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Research Paper

A Scalar Measure of Acoustic Hazard Assessment

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The article addresses the problem of assessing the impact of road modernization on improving the acoustic environment. It formulates a hypothesis about the advisability of adopting the scalar dimension of the decibel space to describe acoustic hazards. It is proposed to reduce the analysis of changes in sound levels to the analysis of changes in the coefficient of exceedance of the recommended noise levels. Its value is determined by the decibel relation of dividing sound levels. The basis for the assessment of the effectiveness of the adopted solution was the analysis of the statistical characteristics of monitored exceedances of recommended noise levels, considered through the prism of the current and proposed measure. They showed greater sensitivity of the proposed coefficient in the assessment of the improvement of the acoustic climate caused by road modernization. For example, the median noise level for nights before the road modernization was 66.9 dB(A), and after the modernization 65.6 dB(A). However, the coefficient of exceedances decreased by approximately 25 %. Numerical simulations, in accordance with the Cnossos noise model, showed that reducing the speed by 10 km/h will reduce the coefficient of exceedances by approximately 20 %.

Keywords: traffic noise; noise hazard; coefficient of exceedances; Cnossos noise model.

1. Introduction

The results obtained from measurements of acoustic parameters expressed on the decibel scale, the algebra of their transformations, and the comparison metric should correctly identify the phenomena under study. However, the noise hazard indicators used today – expressed as the Euclidean measure of the difference between the measurement result and the adopted standard values on the decibel scale – do not adequately reflect their perception by humans (Weidenfeld *et al.*, 2021; Verbeek, 2018; Wunderli *et al.*, 2016; Khan, Burdzik, 2023). These indicators may be difficult to understand for the majority of society and may make it difficult to comprehensively assess the harmfulness of noise. Furthermore, the use of the Euclidean evaluation measure also makes it difficult to interpret the obtained results (Batko *et al.*, 2023; Przysucha *et al.*, 2021; Peters, 2020; Sahu *et al.*, 2021).

Therefore, it is advisable to search for a transformation that reduces the process of identifying acoustic hazards and assessing the acoustic effectiveness of completed road modernizations from the Euclidean space of comparisons of measurement results expressed in the decibel scale to a scalar space. Adopting this concept of solving the problem enables to assess the state of acoustic hazard using classic identification algorithms. The solution sought should also meet the inverse condition, allowing the obtained scalar results to be reduced to the decibel space. This calculation method requires the determination of a new measure of exceedance of the recommended noise indicator values, as well as the development of a new algorithm for controlling acoustic hazard to the environment (Sánchez-Fernández, 2021).

The adopted scalar indicator, integrated with traditional descriptors that are mandatory under regulations, could provide additional information, simplify and reduce the costs of assessing the acoustic quality of the environment, thereby increasing general awareness of the harmful effects of noise (Graziuso *et al.*, 2022; Wunderli *et al.*, 2016). Some attempts to address this problem were made in the work (Sahu *et al.*, 2021), where it was proposed to use a parameter called "noise exposure index" as an alternative measure for assessing acoustic hazards. Similarily, Moroe and Mabaso (2022) proposed to use a pollution modeling technique and a parameter known as the "pollution standard index". This approach takes into account the values of individual noise parameters, which are then compared to a single quality standard number. In (Smiraglia *et al.*, 2016) normalization was used, consisting of Euclidean division of the recorded hourly noise values by the maximum value. In a similar way, Yang *et al.* (2020) and Upadhyay *et al.* (2023) calculated the share of sound energy in each frequency band as a percentage of the total acoustic energy emitted by the tested vehicle. The advantage of these models is that the result is a dimensionless number. However, a weakness of these proposed solutions is the incompatibility of the transformations used with the formalism of decibel algebra.

In this article, the authors aimed to assess noise hazards and the acoustic effectiveness of implemented road modernizations by adopting a measure of exceedance of recommended sound levels in accordance with the decibel algebra relations. They propose to correlate this measure with the relation of references of two sound levels to each other, which is one of the basic relations in decibel algebra. The functional properties of such a solution were verified using an example of assessing acoustic hazards on one of the main communication road of the city of Kielce. This assessment was based on the results of continuous noise monitoring in the vicinity of the analyzed road after its modernization. The functional properties of both acoustic hazard estimation solutions were assessed, comparing the classic Euclidean approach to exceedance comparisons of recommended values with the approach proposed by the authors.

