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Original Article

RESEARCH ON THE NOISE POLLUTION FROM DIFFERENT VEHICLE CATEGORIES IN THE URBAN AREA

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Highlights:

- described noise measurement procedure upon applying Statistical Pass-By (SPB) method;
- established a noise pollution level dependence on the speed of the different types of vehicles;
- established noise level dependence of passenger cars driving on asphalt pavements of different states;
- regression equations and coefficients for determination of the vehicles noise level was found;
- the research results will help to determine a more accurate variation in the traffic noise.

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Abstract. The noise pollution inside urban areas is one of the common problems for the inhabitants. The different levels of a noise are generated from the large amount of sources, including traffic flow on a road of urban areas. Therefore, it is essential to measure and evaluate the road traffic noise in urban areas and its population exposure in order to obtain models of a traffic noise as well as the noise mapping. The current research includes establishing a traffic noise from the different types of vehicles caused by the speed in urban areas and different road pavements (dry, wet and covered with a snow) with generalising the obtained data for more accurate using in future traffic noise models and the noise mapping. The study region is Vilnius (Lithuania), the speed range for different categories of the vehicles in the collected data is 40…130 km/h, with wide ranges of a noise level 20…180 dB. The approach presented in this research of experimental measurements is based on Statistical Pass-By (SPB) method with data proceeding upon implementation of Pearson correlation coefficient. In course of the analysis of the obtained results, it was found that the level of the curves of noise depends on the vehicles' speed what corresponds to the best-measured values and can be used in the traffic noise models and the noise mapping.

Keywords: noise pollution, vehicle, traffic, correlation coefficient, speed, road pavement, sound level, urban area, SPB method.

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Introduction

Nowadays urban areas are usually associated with high levels of noise pollutions. The said noise pollutions, basically inside urban areas, are generated from the different sources, which include:

- commercial and industrial activities (Kephalopoulos *et al.* 2014);
- airports activities (Iglesias-Merchan *et al.* 2015);
- proximity of railways (Bunn, Zannin 2016);
- road traffic (Cueto *et al.* 2017; Paviotti, Vogiatzis 2012);
- mobile machines working at constructions of buildings (Kudźma, Stosiak 2013);
- other sources recognized as highly annoying (Gallo *et al.* 2016), which are promoted by large human population according to the Ihemeje & Onyelowe (2021) research on a review of environmental noise control.

The noise pollution generated by transport infrastructures for the inhabitants of urbanized areas is a very widespread issue in a modern society. Moreover, the noise pollution frequency spectrum generated by the above-mentioned sources is very broad and also includes infrasound (Stosiak 2015). The recent European *Environmental Noise Directive* revision (EC 2017) reported that noise pollution is one of major health problems in Europe.

The road traffic is one of the most common noise source generators inside urban areas. According to Del Pizzo *et al.* (2020), about 100 mln people in the 27 EU Member States are exposed to harmful road traffic noise levels exceeding 55 dB(A) of Day–Evening–Night Noise Level (DENNL), and 32 mln people are exposed to noise levels higher than 65 dB(A) of DENNL. The review of different researches has shown that road traffic noise is a remarkably complex phenomenon and includes different sources of noise generation:

- power and suspension units (Kim *et al.* 2013);
- aerodynamic effects (Torija *et al.* 2011);
- tyre–road interaction (Jung *et al.* 2019; Bravo 2017).

The noise from the tyre-road interaction constitutes the most important source of traffic noise, particularly for traffic speeds inside the cities and urban areas from 35 km/h up to 120 km/h. The noise pollution caused by tyre–road interaction shows a strong degree of variability, depending on properties of both: (1) tyre types and (2) pavement conditions (dry, wet, snow-covered, etc.), since the noise generation mechanisms involve several mechanisms that operate simultaneously. A combination of aerodynamic and vehicle mechanical units vibro-dynamic phenomena occurs in the generation of tyre with a road noise and during an operation of vehicle mechanisms what lead to complex noise vibration at frequencies up to 1 kHz inside a vehicle (Jung *et al.* 2019) and external noise vibration at frequencies even higher than 1 kHz (Del Pizzo *et al.* 2020).

An exposure to such high noise levels on inhabitancies located in the urban areas could lead to a whole list of health effects, such as:

- sleep disorders with awakenings (Muzet 2007);
- learning impairment (Lercher *et al.* 2003);
- hypertension ischemic heart disease (Babisch *et al.* 2012);
- annoyance (Miedema, Oudshoorn 2001).

The prevention of such effects is remanded to mandatory action plans for big infrastructures or urban agglomerations and in order to optimize mitigations, noise generation mechanisms are of paramount interest by Licitra *et al.* (2017) research. Currently, artificial monitoring and noise mapping are the main measures used to monitor and control traffic noise (Tong *et al.* 2014; Vogiatzis 2011; Vogiatzis, Remy 2014), and these measures can visually show the acoustic field distribution and intensity, but cannot reflect the effects of road traffic noise pollution on human beings. Therefore, it is essential to measure and evaluate the road traffic noise in urban areas and its population exposure.

1. Review of the related researches

Many researchers have assessed the population exposure to road traffic noise. In the first step, the Noise Impact Index (NII), which considers the amount of noise and the degree of its effect (Deville *et al.* 2014) was proposed. In addition, Pathak *et al.* (2008) studied the population exposure to road traffic noise by conducting a social survey and drawing a noise map. Ko *et al.* (2011) evaluated the noise pollution and its effect on the exposed people using sample investigations and noise measurements. In their research, Murphy and King (2011) used a noise prediction model to estimate the population exposure to daytime and night-time traffic noise. Nowadays, the calculation of traffic noise has developed into noise mapping (Wang *et al.* 2018); large-scale urban traffic noise maps can be drawn based on certain parameters, such as traffic volume and vehicle speed of the road network (Cai *et al.* 2018). According to Cai *et al.* (2017a) research, the convenience of traffic flow parameter acquisition makes it possible to draw the dynamic traffic noise maps or make a quick update to the noise maps according to the changes of traffic flow in urban area.

The mentioned traffic noise models are used to estimate the sound quality of the environment (Di *et al.* 2018), the noise pollution that residents are exposed (Cai *et al.* 2019), and the sound pressure level that affects the drivers/passengers and inhabitancies in the urban areas near roads traffic (Pathak *et al.* 2008; Huang *et al.* 2016). The accuracy of traffic noise calculation and modelling of noise mapping mainly depends on the primary measuring of noise near the roads and is one of the key issues that researchers focus on. Rey-Gozalo *et al.* (2019) conducted an analysis of the distribution of differences between the measured and calculated sound levels, and found that a measured noise level near road (upon using the accuracy data) helped to develop and improve the noise model and noise mapping in more accurate way than calculated sound levels.

Both the traffic noise models and the noise mapping are methods for calculating the sound pressure level of traffic noise, so they can be used for prediction of the influence of the noise near a road on the inhabitancies located in these areas. The both methods require an accuracy of the initial data for modelling and calculation. The best and right way to obtain a data is noise measuring near a road and showing the obtained results in curves of noise depending on the speed and type of vehicles driven on the road in urban areas. In future, the obtained data will help to develop a model of the vehicle noise emission's extension based on the traffic volume and driving speed of the vehicles.

