fast" characteristic of the sound level meter.

(a) (b)

Fig. 3. General view of the test site: (a) an experimental section with damaged coarse-grained pavement and (b) a general type of coarse-grained pavement

Fig. 4. General view of the test site: (a) an experimental section with smooth fine-grained pavement and (b) the general appearance of smooth fine-grained pavement

The study was carried out with the following vehicles:

- A petrol car (GV): Nissan Qashqai with Michelin Primacy 3 215/55 R18 tires (Fig. 5a). The tire pressure was 0.25 MPa.
- An electric car (BEV): Nissan LEAF Zero Emission with Goodyear 215/50 R17 tires (Fig. 5b). The tire pressure was 0.25 MPa.
- A hybrid car (HEV): Toyota Yaris HYBRID with Dunlop sport Fast response 175/65 R15 84H tires (Fig. 5c). The tire pressure was 0.25 MPa.

The general view of the tires and their tread pattern grooves are shown in Fig. 5. All the tires have a classic summer tread pattern with longitudinal central grooves.

The test could not be performed if the wind speed was greater than 5 m/s and if the sound vibration level exceeded 10 dBA.

The device for measuring noise and vibration VI-410 needed to be set up according to the requirements of the standards. The frequency response A and the timing characteristic F had to be included, and the maximum readings of the sound level meter needed to be recorded [16].

Deviations that were not related to the overall noise measurement were not taken into account. Each measurement needed to be performed at least three times. Measurements were considered valid if the difference between the readings obtained as a result of three consecutive ones was not more than 2 dBA.

The maximum value obtained was taken as the result of the measurements.

A precision sound level meter complying with the requirements of International Electrotechnical Commission Standard IEC 60651: 1979 Sound level meters [17,18] was used.

Noise level measurements were taken with a VI-410 measuring instrument manufactured by Quest Technologies, Poland (Fig. 6.). It is a digital, four-channel device for measuring noise and vibration. The device, using the computer, can perform 1/1 or 1/3 octave analysis in real time [16]. It is also equipped with a sound calibrator with a frequency of 1000 Hz and a sound level of 114 dB.

The results of the noise level measurements were recorded in dB.

The obtained results were transferred to a computer using a USB cable and Quest Suite Professional II software. With its help, the results were presented in tabular and graphical form [19].

3. INVESTIGATION AND RESULTS

The levels of external and internal noise in octave frequency bands are presented in Figs. 7-22. They concern investigations of two types of asphalt pavement—damaged coarse-grained and smooth asphalt in good condition—and speeds of 20, 40, 60, and 90 km/h.

The results of octave bands at speeds of 20, 40, 60, and 90 km/h are shown graphically.

(a) (b) (c)

Fig. 5. Tires of the cars included in the experiments: (a) Michelin Primacy 3 215/55 R18, (b) Goodyear 215/50 R17, and (c) Dunlop sport Fast response

The analysis of the results from Figs. 6-21 shows the following regularities.

External noise

At low frequencies (31.5 Hz), there is a relatively large scatter in the results for the three cars with different drivetrains. Apparently, at these frequencies and at lower noise levels, random disturbances from the environment have a strong influence. The tests were carried out in real road conditions. In the middle frequencies, the lowest noise levels were produced by the gasoline car.

As the driving speed increased from 20 to 90 km/h, the maximum values of the noise level at 1000 Hz increased from 46-50 dB to about 68-77 dB for the damaged coarse-grained pavement.

For the smooth fine-grained pavement, the analogous variation ranged from about 46-50 dB to about 63-74 dB. The difference between the two pavements at the same speed varied from 1-3 dB.