2. Scalar dimension of decibel numbers

The idea of the solution proposed by the authors is to replace the analysis of the values of acoustic parameters expressed on the decibel scale with the analysis of a coefficient (marked as k_i) representing their multiplicity of exceedance relative to reference noise levels values (L_{ref}). This operation can be performed in accordance with the division operation, present in decibel algebra, applied to acoustic disturbances described by sound levels L_i, $i = 0, 1, 2, ..., n$, and L_{ref}:

$$k_i = \frac{10^{0.1L_i}}{10^{0.1L_{\text{ref}}}} = 10^{0.1(L_i - L_{\text{ref}})}, \tag{1}$$

where L_i – the designated noise level, L_{ref} – the reference noise level value, for example, according to the World Health Organization [WHO] (2018): 53 dB for the day or 45 dB for the night. The result obtained in such an operation is a scalar and dimensionless quantity. This means that it is possible to perform further operations on the obtained result, in a manner typical of operations performed on Euclidean numbers. The inverse transformation from the space of scalar numbers to the space of numbers expressed in decibels is determined by multiplying the sound level by the designated scalar k_i. We can transform Eq. (1) as follows:

$$L_i = L_{\text{ref}} + 10\log(k_i). \tag{2}$$

The average value of the sound level can be determined from the relationship:

$$\overline{L} = L_{\text{ref}} + 10\log\overline{k}, \tag{3}$$

where $\overline{k}$ is the average value of exceedances of the reference noise level, e.g., $\overline{k} = \frac{1}{n}\sum_{1}^{n} k_i$ or the median. The average value of exceeding the reference noise level on the decibel scale can be determined from the relationship:

$$\overline{\Delta L} = \overline{L} - L_{\text{ref}} = 10\log\overline{k}. \tag{4}$$

After performing simple transformations, we can determine other parameters, e.g.:

– deviation from the reference value:

$$\sigma_L = \sqrt{\frac{1}{N-1}\sum_{i=1}^{i=N}(10\log k_i)^2}; \tag{5}$$

– positional coefficient of variation:

$$V_{Q_{31}} = \frac{Q_{31}}{\text{Med}} \cdot 100\,\%, \tag{6}$$

where $Q_{31} = 0.5 \cdot [Q_3 - Q_1]$, Q_1, Q_2, and Q_3 – quartiles, corresponding to the first, second, and third quartiles, respectively, and Med – the median of the equivalent sound level;

– dispersion coefficient of quarter deviation:

$$V_{Q_1Q_3} = \frac{Q_3 - Q_1}{Q_1 + Q_3} \cdot 100\,\%. \tag{7}$$

Equation (3), based on the analysis of the variability of the k_i coefficient value, provides conditions for estimating noise hazard assessment. For this reason, the authors decided to use the parameter k_i defined by Eq. (1) to assess the noise of road transport. This parameter is also used to assess the occupational risk of the harmful impact of vibroacoustic disturbances on employees' health (Pleban *et al.*, 2021; Seixas *et al.*, 2005; Roberts *et al.*, 2018). The analysis of the k_i coefficient facilitates the comparison of constant components (expected value or median) and variables of the analyzed signals. The research on the components of the variables contained in the analyzed signals was based, among others, on the analysis of positional coefficients: deviation from the normative value, the coefficient of variation of the quarter deviation (denoted as $V_{Q_{31}}$), and the dispersion coefficient of the quarter deviation (marked as $V_{Q_1Q_3}$).

3. Monitoring of traffic noise hazards

The basis for verification analyzes of the suitability of the proposed noise assessment procedure was data recorded by an automatic station for continuous noise and traffic monitoring located at Popiełuszko Avenue in Kielce. Popiełuszki Avenue consists of four lanes separated by a green belt approximately 3 m wide. This avenue is a section of national road no. 73 and serves as the main the exit route from the center of Kielce towards Tarnów. This avenue is used for transit, urban and suburban traffic. The monitoring station includes a road radar, a sound level meter, and a weather station. Traffic flow was measured with the Wavetronix digital radar. Measurements were carried out 24 hours a day from 2011 to 2016. Traffic volume and speed data were recorded every minute (buffered) and the averaged results were reported every hour. However, due to various technical problems, the monitoring station did not always correctly record traffic parameters, and thereby the database was incomplete.