The one of the first models of noise emissions was published by the Federal Highway Administration (FHWA) (Menge *et al.* 1998) and it included the research on the noise spectrum emissions of a single vehicle. In the research, the vehicles on the road were divided to the few types of classification: (1) motorcycles; (2) passenger cars; (3) medium and heavy trucks; (4) buses. In final, the noise spectrum curves of the vehicles driving on the road at different speed (10…80 miles/h) were obtained and plotted. Can *et al.* (2010) made an experimental measurement on a one-way three-lane road, where the noise spectrum was established based on the flow rate and the speed of vehicle traffic in order to compare a static method and a dynamic method of reproducing the noise spectra. During a research, Zambon *et al.* (2017) classified the vehicle noise spectra by the speed, according to what the speed of the vehicle can be estimated by using patterns. Wang *et al.* (2013) measured the noise of different five passenger vehicles driving at 20...100 km/h speed range for obtaining the relationship between the sound pressure and the speed of vehicle. In their research, Cai *et al.* (2017b) measured and collected the sound of the car driving on wet and dry asphalt road for comparing a noise generated by the vehicle. The research on the influence of road pavement macrotexture on tyre noise of vehicle was conducted by measuring the noise from the vehicle driving on the different road pavements (Gardziejczyk 2014). Li (2018) measured the traffic noise at different locations by various speed limits for statistical analysis of a dependence of sound pressure on the traffic on the road. In their research, Licitra *et al.* (2012) made a comparative analysis of different methods for estimation of urban noise exposure of inhabitants. In their research, Phan *et al.* (2010) conducted a 24 h sound monitoring measurement on eight road sections in different regions for comparing the traffic flow and generated noise on the road in order to obtain curves of its dependence. Buratti *et al.* (2014) and Masovic *et al.* (2013) measured the traffic noise on the urban road for evaluation of its influence and comparing with a standard of noise reduction and traffic noise spectrum (ISO 717-1:2020). Mesihovic *et al.* (2016) compared the both above-mentioned researches with a noise spectrum parts of the international standard ISO 717-1:2020 and the results showed the noise spectrum of urban traffic to be variable.

All the above-mentioned researches cover many aspects of the vehicle traffic noise spectrum measurements in urban areas. The researches on the traffic noise models and the noise mapping require the updated traffic noise spectra measurements very often, since the noise spectrum of urban traffic constantly varies according to Mesihovic *et al.* (2016) and Coelho *et al.* (2011). However, the researches on the traffic noise measurements have not yet obtained the universality data for a traffic noise models and the prediction model of noise mapping, because these above-mentioned researches just involved either qualitative analysis (or just used recording data from several vehicles), which caused their lack of universality. Therefore, they cannot be used for modelling accurately the traffic noise spectrum based on the traffic volume and driving speed of the vehicles, without a modern and generalized data from the measuring. In addition, their data from the measuring on vehicle noise was inadequate to obtain a traffic noise source intensity emission model.

Therefore, the first and the main objective of this research is to establish a traffic noise of the different types of vehicles and speeds in urban areas and generalise the obtained data for more accurate using in traffic noise models and the noise mapping. The second objective of the research includes the noise measuring and data processing on dry, wet and snow-covered road pavements for a comparing analysis. Finally, the obtained data should be generalised and correlated with a measurement for more accurate using in a future mathematical models of traffic noise spectrum and it influences on inhabitancies in different urban areas.

2. Research methodology

This part of the research includes the classification of vehicle types, road condition and explanation of the divisions of speed intervals during a measurement; the description of measuring devices and its setup/installation; description of the performed noise measurement procedure. The measurement results will help to determine a more accurate variation in the traffic noise by using the variable speeds of movement of different categories of vehicles.

2.1. Classification of vehicle types, road condition and speed intervals divisions

The research was conducted in Vilnius City (Lithuania). Measurements were carried out near Botanical Garden of Vilnius University. We chose this place because of clear area, low background noise and low traffic, which enabled doing the measurements of each vehicle separately. According to the mentioned standard, in this place there are no objects to close what can reflect noise. The road surface where the measurements were performed is constructed of standard mastic asphalt concrete with up to 11 mm of crushed stone (AC 11) (pavement without damage); such a road surface is common in the category of main roads on Lithuania (Kleizienė *et al.* 2019). The measurements were performed in total for 14 h on different days and weather conditions, without wind and upon variable air temperature (more details are provided in the experimental studies section). The vehicles are divided into different types, according to vehicles commonly found on Lithuanian urban roads and according to Menge *et al.* (1998) classification, and included: (1) motorcycles; (2) passenger cars; (3) vans; (4) buses; (5) light and heavy trucks. The method of collecting data was in line with the international standard ISO 10844:2021. During the collection of data samples, the range speed of the different vehicles types – 40...130 km/h. According to Yang *et al.* (2020) research, it can be pointed out that the speed step size interval should be less than 10 km/h, since the difference between the noise spectrum curves is significant. The smaller speed intervals – the more accurate the noise spectrum (curves) can be obtained, but the more data is required to collect.

In the current research, the speed intervals for a different vehicles type were divided by a step size of 1 km/h, what required a large sample size of collected data. The speed range in the collected data is 75...130 km/h for motorcycles; 45...120 km/h for passenger cars; 55...100 km/h for vans; 45...95 km/h for light and heavy trucks; the speed range for the buses was concentrated at the range 40...85 km/h, since for this type of vehicles, the speed is limited by the requirements set for driving on roads.

2.2. Measuring devices and setups

In the current research, a *Traffic Counter TC25* with a *Doppler Radar* speed sensor was used for measuring the dynamic processes of traffic flow and *Noise Analyser Brüel*

& *Kjær 2250* was used for measuring vehicle noise; they are shown in Figure 1. The *Traffic Counter TC25* was recording the number of vehicles in traffic and their average speed, the length (the vehicles additionally were classified according to their lengths), direction of vehicles movement and safe distance to the previous vehicle. The operating frequency of the traffic counter *Traffic Counter TC25* is 24.125 GHz / 5 mW. There are two main ways to select the right installation height for this device according to the possible conditions for a measuring:

- the 1st method of installation: the traffic counter is installed at a height of approximately 1 m above the ground. The inner housing is oriented to a horizontal position (Figure 1a). The advantage of this method is that it is easy to determine the right measuring angle and it covers several traffic lanes well. The disadvantage of such an installation is that the vehicle in the nearest lane usually blocks the vehicle in other lanes;
- the 2nd method of installation: the traffic counter is installed higher than 1 m above the ground and depending on the distance of the pole from the road. In this case, the inner housing must be inclined at 30° (Figure 1b). This method requires more attention when determining the appropriate height based on the distance from the road and determining the angle in front direction of vehicle movement.

For more accurate measurements, the height and distance of device installation must be set and the radius of the device installation should cover all road lines for measuring. In this case, it is necessary to determine the exact angle between the direction of vehicle movement in the traffic flow and the direction of traffic counter installation. The 1st installation method was chosen since it required a lower height of installation and still fully covered the road line for measuring. Therefore, the traffic counter classifier was oriented at 45° angle to the direction of vehicle movement (Figure 2).

The monitoring area depends on the distance to the pole on which the device is mounted and the height of its mounting. The traffic flow counter beam's width is 12°. The monitoring area of the device is calculated according to the installation height h and the distance from the carriageway d:

$$d_1 = 1.09 \cdot h; \quad (1)$$

$$d_2 = 3.17 \cdot h. \quad (2)$$

The stored data was transmitted to a computer directly via a RS232 connection to avoid an extraneous interference. Before processing of recording, the previous data was deleted, since it can significantly skew the obtained test results.