Table 1

Main technical characteristics of the compared cars

Technical characteristics	**Toyota Yaris (P3) Hybrid**	**Nissan Qashqai**	**Nissan LEAF Zero Emission**
Model	1.5 HSD Hybrid 100 Hp	1.6 DIG-T (163 Hp)	LEAF 40KWH
Maximal power	55 kW /4800 min^{-1}	121 kW/ 5600 min^{-1}	-
Maximal torque	111 Nm /4400 min^{-1}	240 Nm /2000-4000 min^{-1}	-
Maximal power of the electric system	45 kW	-	110 kW
Maximal torque of the electric system	207 Nm	-	320 Nm
Capacity of the battery	0.94 kWh	-	40 kWh
EURO standard	EURO V	EURO 6	-
Tire dimensions	175/65 R15	215/55 R18	215/50 R17
Maximal speed	165 km/h	200 km/h	144 km/h
Acceleration time from 0 to 100 km/h	11.8 s	8.9 s	7.9 s
Weight	1120 kg	1458 kg	1544 kg

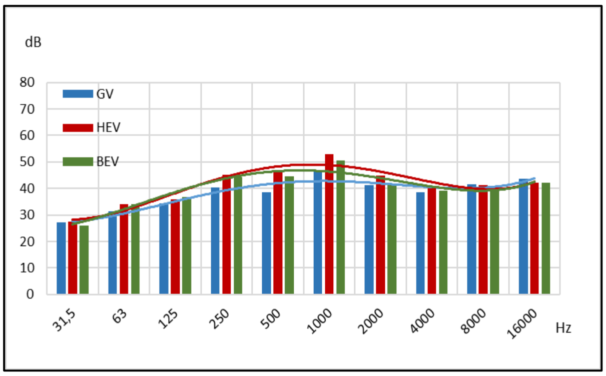

Fig. 6. External noise level spectrum at a speed of 20 km/h on damaged coarse-grained asphalt

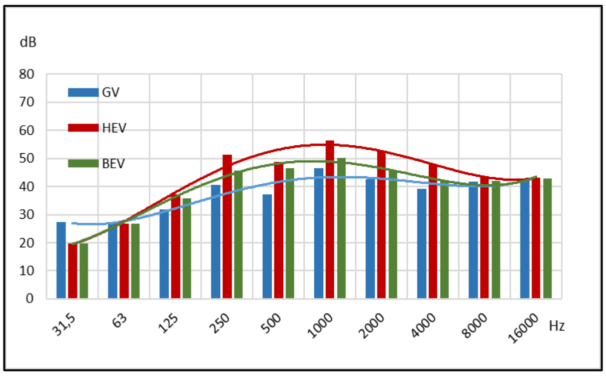

Fig. 7. External noise level spectrum at a speed of 20 km/h on smooth asphalt in good quality

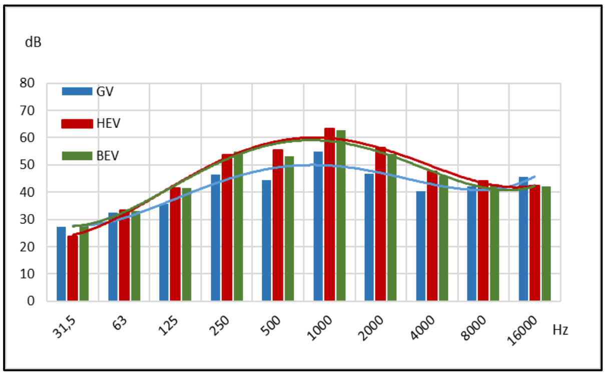

Fig. 8. External noise level spectrum at a speed of 40 km/h on damaged coarse-grained asphalt

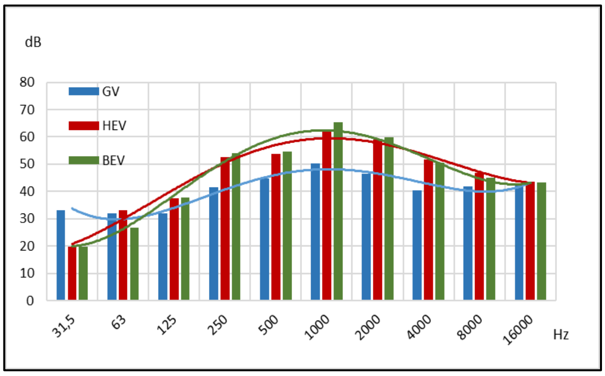

Fig. 9. External noise level spectrum at a speed of 40 km/h on smooth asphalt in good quality