Based on the counts, traffic volume (understood as the sum of the number of light motor vehicles, medium heavy vehicles, heavy vehicles, and powered two-wheelers registered during the specified time period on all four lanes) and speed were calculated, divided into seven days of the week, hours and three sub-periods of the day. Because no data was recorded for some days, only days for which traffic parameters were recorded hourly throughout the entire 24-hour period were included in the analysis. Acoustic measurements were carried out with the SVAN 958A device, which is a four-channel, digital vibration and sound level meter of class 1. A condenser microphone from Microtech Gefell MK 250, prepolarized 1/2″, class 1, with a sensitivity of 50 mV/Pa and an SV 12L preamplifier, was used. Detailed information about the measurement station is presented in the paper (Bąkowski, Radziszewski, 2022). Calculations of the equivalent sound level were performed for three time sub-periods, i.e., day – from 6 a.m. to 6 p.m., evening – from 6 p.m. to 10 p.m., and night – from 10 p.m. to 6 a.m.

The study analyzed the results of acoustic measurements carried out in the period from March 25, 2016 to June 25, 2016. It should be noted that in 2013–2014 Popiełuszki Avenue was thoroughly modernized. In 2016, there was a 13.1 %. increase in traffic volume compared to 2011 for all vehicle types. The analysis of the distribution of individual vehicle groups in the traffic structure in 2016 showed that the predominant group are light motor vehicles, whose share in the traffic flow increased to 71 % and on Sundays to 84 %. The next group were medium heavy vehicles, for which the share in the analyzed period did not change significantly and amounted to 18 % and on Sundays 11 %. The share of heavy vehicles was 8 % and on Sundays 2 %. Furthermore, the speed below which 85 % of vehicles on lanes 2 and 3 traveled was 85 km/h in 2011 and 81 km/h in 2016. In turn, the speed of vehicles in the analyzed period on lanes 1 and 4 was approximately 72 km/h (Bąkowski, Radziszewski, 2022).

Road noise in urbanized areas can be analyzed based on adopted parameters, time intervals and road location within the communication system (Lu *et al.*, 2019; Jandacka *et al.*, 2022; Meller *et al.*, 2023). Within one year or one week, the variability of road noise is significantly different from the variability on weekdays or weekends and holidays (Bąkowski, Radziszewski, 2022). The problem of traffic noise on weekends is much less frequently analyzed in the literature, which is mainly due to lower traffic flow, especially heavy vehicles. However, as the authors' research has shown, when traffic volume decreases, vehicle speed increases and, as a result, the sound pressure level does not change significantly, especially when the equivalent sound level on the decibel scale is used as a measure (Bąkowski, Radziszewski, 2023). For this reason, the authors decided to conduct a noise analysis on Fridays, when traffic volume is highest, and on Sundays, when it is lowest. The analyzes were carried out for the night time sub-period because, as noise during this time is most annoying to residents (European Environment Agency, 2020).

Figure 1 shows the results of the equivalent sound level (marked L_{Ni}) and the k_i coefficient calculated for subsequent nights, i.e., in the time interval from 10 p.m. to 6 a.m. in 2016.

The values of the L_{Ni} parameter range from approximately 64 dB(A) to 68 dB(A) and from approximately 62 dB(A) to 64 dB(A) on Sundays. The values of selected L_{Ni} parameters in 2016, two years after the completion of the road modernization, are presented in Table 1. The median L_{Ni} in 2016 was 65.6 dB(A) and 66.9 dB(A) in 2011. However, the maximum value of L_{Ni} in 2016 was 68 dB(A), whereas it was 69.7 dB(A) in 2011. The high variability in noise levels may cause much greater nuisance to local residents than suggested by the median value alone. The type A uncertainty of noise measurements u_A determined in accordance with the ISO standard (International Organization for Standardization, 2016) is less than 0.2 dB(A). The presented data on the decibel scale suggests that despite the road modernization, the noise level values have only changed slightly.