The *Noise Analyser Brüel & Kjær 2250* with a single-channel input for a microphone was used for a noise measurement. The frequency range of the noise analyser is from 3 Hz to 20 kHz, the noise level was set from 16.6 to 140 dB, according to operating range of device. The specification for the type of microphone 4189 used speci-

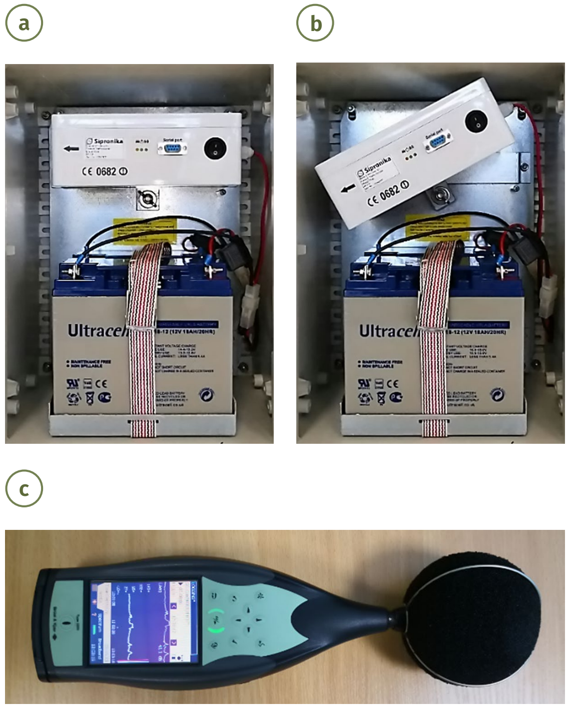

Figure 1. Measuring devices:
(a) horizontal traffic counter internal housing position;
(b) angular traffic counter internal housing position (inclined at 30°);
(c) *Noise Analyser Brüel & Kjær 2250*

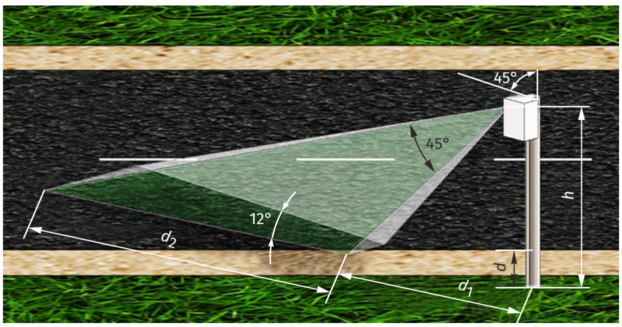

Figure 2. Traffic flow counter setting on the observation area

fies a temperature coefficient of –0.006 dB/°C, the noise level data $LA_{eq,\,20\,°C}$ was measured at air temperature of 20 °C and based on the equation:

$$LA_{eq,\,20\,°C} = LA_{eq,\,°C} - \frac{20 - T_{air}}{0.006}, \quad (3)$$

where: $LA_{eq,\,°C}$ – is the measured noise level at the temperature T_{air} [dB]; T_{air} – the air temperature during the experiment [°C].

In order to protect the suppressing the sound of wind gusts used during the traffic flow noise recording and to prevent sound reflections from nearby objects, the *Noise Analyser Brüel & Kjær 2250* was mounted on a stand above the ground. The data recorded by the noise analyser is processed by the *Brüel & Kjær* software – Measurement Partner Suite (*https://www.bksv.com/en/instruments/handheld/post-processing-software/measurement-partner-suite-5503*). The recorded data was exported to a computer for further noise level analysis.

2.3. Noise measurement procedure

The noise measurement procedure was performed according to the instructions provided in the international standard ISO 11819-1:2023. The measurement of noise emitted by road vehicles (Statistical Pass-By – SPB) was carried out in order to obtain the dependence of the vehicles' noise on the speed and the road conditions.

According to the instructions, there were no objects around the microphone within a radius 25 m that could reflect sound. That why the *Noise Analyser Brüel & Kjær 2250* was installed in an open area free of sound-reflecting objects. The device was mounted on a stand at a height of 1.2 m above the ground and 7.5 m from the centre of the test lane (Figure 3a). The *Traffic Counter TC25* was installed at a distance of 2 m from the carriageway, at 1 m height, directed in 45° to the road so that the position of the recorded vehicle was in front of the noise analyser at the same time. Before recording, the *Noise Analyser Brüel & Kjær 2250* and *Traffic Counter TC25* were synchronised. The data for analysis was recorded in the real-time and include recording: time, speed of each vehicle by the category and noise from it. The vehicle was registered only when there were no other vehicles in the adjacent lane and the tested lane (Figure 3b) in order to avoid an overlay sounds.

After the record procedure, the data from the *Noise Analyser Brüel & Kjær 2250* is transferred to a computer and the noise level values are selected at the appropriate time when the vehicles were recorded according to class

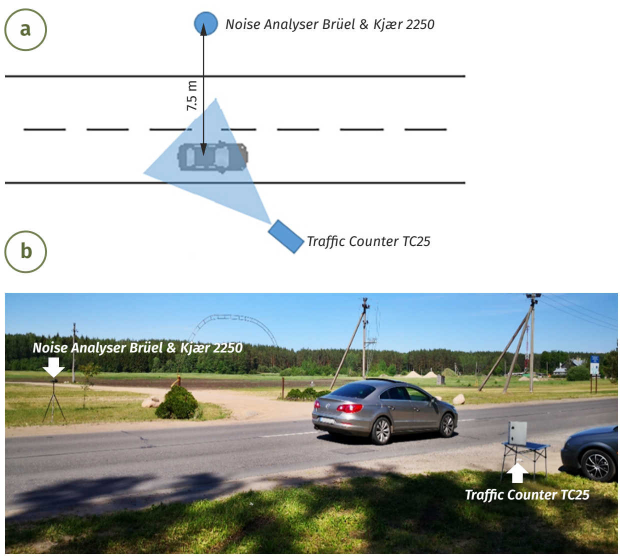

Figure 3. Noise measurement procedure upon applying SPB method:
(a) scheme of devices' location during the measurements;
(b) a view of noise measurement procedure

classificatory by *Traffic Counter TC25*. The latter provided more accurate results of dependence of the noise level of individual vehicle speed for a data analysis.

3. Results and data processing

Since the noise level measurements were performed for 10 times (in total 14 h) on different days and weather conditions, during which the air temperature varied (without wind), the obtained data were converted to a noise level corresponding to an air temperature of 20 °C, according to the Equation (3).

For a determination of the most appropriate regression functions and application of the formula used by (Podvezko, Sivilevičius 2013), the Pearson correlation coefficient $r_{v_i,\,LA_{eqi}}$ can be found from:

$$r_{v_i,\,LA_{eqi}} = \frac{r_1}{r_2}, \tag{4}$$

where:

$$r_1 = m \cdot \sum_{i=1}^{m} v_i \cdot LA_{eqi} - \sum_{i=1}^{m} v_i \cdot \sum_{i=1}^{m} LA_{eqi};$$

$$r_2 = \sqrt{m \cdot \sum_{i=1}^{m} v_i^2 - \left(\sum_{i=1}^{m} v_i\right)^2} \times \sqrt{m \cdot \sum_{i=1}^{m} LA_{eq_i}^2 - \left(\sum_{i=1}^{m} LA_{eq_i}\right)^2};$$

where: m – number of registered vehicles; v_i – speed of the ith vehicle [km/h]; LA_{egi} – noise level emitted by the ith vehicle [dB].