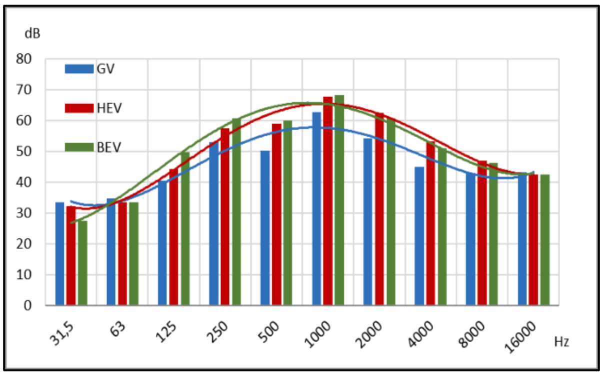

Fig. 10. External noise level spectrum at a speed of 60 km/h on damaged coarse-grained asphalt

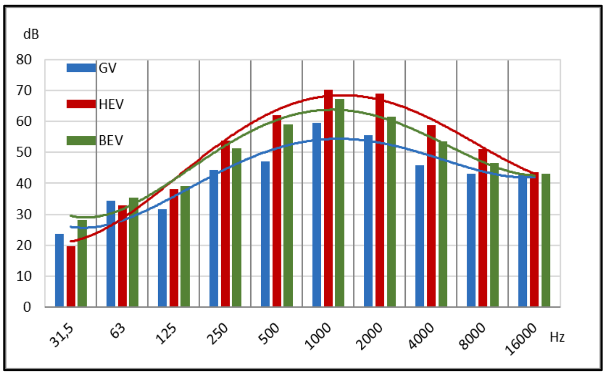

Fig. 11. External noise level spectrum at a speed of 60 km/h on smooth asphalt in good quality

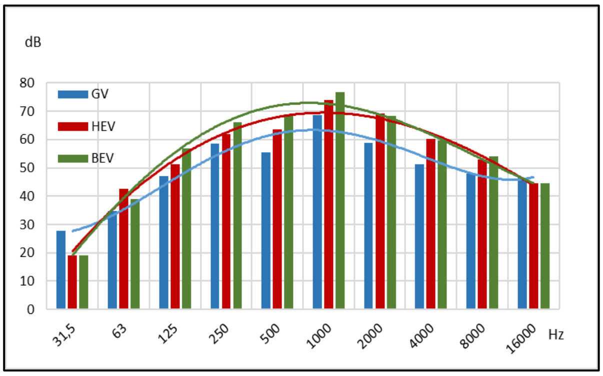

Fig. 12. External noise level spectrum at a speed of 90 km/h on damaged coarse-grained asphalt

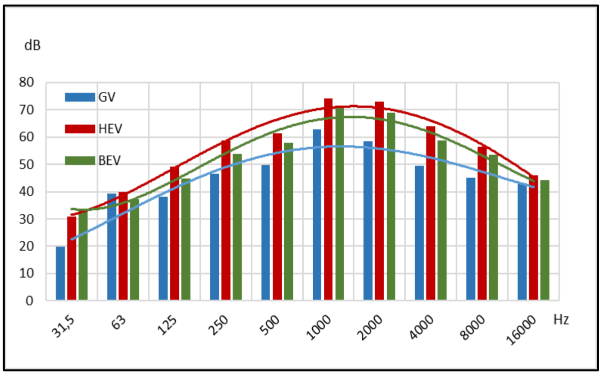

Fig. 13. External noise level spectrum at a speed of 90 km/h on smooth asphalt in good quality

Internal noise

The internal noise dissipation for all three cars on both pavements was also high, at 31.5 Hz. In this range, the electric car was the loudest. In the middle frequencies, the gasoline car had the lowest noise levels, and the hybrid car had the highest.

As the driving speed increased from 20 to 90 km/h, the maximum values of the noise level at 1000 Hz increased from 43-48 dB to about 59-61 dB on the damaged coarse-grained pavement.

On the smooth fine-grained pavement, the analogous variation ranged from about 40-45 dB to about

49-56 dB. The difference between the two pavements at the same speed varied from 3-8 dB.

The results for external noise on the damaged coarse-grained pavement show that at low frequencies (31.5 and 63 Hz), there was no clear domination of external noise for some of the cars. At the frequencies of 125, 250, 500, and 1000 Hz, the electric car and hybrid car yielded similar results, while the petrol car had a lower noise level. At high frequencies, the results for all three cars were very similar.