The analysis of acoustic hazards using the k_i parameter indicates more suggestively than the decibel

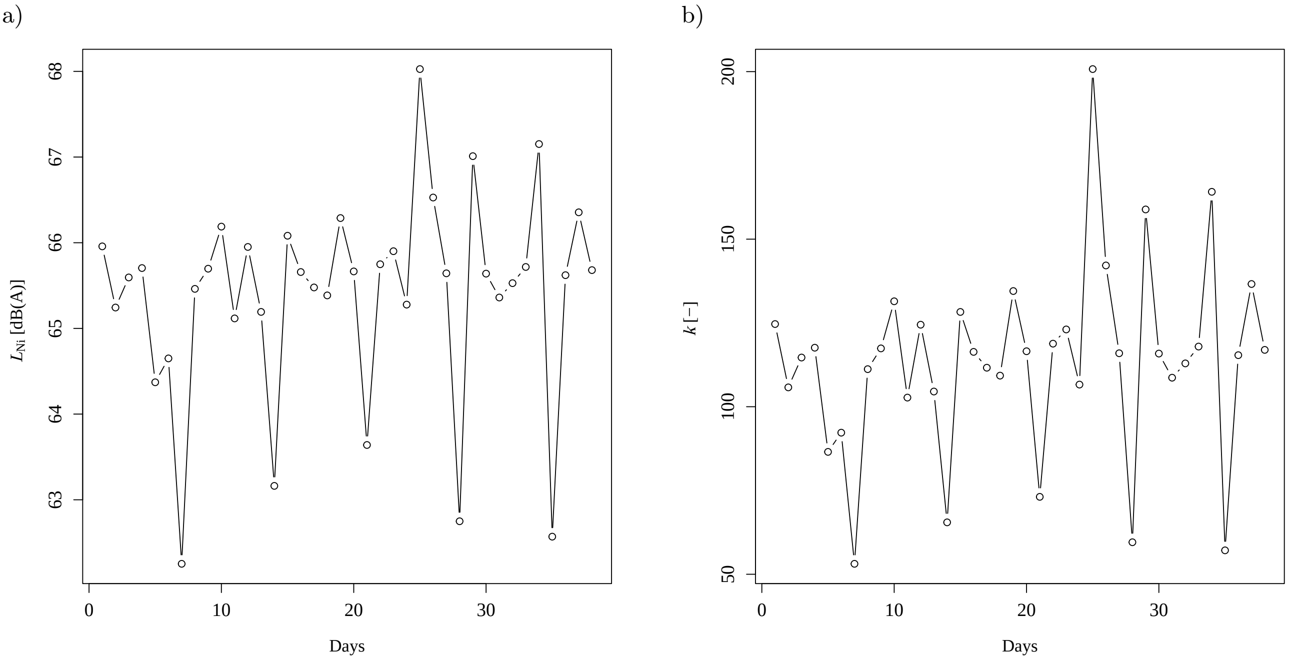

Fig. 1. Noise parameters experimentally determined for individual nights: a) equivalent sound level L_{Ni} values on the decibel scale; b) coefficient k_i of multiplicity of exceedance of the recommended noise levels by WHO (45 dB) noise levels.

Table 1. Road noise statistics on the decibel scale and coefficient k_i of noise level 45 dB recommended by WHO, two years after road modernization.

	L_{eq}	Q_2	$\bar{k}$	σ	Q_3	L_i [max]	k_i [max]	u_A	$V_{Q_{31}}$ [%]	$V_{Q_1Q_3}$ [%]
L_N [dB(A)]	65.5	65.6	–	1.2	65.9	68.0	–	0.19	7.9	7.9
k_N $L_0 = 45$ [dB]	–	116	114	29	124	–	201	4.6	7.9	7.9

$L_{\mathrm{eq}} = 10\log\left(\frac{1}{N}\sum_{i=1}^{i=N} 10^{0.1L_i}\right)$ – logarithmic mean; $\sigma_{L_{\mathrm{eq}}} = \sqrt{\frac{1}{N-1}\sum_{i=1}^{i=N}(L_i - L_{\mathrm{eq}})^2}$ – standard deviation;

$\sigma_k = \sqrt{\frac{1}{N-1}\sum_{i=1}^{i=N}\left(k_i - \bar{k}\right)^2}$ – standard deviation; $u_A = \sqrt{\frac{1}{n(n-1)}\sum_{i=1}^{n}(L_i - L_{\mathrm{eq}})^2}$– uncertainty;

$k_i = 10^{0.1(L_{\mathrm{Ni}}-45)}$ – multiplicity of the sound level recommended by WHO for the day–night time;

L_N – noise level for the sub-period of day–night, on subsequent days.

scale the dangers resulting from exceedance of the recommended road noise levels (see Table 1) and the acoustic effects of road modernization (Pleban *et al.*, 2021). The arithmetic mean of this parameter is 114, which means that the noise energy emission is 114 times higher than recommended by WHO. Even on Sundays, the k_i value ranges from about 50 to 70, as shown in Fig. 1b.