Based on the magnitude of the correlation coefficient, the conclusions about the strength of the correlation relationship can be made. The correlation coefficient of the regression line indicates the strength of the relationship, the scale of values of which is provided in Table 1.

The correlation coefficient of the regression line should not be less than the calculated minimum value $r_{\min}$ of the correlation coefficient by Podvezko & Sivilevičius (2013), only in this case the obtained regression curve correlates with the measurement results:

$$r_{\min} = \frac{t_{\alpha,\,n}}{\sqrt{m - 2 + t_{\alpha,\,n}^2}}, \tag{5}$$

where: $t_{\alpha,\,n}$ – Student's t-distribution coefficient at the degree of freedom $n = m - 2$ and level of confidence α.

The limits of the level of confidence (confidence index CI_i), which is likely to be a parameter of the measurement, are calculated according to equation (Hespanhol *et al.* 2019):

$$CI_i = LA_{eq(v_i)} \pm t_{\alpha,n} \cdot SE \cdot \sqrt{\frac{1}{n} + \frac{\left(v_i - \bar{v}\right)^2}{\sum_{i=1}^{m}\left(\left(v_i - \bar{v}\right)^2\right)}}, \tag{8}$$

where: $LA_{eq(v_i)}$ – the level of noise [dB] at speed v_i [km/h];

Table 1. The scale of correlation coefficient values (Mukaka 2012)

Very strong	Strong	Medium	Weak	Very weak	No correlation
±1	from ±1 to ±0.7	from ±0.7 to ±0.5	from ±0.5 to ±0.2	from ±0.2 to 0	0

SE – standard error; *n* – degree of freedom; v_i – speed of the *i*th vehicle [km/h]; $\bar{v}$ – average speed of the vehicles [km/h].

The minimum correlation coefficient and the limits of the confidence interval are calculated at the confidence level of 0.05, which is sufficient to determine the correlation of the data.

During the measurements, 10 motorcycles, 570 passenger cars, 65 vans, 68 buses, 40 light and 60 heavy trucks driving on dry asphalt pavement, were recorded. According to the measurements, the noise level ranges were established for each group (shown in Figure 4): for motorcycles – 74...83 dB at the 72...130 km/h speed range; for passenger cars – 66...84 dB at the 45...119 km/h speed range; for vans – 72...81 dB at the 56...99 km/h speed range; for buses – 70...84 dB at the 41...82 km/h speed range; for light trucks – 73...84 dB at the 52...94 km/h speed range; for heavy trucks – 75...87 dB at the 43...94 km/h speed range.

Upon striving to generalise the obtained data for a more accurate applying in future traffic noise models and the noise mapping, the regression curves were used to analyse the speed dependence on the noise level of the vehicles groups (their equations and coefficients of determination are presented in Table 2).

According to the analysis of the obtained results, the polynomial curve was found to correspond best to the values measured for motorcycles (R^2 = 0.4186); passenger cars (R^2 = 0.3433); vans (R^2 = 0.3644); light trucks (R^2 = 0.3827); heavy trucks (R^2 = 0.4297). The exponential curve (Figure 4) corresponds to the best-measured values for buses (R^2 = 0.208). Since, the correlation coefficient for the regression lines that shows the average relationship with the recorded data (for motorcycles $r = 0.647 > r_{min} = 0.632$; for passenger cars $r = 0.571 > r_{min} = 0.082$; for vans $r = 0.601 > r_{min} = 0.244$; for light trucks $r = 0.597 > r_{min} = 0.312$; for heavy trucks $r = 0.632 > r_{min} = 0.254$; for buses $r = 0.449 > r_{min} = 0.239$) and its values are higher than the minimum value of the correlation coefficient, the regression curve correlates with the measured experimental data and can be accepted for using in a simulation and obtaining traffic noise models and the noise mapping.

Moreover, a research was performed for a determination of a dependence of the noise level of vehicles on the speed under different road surface conditions (for example, passenger cars, since this vehicle type is commonly used in urban areas). In addition to dry asphalt pavement, measurements and data proceeding of the results for wet, dry snow-covered and dry snow-covered with snow ruts asphalt pavements were performed. The measurements of a dependence of the noise level emitted by passenger cars on their speed were performed at the same location and with the same arrangement of measuring devices and setups as for previous measurements. During the measurements, 24 passenger cars driving on wet asphalt, 58 passenger cars driving on dry snow-covered asphalt pavement and 28 passenger cars driving on snow-covered with a ruts asphalt pavement, were registered. The analysed data of the noise level depends on passenger cars speed on the wet asphalt, dry snow-covered asphalt and covered with dry snow (snow ruts) asphalt pavements; it is plotted by regression curves (Figure 5) and its equations and coefficients of determination are presented in Table 3. The registered noise levels varied from 68 to 85 dB at 41...130 km/h vehicles speed on wet asphalt; from 65 to 77 dB at 50...91 km/h vehicles speed on dry snow-covered asphalt; from 71 to 81 dB at 54...116 km/h vehicles speed on asphalt-covered with dry snow and snow ruts.

The logarithmic curve (Figure 5) was found to correspond to the best-measured values for passenger cars driving on wet asphalt (by largest coefficient of the curve determination R^2 = 0.6093) and for measurements on dry snow-covered pavement (R^2 = 0.5744) and on asphalt-covered with dry snow and snow ruts (R^2 = 0.5098); the polynomial curves correspond to the best-measured values. Since, the correlation coefficient for the regression lines that shows the average relationship with the recorded data (for wet pavement $r = 0.755 > r_{min} = 0.513$; for pavement with a dry snow $r = 0.757 > r_{min} = 0.259$; for asphalt-covered with dry snow and snow ruts $r = 0.714 > r_{min} = 0.374$) and its values are higher than the minimum value of the correlation coefficient, the regression curve correlates with the measured experimental data and can be accepted for using in a simulation and obtaining traffic noise models as well as the noise mapping.

Summarizing the dependence of the noise level of individual vehicles categories on the speed and asphalt pavements, the best-fit curves are presented in Figure 6, with a comparative analysis.

Compared to passenger cars with an average noise level 71 dB, on the speed 50 km/h, other vehicles are moderately noisier: motorcycles emit 3 dB (4.2%) higher noise; vans – 4.3 dB (6%); buses – 2.9 dB (4.1%); light trucks – 1.9 dB (2.6%); heavy trucks – 6.4 dB (9%). At the speed of 90 km/h with 77.7 dB for passenger cars, other vehicles are still moderately noisier: motorcycles – 0.4 dB (0.5%); vans – 3.2 dB (4.1%); buses – 2.3 dB (2.9%); light trucks – 2.5 dB (3.3%); heavy trucks – 5.7 dB (7.3%). A comparison of passenger cars with an average noise level of 71 dB, on dry asphalt at 50 km/h and wet asphalt has an average noise level of 1.8 dB (2.5%) on dry snow-covered asphalt – 4.5 dB (6.8%) lower and 0.1 dB (0.2%) lower when driving on dry snow with snow ruts asphalt pavement. On dry asphalt at 90 km/h, the average passenger cars noise emission is 77 dB, while on wet roads it is 2.8 dB (3.6%) higher, and on dry snow-covered asphalt noise 1.7 dB (2.2%) lower and 0.6 dB (0.8%) lower when driving on dry snow with snow ruts asphalt pavement.