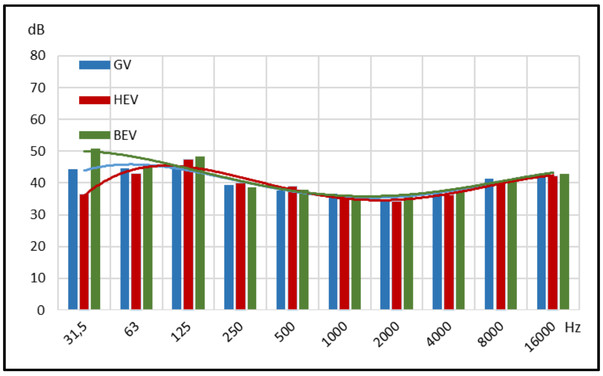

Fig. 14. Internal noise level spectrum at a speed of 20 km/h on damaged coarse-grained asphalt

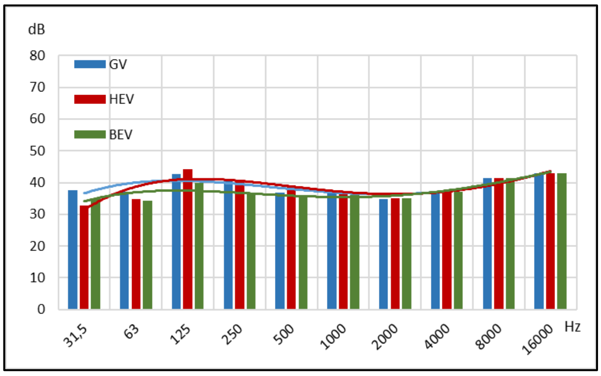

Fig. 15. Internal noise level spectrum at a speed of 20 km/h on smooth asphalt in good quality

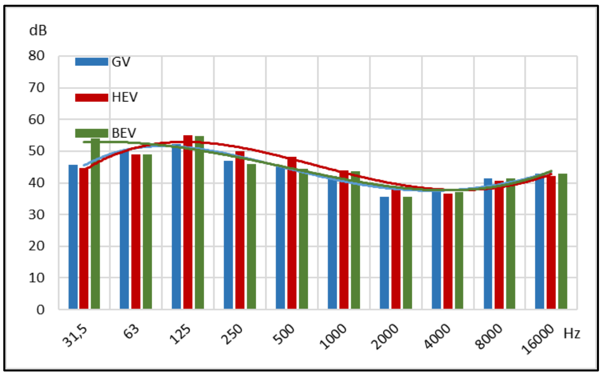

Fig. 16. Internal noise level spectrum at a speed of 40 km/h on damaged coarse-grained asphalt

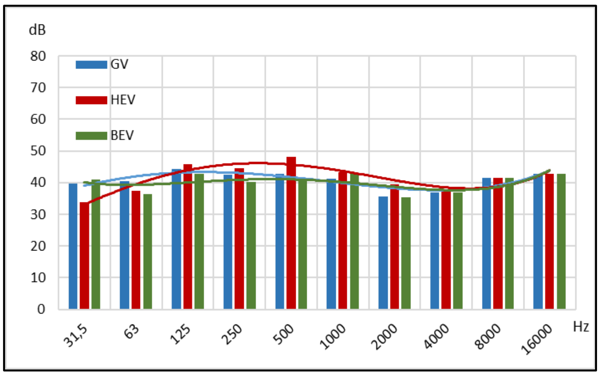

Fig. 17. Internal noise level spectrum at a speed of 40 km/h on smooth asphalt in good quality

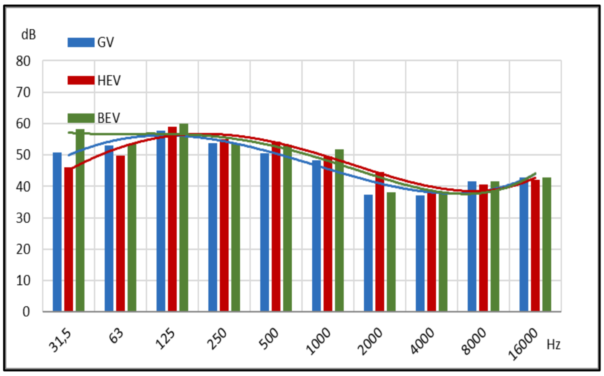

Fig. 18. Internal noise level spectrum at a speed of 60 km/h on damaged coarse-grained asphalt