The analysis of the value of the coefficient k_i after the completion of the road modernization also indicates a reduction in the nuisance of acoustic disturbances. The type A uncertainty of determining k_i is about 5. The arithmetic mean of the k_i parameter decreased after the road modernization by about 24 %. However, the maximum value of k_i decreased by approximately 31 %. It can be seen that the values of the relative variability coefficients L_{Ni} and k_i are equal regardless of the calculation method. This confirms the correctness of the applied calculation procedures for these coefficients. The values of noise variability coefficients were reduced by approximately 54 %, which confirms that vehicle traffic has calmed down to some extent. This contributes to increasing the safety of road users.

The values of noise parameters averaged over the year for individual nights are used in the development of static noise maps and indicate the possibility of health problems among local residents (WHO, 2018; Sramek *et al.*, 2022; Ranpise, Tandel, 2022). Additional information about the risk of acoustic hazards can be obtained by analyzing the values of noise parameters averaged over the year, on different days of the week, and during subsequent hours of the day. Such information may facilitate taking administrative actions aimed at reducing noise nuisance, e.g., limiting speed and movement of certain groups of vehicles at

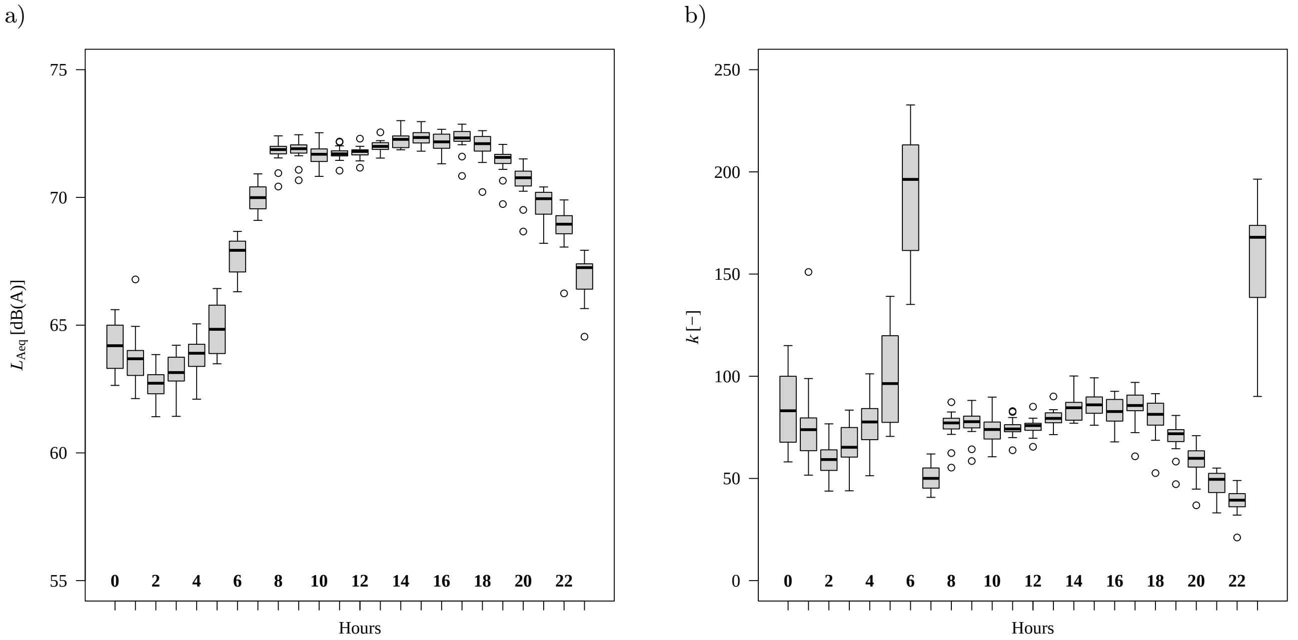

Fig. 2. Box plot of traffic noise on Fridays: a) noise level on the decibel scale in subsequent hours of the day; b) coefficients of exceedance of the noise level recommended by WHO.

certain hours of the day. Figure 2a shows the box plot of the noise level, and Fig. 2b shows the exceedance rates in subsequent hours on Fridays. Comparing both of these drawings, it can be seen that the scalar scale has a higher resolution, which facilitates the analysis of changes and the identification of extreme noise values. Figure 2b shows that exceedances of permissible noise levels in the morning and late at night are the highest for the entire 24-hour period.