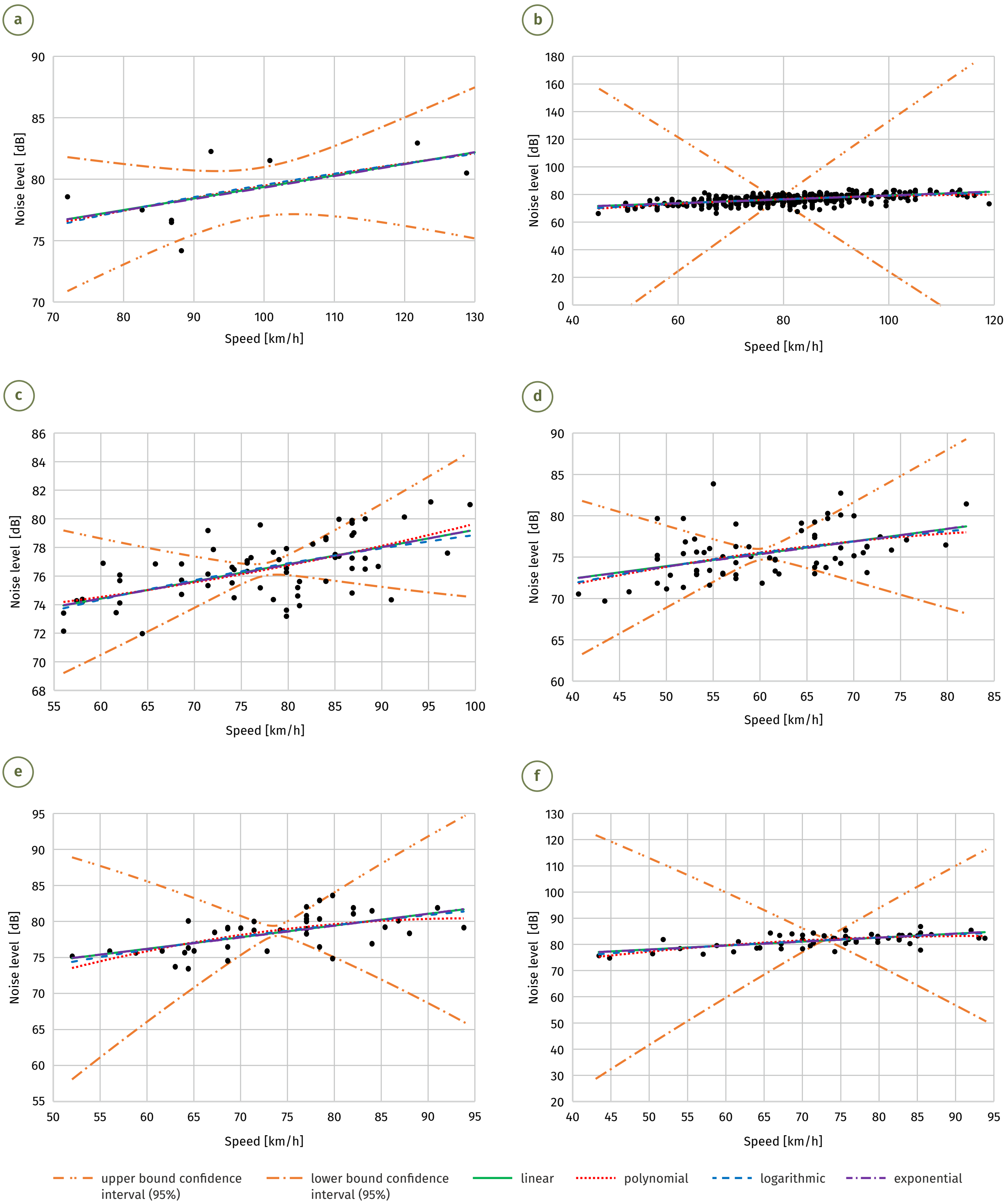

Figure 4. Noise level dependence on the speed when driving on dry asphalt for: (a) motorcycles; (b) passenger cars; (c) vans; (d) bus; (e) light trucks; (f) heavy trucks

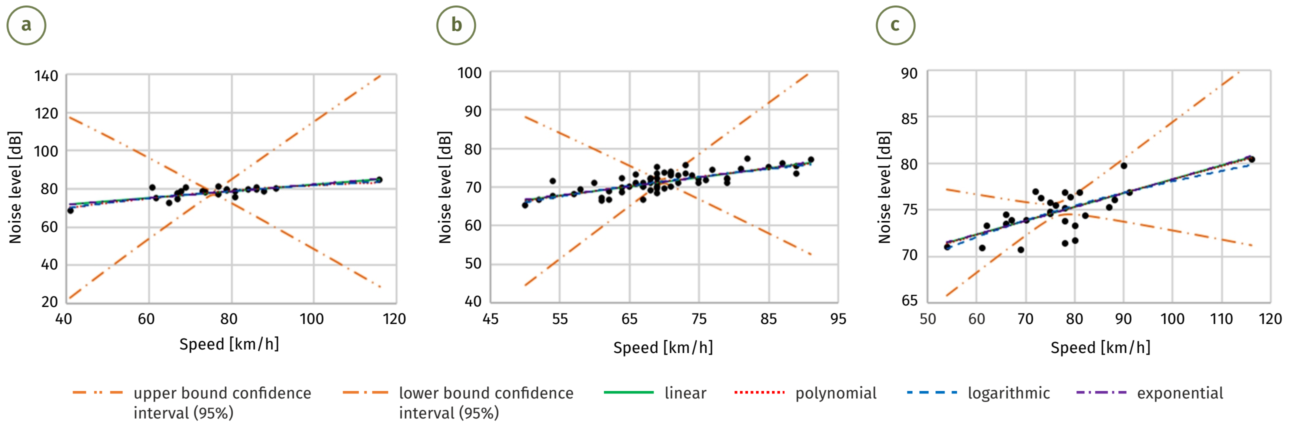

Figure 5. The dependence of noise levels for a passenger car driving on:
(a) wet asphalt; (b) dry snow-covered asphalt; (c) asphalt-covered with dry snow and snow ruts

Table 2. Regression equations and coefficients for determination of the vehicles' noise level

Vehicles	Regression curves and their equations			
	Linear	Polynomial	Logarithmic	Exponential
Motor-cycles	$LA_{eq} = 0.0938 \cdot v + 69.974$; $R^2 = 0.4182$	$LA_{eq} = -0.00031 \cdot v^2 + 0.1465 \cdot v + 67.335$; $R^2 = 0.4186$	$LA_{eq} = 9.5001 \cdot \ln(v) + 35.796$; $R^2 = 0.4133$	$LA_{eq} = 70.452 \cdot e^{0.0012 \cdot v}$; $R^2 = 0.4131$
Pas-senger cars	$LA_{eq} = 0.1385 \cdot v + 65.415$; $R^2 = 0.3294$	$LA_{eq} = -0.0015 \cdot v^2 + 0.3927 \cdot v + 55.311$; $R^2 = 0.3433$	$LA_{eq} = 11.1140 \cdot \ln(v) + 27.924$; $R^2 = 0.3415$	$LA_{eq} = 66.101 \cdot e^{0.0018 \cdot v}$; $R^2 = 0.3240$
Vans	$LA_{eq} = 0.1202 \cdot v + 67.203$; $R^2 = 0.3615$	$LA_{eq} = 0.0009 \cdot v^2 - 0.0151 \cdot v + 72.226$; $R^2 = 0.3644$	$LA_{eq} = 8.8594 \cdot \ln(v) + 38.072$; $R^2 = 0.3557$	$LA_{eq} = 67.734 \cdot e^{0.0016 \cdot v}$; $R^2 = 0.3612$
Buses	$LA_{eq} = 0.1501 \cdot v + 66.391$; $R^2 = 0.2014$	$LA_{eq} = -0.0021 \cdot v^2 + 0.3910 \cdot v + 59.173$; $R^2 = 0.2052$	$LA_{eq} = 9.0855 \cdot \ln(v) + 38.305$; $R^2 = 0.2063$	$LA_{eq} = 66.812 \cdot e^{0.0020 \cdot v}$; $R^2 = 0.2070$
Light trucks	$LA_{eq} = 0.1610 \cdot v + 66.484$; $R^2 = 0.3564$	$LA_{eq} = -0.0038 \cdot v^2 + 0.7172 \cdot v + 46.464$; $R^2 = 0.3827$	$LA_{eq} = 11.8510 \cdot \ln(v) + 27.550$; $R^2 = 0.3676$	$LA_{eq} = 67.271 \cdot e^{0.0021 \cdot v}$; $R^2 = 0.3582$
Heavy trucks	$LA_{eq} = 0.1505 \cdot v + 70.530$; $R^2 = 0.3877$	$LA_{eq} = -0.0031 \cdot v^2 + 0.5996 \cdot v + 55.318$; $R^2 = 0.4296$	$LA_{eq} = 10.4510 \cdot \ln(v) + 36.821$; $R^2 = 0.4118$	$LA_{eq} = 71.042 \cdot e^{0.0019 \cdot v}$ $R^2 = 0.3932$