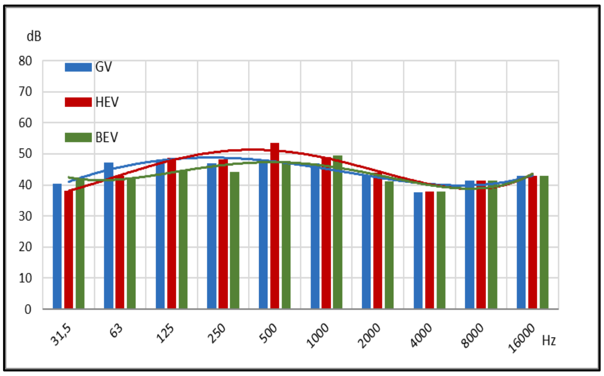

Fig. 19. Internal noise level spectrum at a speed of 60 km/h on smooth asphalt in good quality

The graphs show that on the smooth asphalt pavement at low frequencies (31.5, 63, and 125 Hz), the outcomes were the same. At frequencies above 250 Hz, the hybrid car was the loudest. At high frequencies, the results for all three cars were very similar.

The results obtained by octave bands show that the values for the external noise dominated the values in the middle-frequency bands and for the internal noise in the low-frequency bands. For all types of vehicles and road surfaces, the external noise's maximum value was 1000 Hz, while the maximum levels of internal noise ranged from 125-500 Hz. This shows that the external noise was strongly influenced by the noise generated by the contact of the tires with the road and the internal noise generated by the elements of the drive system. These conclusions are valid for all three types of cars.

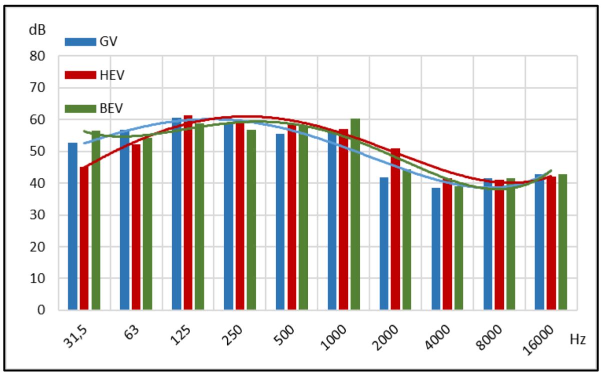

Fig. 20. Internal noise level spectrum at a speed of 90 km/h on damaged coarse-grained asphalt

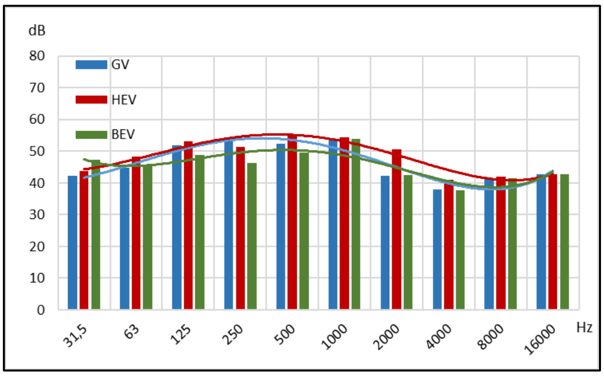

Fig. 21. Internal noise level spectrum at a speed of 90 km/h on smooth asphalt in good quality