A sudden change in the k_i value can be seen in Fig. 2b at 6 a.m. and 11 p.m. It results from the change in the L_{ref} value from 45 dB for the night sub-period to 53 dB for the day sub-period (WHO, 2018). The noise level on Sundays increases gradually from 6 a.m. to its maximum value at 3 p.m., and then gradually decreases, as shown in Fig. 3a. In the case of Sundays, it can be seen in Fig. 3b that the maximum value of the k_i coefficient occurs at 11 p.m.

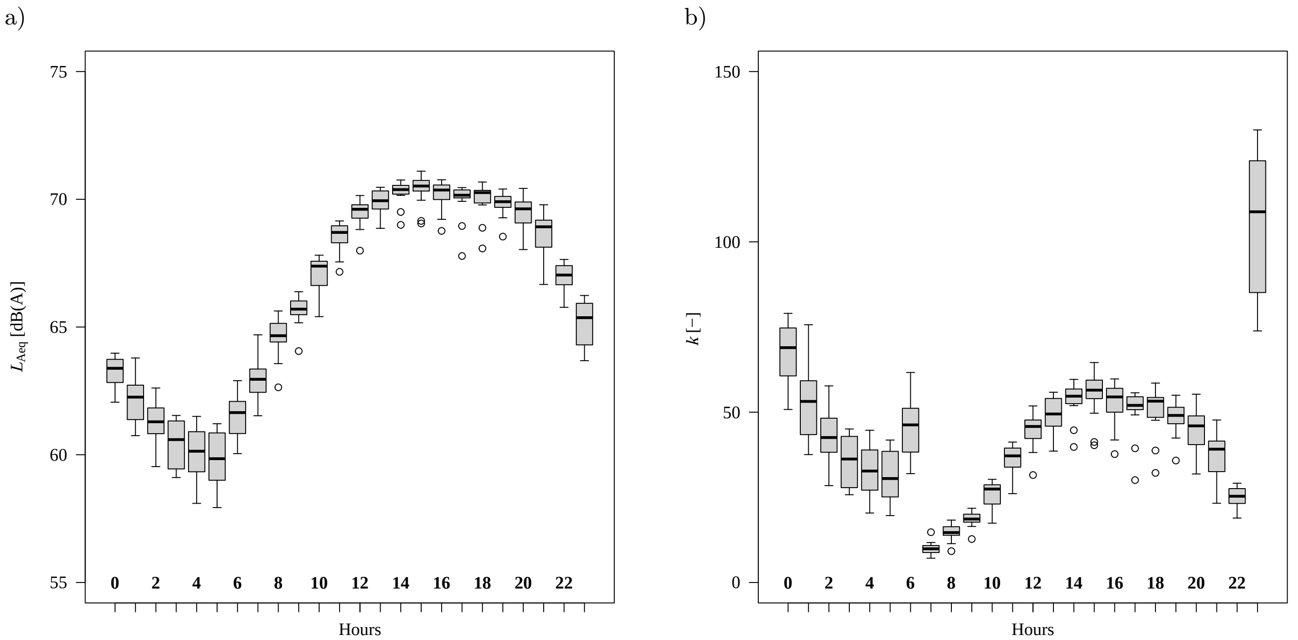

Fig. 3. Box plot of traffic noise on Sundays: a) noise level on the decibel scale in subsequent hours of the day; b) coefficients of exceedance of the noise level recommended by WHO.