Table 3. Regression equations and coefficients for determination of the vehicles' noise level

Asphalt pavement conditions	Regression curves and their equations			
	Linear	Polynomial	Logarithmic	Exponential
Wet asphalt	$LA_{eq} = 0.1756 \cdot v + 64.660$; $R^2 = 0.5693$	$LA_{eq} = -0.0013 \cdot v^2 + 0.3935 \cdot v + 56.422$; $R^2 = 0.5962$	$LA_{eq} = 13.206 \cdot \ln(v) + 21.057$; $R^2 = 0.6093$	$LA_{eq} = 65.464 \cdot e^{0.0023 \cdot v}$; $R^2 = 0.5641$
Dry snow-covered asphalt	$LA_{eq} = 0.2356 \cdot v + 54.905$; $R^2 = 0.5733$	$LA_{eq} = -0.0007 \cdot v^2 + 0.3513 \cdot v + 50.866$; $R^2 = 0.5744$	$LA_{eq} = 16.353 \cdot \ln(v) + 2.0576$; $R^2 = 0.5725$	$LA_{eq} = 56.614 \cdot e^{0.0033 \cdot v}$; $R^2 = 0.5714$
Asphalt-covered with dry snow and snow ruts	$LA_{eq} = 0.1482 \cdot v + 63.461$; $R^2 = 0.5096$	$LA_{eq} = -0.0001 \cdot v^2 + 0.1702 \cdot v + 62.571$; $R^2 = 0.5098$	$LA_{eq} = 11.743 \cdot \ln(v) + 23.9800$; $R^2 = 0.5044$	$LA_{eq} = 64.355 \cdot e^{0.002 \cdot v}$; $R^2 = 0.5014$

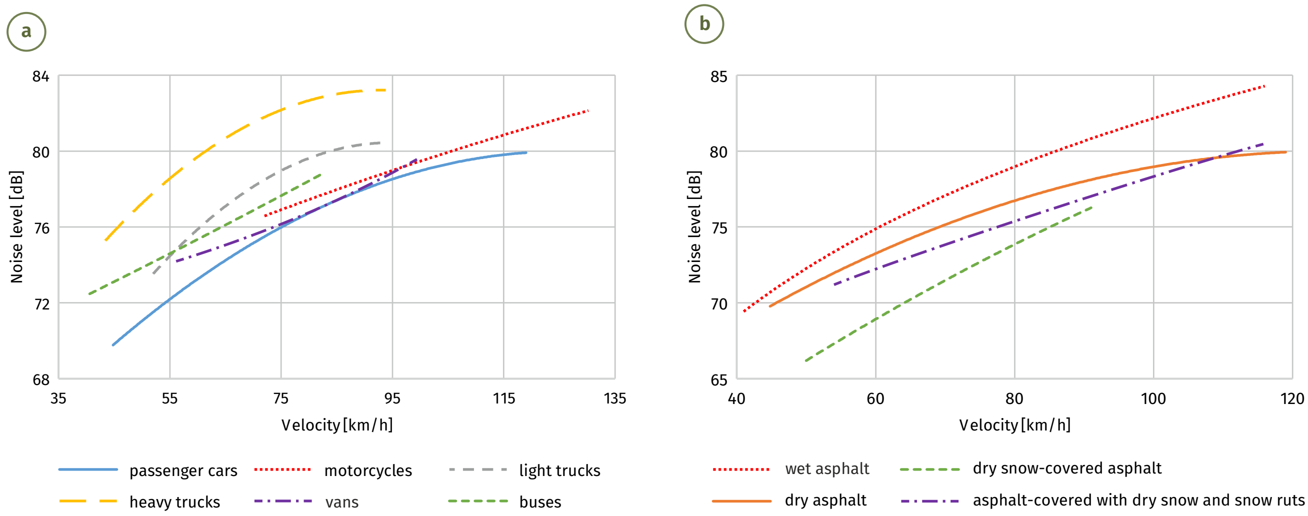

Figure 6. Generalized noise level dependence:
a) different vehicle categories on the dry asphalt; b) passenger cars driving on asphalt pavements of different states

The obtained results show that in comparison with passenger cars, other categories of vehicles (motorcycles, vans, buses, light and heavy trucks) are moderately noisier, with order of driving on wet road pavements compering to snow-covered and dry road surfaces. The results of research and the obtained correlation curves of noise levels will be used in the future traffic noise models and the noise mapping.

Conclusions

The main results of the current research include establishing the dependence of traffic noise levels of the different types of vehicles (motorcycles, passenger cars, vans, buses, light and heavy trucks) on the speed in urban areas and different road pavements (dry, wet, with a snow and snow ruts) and generalising of the obtained data for more accurate using in future traffic noise models and the noise mapping. The approach presented in this research of experimental measurements is based on SPB method with a data proceeding with implementation of Pearson correlation coefficient. The noise level measurements were performed for 10 times (in total 14 h) on different days and weather conditions, during which the air temperature varied (without wind) and in a total more than 900 vehicles were inspected under the measurement period.

According to the measurements, the noise level ranges for each group of vehicles and for different road condition pavements were established. The obtained results show that compared to passenger cars, other categories of vehicles are moderately noisier, with order of driving on a wet road pavements compering to snow-covered and dry road surfaces. In course of analyses of the obtained results, it was found that the curves corresponding to the best-measured values can be used in the traffic noise models and the noise mapping. The polynomial curve was found to correspond best to the values measured for motorcycles, passenger cars, vans, light and heavy trucks. The exponential curve corresponds to the best-measured values for buses. The logarithmic curve was found to correspond to the best-measured values for passenger cars driving on wet asphalt and for measurements on dry snow-covered pavement, additionally on asphalt-covered with dry snow and snow ruts the polynomial curve is correspond to the best-measured values. The correlation coefficient for the regression lines that shows the average relationship with the recorded data, is higher than the minimum value of the correlation coefficient, the regression curve correlates with the measured experimental data and can be accepted for a using in a simulation and obtaining traffic noise models and the noise mapping.

Disclosure statement

The authors have no conflicts of interest to declare that are relevant to the content of this article.