Table 2

Octave bands noise level models

Type of pavement	**20 km/h**	**40 km/h**	**60 km/h**	**90 km/h**	**Car**
		External noise			
Damaged coarse-grained asphalt	$y = 0.0307x^4 - 0.6209x^3 + 3.7167x^2 - 4.204x + 28.569$	$y = 0.0643x^4 - 1.348x^3 + 8.6293x^2 - 14.709x + 35.22$	$y = 0.0828x^4 - 1.8337x^3 + 12.599x^2 - 26.031x + 48.973$	$y = 0.0641x^4 - 1.3539x^3 + 8.1284x^2 - 8.1928x + 29.065$	GV
	$y = 0.0509x^4 - 1.0669x^3 + 6.6521x^2 - 9.7619x + 32.358$	$y = 0.0636x^4 - 1.3502x^3 + 8.145x^2 - 8.3246x + 25.775$	$y = 0.0816x^4 - 1.8608x^3 + 12.884x^2 - 24.62x + 45.542$	$y = 0.0027x^4 - 0.0077x^3 - 2.248x^2 + 25.149x - 2.3417$	HEV
	$y = 0.0379x^4 - 0.7367x^3 + 3.9012x^2 - 1.4848x + 24.817$	$y = 0.0736x^4 - 1.5735x^3 + 9.9338x^2 - 14.696x + 33.808$	$y = 0.0675x^4 - 1.4275x^3 + 8.4001x^2 - 7.2049x + 26.95$	$y = 0.0188x^4 - 0.3002x^3 - 0.8571x^2 + 24.747x - 4.5167$	BEV
Smooth asphalt in good quality	$y = 0.0435x^4 - 0.9533x^3 + 6.5666x^2 - 12.973x + 34.283$	$y = 0.0732x^4 - 1.6598x^3 + 12.177x^2 - 29.955x + 53.173$	$y = 0.0578x^4 - 1.3307x^3 + 9.3366x^2 - 17.442x + 35.326$	$y = 0.0178x^4 - 0.3992x^3 + 1.8223x^2 + 6.5864x + 14.464$	GV
	$y = 0.0505x^4 - 1.064x^3 + 6.2266x^2 - 3.8181x + 18.025$	$y = 0.041x^4 - 0.8993x^3 + 5.2466x^2 - 0.9298x + 17.308$	$y = 0.0576x^4 - 1.3716x^3 + 9.3119x^2 - 11.727x + 24.975$	$y = 0.026x^4 - 0.7102x^3 + 4.9588x^2 - 3.061x + 30.292$	HEV
	$y = 0.0457x^4 - 0.907x^3 + 4.8738x^2 - 1.0811x + 16.542$	$y = 0.0816x^4 - 1.8023x^3 + 11.786x^2 - 17.646x + 27.533$	$y = 0.0746x^4 - 1.7315x^3 + 12.199x^2 - 23.41x + 42.367$	$y = 0.0476x^4 - 1.2149x^3 + 9.1418x^2 - 17.426x + 43.133$	BEV
		Internal noise			

Damaged coarse-grained asphalt	$y = -0.025x^4 + 0.637x^3 - 5.1107x^2 + 13.186x + 35.186$	$y = -0.0169x^4 + 0.5483x^3 - 5.5337x^2 + 18.52x + 31.969$	$y = 0.0062x^4 + 0.0741x^3 - 2.5347x^2 + 12.06x + 40.305$	$y = 0.0266x^4 - 0.3724x^3 + 0.4877x^2 + 5.4978x + 46.858$	GV
	$y = -0.0417x^4 + 1.0886x^3 - 9.4003x^2 + 29.622x + 14.725$	$y = -0.0068x^4 + 0.3562x^3 - 4.5945x^2 + 18.456x + 29.823$	$y = 0.0164x^4 - 0.1482x^3 - 1.2515x^2 + 11.715x + 34.9$	$y = 0.0259x^4 - 0.377x^3 + 0.2824x^2 + 9.64x + 35.363$	HEV
	$y = -0.0173x^4 + 0.4232x^3 - 3.0008x^2 + 4.4951x + 48.005$	$y = 0.0033x^4 + 0.0432x^3 - 1.1081x^2 + 2.7124x + 51.209$	$y = 0.0336x^4 - 0.5837x^3 + 2.8547x^2 - 5.3784x + 60.148$	$y = 0.0655x^4 - 1.3143x^3 + 8.1269x^2 - 17.652x + 67.085$	BEV
Smooth asphalt in good quality	$y = -0.0092x^4 + 0.3039x^3 - 3.0166x^2 + 10.452x + 28.872$	$y = 0.0066x^4 - 0.0265x^3 - 0.8591x^2 + 5.6196x + 34.311$	$y = 0.0091x^4 - 0.0703x^3 - 0.8929x^2 + 7.7434x + 34.204$	$y = 0.0445x^4 - 0.8014x^3 + 3.7836x^2 - 1.8495x + 40.579$	GV
	$y = -0.0158x^4 + 0.4994x^3 - 5.0781x^2 + 19.279x + 16.736$	$y = 0.019x^4 - 0.2548x^3 + 0.0636x^2 + 7.7034x + 25.598$	$y = 0.0364x^4 - 0.6487x^3 + 2.8925x^2 + 0.3028x + 35.527$	$y = 0.0368x^4 - 0.712x^3 + 3.7886x^2 - 3.688x + 44.908$	HEV
	$y = -0.0107x^4 + 0.3078x^3 - 2.7732x^2 + 9.2095x + 27.31$	$y = 0.0258x^4 - 0.5037x^3 + 3.1665x^2 - 7.1843x + 44.608$	$y = 0.0431x^4 - 0.8824x^3 + 5.6634x^2 - 12.145x + 49.775$	$y = 0.0529x^4 - 1.1x^3 + 7.2602x^2 - 16.994x + 58.268$	BEV