The analyses conducted revealed that road modernization contributed to the reduction of acoustic hazards, but this reduction is still not satisfactory. For this reason, in this study, the authors decided to conduct numerical simulations consistent with the Cnossos noise model to assess the impact of selected administrative restrictions on noise parameters. Simulations were performed to evaluate the effects of introducing a ban on heavy vehicles traffic at night on Fridays and Sundays. The calculations indicated that the lack of heavy vehicles would result in a decrease in the value of the k_i coefficient, e.g., on Fridays at 6 a.m. from approximately 196 to 106, which corresponds to a change in the sound level from 68 dB(A) to 65.25 dB(A). However, on Sundays, e.g., at 6 a.m., this ban would result in a decrease in the value of the k_i coefficient from approximately 46 to 38, which corresponds to a change in the sound level from 61.65 dB(A) to 60.80 dB(A). Simulations were also carried out on the impact of reducing the speed of each vehicle by 10 km/h and 20 km/h on noise, e.g., at 6 a.m. in the vicinity of the monitoring station. The calculations showed that the speed decreased:

a) a reduction of 10 km/h on Fridays led to a decrease in the value of the k_i coefficient from approximately 196 to 158, which corresponds to a reduction in the noise level from 68 dB(A) to 67 dB(A);
b) a reduction of 20 km/h on Fridays resulted in a decrease in the value of the k_i coefficient from approximately 196 to 128, which corresponds to a reduction in the noise level from 68 dB(A) to 66 dB(A);
c) on Sundays, a reduction of 10 km/h caused a decrease in the value of the k_i coefficient, e.g., from approximately 46 to 37, which corresponds to a reduction in the noise level from 62 dB(A) to 61 dB(A);
d) on Sundays, a reduction of 20 km/h led to a decrease in the value of the k_i coefficient from approximately 46 to 29, which corresponds to a reduction in the noise level from 62 dB(A) to 60 dB(A). The results obtained from these simulations indicate that even a slight reduction in the speed of each vehicle results in satisfactory noise reduction effects.

4. Summary and conclusions

The article discusses the problem of the correctness of the applied rules for assessing the state of acoustic hazards to the environment, expressed on the decibel scale, based on the Euclidean measure for assessing exceedances of normative values. It emphasizes the need to modify algorithms for assessing acoustic hazards, taking into account the appropriate metric for their comparison. The study proposes an original solution for controlling acoustic hazards based on the number of times the recomended values are exceeded. The solution used eliminates methodological and metrological paradoxes of currently used procedures based on the Euclidean measure of exceedance of recomended values. The proposed procedure allows for:

- transformation of the analysis of decibel-based noise hazard assessments into scalar number calculations within the Euclidean space;
- simulations and identification of noise hazards using standard calculation packages, including classic uncertainty estimation procedures regarding exceedances of permissible noise levels.

The article presents the results of the analysis of the proposed solution and the assessment of its usefulness, based on the example of diagnosing the state of noise hazards in the vicinity of one of the main streets of the city of Kielce. Its use enabled an objective assessment of the acoustic effects of a comprehensive road modernization. As research into acoustic hazards in its surroundings has shown, there has been some reduction in the noise level. The analyzes were performed using noise measures on the decibel scale and the proposed scalar measure of the multiplicity of exceeding the recommended sound level. The reduction in noise levels assessed according to the first measure suggests slight changes in the emission of acoustic hazards. For example, the median L_{Ni} before the road modernization was 66.9 dB(A) and after the modernization 65.6 dB(A). The assessment of the impact of road modernization on traffic noise according to the proposed method, i.e., assessing the value of the coefficient k_i of multiplicity of exceedances of recomended noise level, showed a decrease of approximately 25 % for the night sub-period. The maximum values of coefficient k_i after road modernization decreased by 32 %. Analyses of the coefficients of variation of noise level showed a decrease in their values after road modernization by approximately 40 %, regardless of the scale used. The time of calculating the values of the analyzed parameters (for example $V_{Q_1Q_3}$) based on coefficient k_i is approximately 20 % shorter than when using the decibel scale. The results of the conducted numerical simulations justify the advisability of introducing road signs with variable content to enforce certain limits on the values of vehicle traffic parameters at certain hours of the day.

Overall, the proposed procedure for assessing acoustic hazards to the environment takes into account the premises that support the need to revise the solutions currently used in the practice of environmental control. This procedure may offer a response to the need of implementing new methods for diagnosing acoustic hazards generated by road transport.

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Additional information

The authors declare that there are no competing financial interests and that all material taken from other sources (including their own published works) is clearly cited, and that appropriate permits were obtained.

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