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References

Babisch, W.; Swart, W.; Houthuijs, D.; Selander, J.; Bluhm, G.; Pershagen, G.; Dimakopoulou, K.; Haralabidis, A. S.; Katsouyanni, K.; Davou, E.; Sourtzi, P.; Cadum, E.; Vigna-Taglianti, K.; Floud, S.; Hansell, A. L. 2012. Exposure modifiers of the relationships of transportation noise with high blood pressure and noise annoyance, *The Journal of the Acoustical Society of America* 132(6): 3788–3808. https://doi.org/10.1121/1.4764881

Bravo, T. 2017. An analytical study on the amplification of the tyre rolling noise due to the horn effect, *Applied Acoustics* 123: 85–92. https://doi.org/10.1016/j.apacoust.2017.03.009

Bunn, F.; Zannin, P. H. T. 2016. Assessment of railway noise in an urban setting, *Applied Acoustics* 104: 16–23. https://doi.org/10.1016/j.apacoust.2015.10.025

Buratti, C.; Belloni, E.; Moretti, E. 2014. Facade noise abatement prediction: new spectrum adaptation terms measured in field in different road and railway traffic conditions, *Applied Acoustics* 76: 238–248. https://doi.org/10.1016/j.apacoust.2013.08.016

Cai, M.; Lan, Z.; Zhang, Z.; Wang, H. 2019. Evaluation of road traffic noise exposure based on high-resolution population distribution and grid-level noise data, *Building and Environment* 147: 211–220. https://doi.org/10.1016/j.buildenv.2018.08.037

Cai, M.; Yao, Y., Wang, H. 2018. Urban traffic noise maps under 3D complex building environments on a supercomputer, *Journal of Advanced Transportation* 2018: 7031418. https://doi.org/10.1155/2018/7031418

Cai, M.; Yao, Y.; Wang, H. 2017a. A traffic-noise-map update method based on monitoring data, *The Journal of the Acoustical Society of America* 141(4): 2604–2610. https://doi.org/10.1121/1.4979808

Cai, M.; Zhong, S.; Wang, H.; Chen, Y.; Zeng, W. 2017b. Study of the traffic noise source intensity emission model and the frequency characteristics for a wet asphalt road, *Applied Acoustics* 123: 55–63. https://doi.org/10.1016/j.apacoust.2017.03.006

Can, A.; Leclercq, L.; Lelong, J.; Botteldooren, D. 2010. Traffic noise spectrum analysis: dynamic modeling vs. experimental observations, *Applied Acoustics* 71(8): 764–770. https://doi.org/10.1016/j.apacoust.2010.04.002

Coelho, J. B.; Vogiatzis, K.; Licitra, G. 2011. The CNOSSOS-EU initiative: a framework for road, railway, aircraft and industrial noise modelling for strategic noise mapping in EU Member States, in *18th International Congress on Sound and Vibration 2011* (*ICSV 18*), 10–14 July 2011, Rio de Janeiro, Brazil, 1: 789–795.

Cueto, J. L.; Petrovici, A. M.; Hernández, R.; Fernández, F. 2017. Analysis of the impact of bus signal priority on urban noise, *Acta Acustica United with Acustica* 103(4): 561–573.

Del Pizzo, L. G.; Teti, L.; Moro, A.; Bianco, F.; Fredianelli, L.; Licitra, G. 2020. Influence of texture on tyre road noise spectra in rubberized pavements, *Applied Acoustics* 159: 107080. https://doi.org/10.1016/j.apacoust.2019.107080

Deville, P.; Linard, C.; Martin, S.; Gilbert, M.; Stevens, F. R.; Gaughan, A. E.; Blondel, V. D.; Tatem, A. J. 2014. Dynamic population mapping using mobile phone data, *Proceedings of the National Academy of Sciences* (*PNAS*) 111(45): 15888–15893. https://doi.org/10.1073/pnas.1408439111

Di, H.; Liu, X.; Zhang, J.; Tong, Z.; Ji, M.; Li, F.; Feng, T.; Ma, Q. 2018. Estimation of the quality of an urban acoustic environment based on traffic noise evaluation models, *Applied Acoustics* 141: 115–124. https://doi.org/10.1016/j.apacoust.2018.07.010

EC. 2017. *Report from the Commission to the European Parliament and the Council on the Implementation of the Environmental Noise Directive in Accordance with Article 11 of Directive 2002/49/EC*. COM/2017/0151 final. European Commission (EC). Available from Internet: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52017DC0151

Gallo, P.; Fredianelli, L.; Palazzuoli, D.; Licitra, G.; Fidecaro, F. 2016. A procedure for the assessment of wind turbine noise, *Applied Acoustics* 114: 213–217. https://doi.org/10.1016/j.apacoust.2016.07.025

Gardziejczyk, W. 2014. Influence of road pavement macrotexture on tyre/road noise of vehicles, *The Baltic Journal of Road and Bridge Engineering* 9(3):180–190. https://doi.org/10.3846/bjrbe.2014.23

Huang, H. B.; Huang, X. R.; Li, R. X.; Lim, T. C.; Ding, W. P. 2016. Sound quality prediction of vehicle interior noise using deep belief networks, *Applied Acoustics* 113: 149–161. https://doi.org/10.1016/j.apacoust.2016.06.021

Hespanhol, L.; Vallio, C. S.; Costa, L. M.; Saragiotto, B. T. 2019. Understanding and interpreting confidence and credible intervals around effect estimates, *Brazilian Journal of Physical Therapy* 23(4): 290–301. https://doi.org/10.1016/j.bjpt.2018.12.006

Iglesias-Merchan, C.; Diaz-Balteiro, L.; Soliño, M. 2015. Transportation planning and quiet natural areas preservation: aircraft overflights noise assessment in a National Park, *Transportation Research Part D: Transport and Environment* 41: 1–12. https://doi.org/10.1016/j.trd.2015.09.006

Ihemeje, J.; Onyelowe, K. C. 2021. State-of-the-art review on the assessment and modelling of traffic noise intensity on roadside dwellers: the Port Harcourt, Nigeria case, *Cleaner Engineering and Technology* 5: 100328. https://doi.org/10.1016/j.clet.2021.100328

ISO 717-1:2020. *Acoustics – Rating of Sound Insulation in Buildings and of Building Elements – Part 1: Airborne Sound Insulation*.

ISO 10844:2021. *Acoustics – Specification of Test Tracks for Measuring Sound Emitted by Road Vehicles and Their Tyres*.

ISO 11819-1:2023. *Acoustics – Measurement of the Influence of Road Surfaces on Traffic Noise – Part 1: Statistical Pass-by Method*.