y = noise level in dB; **x** = frequency in Hz

Based on the experimental results, regression models were developed for different cars and pavement types. The models are summarized in Table 2. The models can be used in future research.

A summary of the results by octave bands from the experiments at different speeds is provided in Table 3. It can be seen that the values for external noise predominate in the middle-frequency bands, while the values for internal noise predominate in the low-frequency bands.

In all three types of tested cars, and for both types of road surfaces, the external noise's maximum value was most often 1000 Hz. High levels of internal noise were reported at low frequencies from 31.5 Hz to 1 kHz, with a predominance of 125 and 500 Hz.

These results show that external noise is strongly influenced by the noise from the contact of the tires with the road, while internal noise is influenced by the noise from the elements of the drive system. These conclusions are valid for all three types of cars.

Table 3

Disposition of the maximal noise level in octave bands

Type of pavement	**Octave bands with the maximal noise level**			
	20 km/h	40 km/h	60 km/h	90 km/h
External noise				
Damaged coarse-grained asphalt	1000 Hz	1000 Hz	1000 Hz	1000 Hz
Smooth asphalt in good quality	1000 Hz	1000 Hz	1000-2000 Hz	1000-2000 Hz
Internal noise				
Damaged coarse-grained asphalt	125 Hz	125 Hz	125 Hz	125-500 Hz
Smooth asphalt in good quality	125 Hz	125-500 Hz	500 Hz	500-1000 Hz

4. CONCLUSIONS

This article investigated the level of external and internal noise of three cars with different traction systems. The experiments were conducted on the two types of pavement at different speeds ranging from 20 to 90 km/h. New data, which confirmed the hypothesis, were collected. Based on the obtained results, several conclusions and generalizations can be made.

The experiments confirmed that the noise generated by a car depends on the conditions of the road surface, the speed of the vehicle, the tread pattern of the tires, the type of drive, and the elements of the body. An obvious difference in noise levels was detected at the same speed on different surfaces.

The results show that the noise levels of the three cars exhibited minimal differences. Modern cars with internal combustion engines have good noise reduction systems (exhaust systems), which are responsible for the comparable noise levels.

The results by octave bands show that the values of external noise dominated the values in the middle-frequency bands and that the values of internal noise dominated the values in the low-frequency bands. Regardless of the type of vehicle and the road surface, the external noise's maximum value was 1000 Hz, while the maximum levels of internal noise ranged from 125-500 Hz. This shows that external noise is strongly influenced by the noise generated by the contact of the tires with the road, while internal noise is affected by the noise from the elements of the drive system. These conclusions are valid for all three types of cars.

The internal noise spectrum has maximums at relatively low frequencies. The main cause of this is the transformative properties of the construction. The low level of internal noise is due to the good sound insulation of the cabin. For internal noise, the acoustic emissions and the vibrations of the vehicle structure are dominant. Effectively reducing noise levels requires efforts that focus on external noise (specifically, on the tire structure) and internal noise (specifically, the driving system)."

As vehicle speed increases, the maximum levels of noise emissions are registered at higher octave frequency bands.

Acknowledgments

This study was supported by the "Scientific researches" fund of the University of Ruse "Angel Kanchev."

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Received 29.02.2022; accepted in revised form 31.05.2023