Jung, W.; Elliott, S. J.; Cheer, J. 2019. Local active control of road noise inside a vehicle, *Mechanical Systems and Signal Processing* 121: 144–157. https://doi.org/10.1016/j.ymssp.2018.11.003

Kephalopoulos, S.; Paviotti, M.; Anfosso-Lédée, F.; Van Maercke, D.; Shilton, S.; Jones, N. 2014. Advances in the development of common noise assessment methods in Europe: the CNOSSOS-EU framework for strategic environmental noise mapping, *Science of the Total Environment* 482–483: 400–410. https://doi.org/10.1016/j.scitotenv.2014.02.031

Kim, Y.-D.; Jeong, J.-E.; Park, J.-S.; Yang, I.-H.; Park, T.-S.; Muhamad, P. B.; Choi, D.-H.; Oh, J.-E. 2013. Optimization of the lower arm of a vehicle suspension system for road noise reduction by sensitivity analysis, *Mechanism and Machine Theory* 69: 278–302. https://doi.org/10.1016/j.mechmachtheory.2013.06.010

Kleizienė, R.; Šernas, O.; Vaitkus, A.; Simanavičienė, R. 2019. Asphalt pavement acoustic performance model, *Sustainability* 11(10): 2938. https://doi.org/10.3390/su11102938

Ko, J. H.; Chang, S. I.; Kim, M.; Holt, J. B.; Seong, J. C. 2011. Transportation noise and exposed population of an urban area in the Republic of Korea, *Environment International* 37(2): 328–334. https://doi.org/10.1016/j.envint.2010.10.001

Kudźma, Z.; Stosiak, M. 2013. Reduction of infrasounds in machines with hydrostatic drive, *Acta of Bioengineering and Biomechanics* 15(2): 51–64. https://doi.org/10.5277/abb130206

Lercher, P.; Evans, G. W.; Meis, M. 2003. Ambient noise and cognitive processes among primary schoolchildren, *Environment and Behavior* 35(6): 725–735. https://doi.org/10.1177/0013916503256260

Li, Z. 2018. Spectral comparison of pass-by traffic noise, in *ASME 2018 Noise Control and Acoustics Division Session presented at INTERNOISE 2018*, 26–29 August 2018, Chicago, IL, US, 1–8. https://doi.org/10.1115/NCAD2018-6149

Licitra, G.; Ascari, E.; Brambilla, G. 2012. Comparative analysis of methods to estimate urban noise exposure of inhabitants, *Acta Acustica United with Acustica* 98(4): 659–666.

Licitra, G.; Ascari, E.; Fredianelli, L. 2017. Prioritizing process in action plans: a review of approaches, *Current Pollution Reports* 3(2): 151–161. https://doi.org/10.1007/s40726-017-0057-5

Masovic, M.; Mijic, M.; Sumarac Pavlovic, D. 2013. Comparison between the spectrum shape of traffic noise in Belgrade and the ISO 717-1 reference spectrum, *Proceedings of the InterNoise 2013*, 15–18 September 2013, Innsbruck, Austria, 2370–2375.

Menge, C. W.; Rossano, C. F.; Anderson, G. S.; Bajdek, C. J. 1998. *FHWA Traffic Noise Model, Version 1.0. Technical Manual*. Report No FHWA-PD-96-010, DOT-VNTSC-FHWA-98-2. US Department of Transportation, Federal Highway Administration (FHWA), Washington, DC, US. 186 p. Available from Internet: https://rosap.ntl.bts.gov/view/dot/10000

Mesihovic, M.; Rindel, J. H.; Milford, I. 2016. The need for updated traffic noise spectra, used for calculation of sound insulation of windows and facades, in *Proceedings of the InterNoise 2016*, 21–24 August 2016, Hamburg, Germany, 3890–3897.

Miedema, H. M.; Oudshoorn, C. G. 2001. Annoyance from transportation noise: relationships with exposure metrics DNL and DENL and their confidence intervals, *Environmental Health Perspectives* 109(4): 409–416.
https://doi.org/10.1289/ehp.01109409

Mukaka, M. M. 2012. Statistics corner: a guide to appropriate use of correlation coefficient in medical research, *Malawi Medical Journal* 24(3): 69–71.

Murphy, E.; King, E. A. 2011. Scenario analysis and noise action planning: modelling the impact of mitigation measures on population exposure, *Applied Acoustics* 72(8): 487–494.
https://doi.org/10.1016/j.apacoust.2010.10.006

Muzet, A. 2007. Environmental noise, sleep and health, *Sleep Medicine Reviews* 11(2): 135–142
https://doi.org/10.1016/j.smrv.2006.09.001

Pathak, V.; Tripathi, B. D.; Mishra, V. K. 2008. Evaluation of traffic noise pollution and attitudes of exposed individuals in working place, *Atmospheric Environment* 42(16): 3892–3898.
https://doi.org/10.1016/j.atmosenv.2007.12.070

Paviotti, M.; Vogiatzis, K. 2012. On the outdoor annoyance from scooter and motorbike noise in the urban environment, *Science of the Total Environment* 430: 223–230.
https://doi.org/10.1016/j.scitotenv.2012.05.010

Phan, H. Y. T.; Yano, T.; Sato, T.; Nishimura, T. 2010. Characteristics of road traffic noise in Hanoi and Ho Chi Minh City, Vietnam, *Applied Acoustics* 71(5): 479–485.
https://doi.org/10.1016/j.apacoust.2009.11.008

Podvezko, V.; Sivilevičius, H. 2013. The use of AHP and rank correlation methods for determining the significance of the interaction between the elements of a transport system having a strong influence on traffic safety, *Transport* 28(4): 389–403.
https://doi.org/10.3846/16484142.2013.866980

Rey-Gozalo, G.; Gómez Escobar, V.; Morillas, J. M. B.; Montes González, D.; Moraga, P. A. 2019. Statistical attribution of errors in urban noise modeling, *Applied Acoustics* 153: 20–29.
https://doi.org/10.1016/j.apacoust.2019.04.001

Stosiak, M. 2015. Ways of reducing the impact of mechanical vibrations on hydraulic valves, *Archives of Civil and Mechanical Engineering* 15(2): 392–400.
https://doi.org/10.1016/j.acme.2014.06.003

Tong, Y.; Jiang, Y.; Zhou, Z.; Ma, D. 2014. The monitoring and prevention of traffic noise in urban road, *Advanced Materials Research* 933: 1008–1013.
https://doi.org/10.4028/www.scientific.net/AMR.933.1008

Torija, A. J.; Ruiz, D. P.; De Coensel, B.; Botteldooren, D.; Berglund, B.; Ramos-Ridao, Á. 2011. Relationship between road and railway noise annoyance and overall indoor sound exposure, *Transportation Research Part D: Transport and Environment* 16(1): 15–22. https://doi.org/10.1016/j.trd.2010.07.012

Vogiatzis, K. 2011. Strategic environmental noise mapping & action plans in Athens ring road (Atiiki Odos) – Greece, *WSEAS Transactions on Environment and Development* 7(10): 315–324. Available from Internet: http://www.wseas.us/e-library/transactions/environment/2011/54-290.pdf

Vogiatzis, K.; Remy, N. 2014. Strategic noise mapping of Herakleion: the aircraft noise impact as a factor of the int. airport relocation, *Noise Mapping* 1(1): 15–31.
https://doi.org/10.2478/noise-2014-0003

Wang, H.; Chen, H.; Cai, M. 2018. Evaluation of an urban traffic noise–exposed population based on points of interest and noise maps: the case of Guangzhou, *Environmental Pollution* 239: 741–750. https://doi.org/10.1016/j.envpol.2017.11.036

Wang, Y.; Wie, J.-S.; Zhang, S.-B.; Zhang, P.; Li, X.-T.; Liu, Y.-H. 2013. Study on the noise spectrum emitted by constant-velocity small passenger vehicles, *Environmental Monitoring in China* (5): 173–175. (in Chinese).

Yang, W.; Cai, M.; Luo, P. 2020. The calculation of road traffic noise spectrum based on the noise spectral characteristics of single vehicles, *Applied Acoustics* 160: 107128.
https://doi.org/10.1016/j.apacoust.2019.107128

Zambon, G.; Roman, H. E.; Benocci, R. 2017. Vehicle speed recognition from noise spectral patterns, *International Journal of Environmental Research* 11(4): 449–459.
https://doi.org/10.1007/s41742-017-0040-4