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Assessment of changes in environmental pollution by road noise using a scalar measure

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Abstract: The article addresses the issue of assessing the impact of road rebuilding on traffic noise pollution. To assess noise hazards, parameters expressed on the decibel scale were used, and a new measure was proposed - a scalar reference that compares the sound level value to the recommended threshold. This measure is based on Weber Fechner's law, which relates to human perception of changes in sound levels. It was derived through the decibel algebra applied to measurement results and is called the "coefficient of exceedance of the recommended sound level". Its usefulness was verified by analyzing the results of measurements of traffic and noise parameters before and two years after the reconstruction of a section of the national road in Kielce. An assessment was made of traffic volume, vehicle speed, and road vehicle noise. The analysis evaluated the absolute values, variability and uncertainty of results obtained for the entire year, Fridays and Sundays. Significant differences in traffic parameter values were observed between the lanes entering and leaving the city on weekdays and weekends. The analysis showed a 28% increase in traffic volume following the road reconstruction. The current measure, which compares the difference in noise levels before and after the road reconstruction, indicates that while noise levels have decreased, they still exceed the normative values. For the same parameters, the median coefficient of exceedance decreased by approximately 17%, and the maximum coefficient of exceedance decreased by approximately 15%. The diagnostic usefulness of the coefficient of exceedance was further assessed using noise simulations based on the Cnossos-EU model. These simulations showed the high sensitivity of the proposed scalar noise measure to changes in vehicle speed and traffic volume. The simulations also indicated that to meet the Polish noise normative values, traffic volume would need to reduced by 50%, and the vehicle speed would need to be capped at 50 km/h. Additionally, the simulations suggested that even more stringent traffic restrictions would be necessary to meet the World Health Organization's noise recommendations.

Introduction

Research on the impact of transport-related nuisances on both people and the environment is widely discussed in numerous publications worldwide. Issues such as air pollution, noise, vibration, and other environmental hazards, such as road accidents, are primarily influenced by traffic parameters. Therefore, the foundation of any research in this area is the measurement and analysis of data obtained through road traffic monitoring systems [1-3]. These systems can be classified into invasive technologies, such as induction loop detectors, magnetic sensors, and weigh-in-motion systems, and non-invasive technologies, such as microwave systems, cameras, and GPS-based systems.

An analysis of traffic intensity distribution showed that, in cases of uninterrupted traffic flows (e.g., on highways), the distribution often follows a normal pattern. However, in urban areas with intermittent traffic flows, this distribution usually deviates from normal [4-5]. Traffic in urban areas is characterized by high variability, which significantly complicates management, such as estimating vehicle travel times. The variability of traffic parameters can be analyzed depending on the chosen time interval and the location of the road within the urban communication system [6]. Many studies have examined the influence of predetermined parameters on changes in traffic intensity, with one key factor being the day of the week. Research has shown that daily traffic volume profiles can vary significantly, which is crucial for effective traffic management. A day can be divided into 24 hours, with traffic parameters potentially differing each hour. Additionally, the day can be segmented into even smaller time intervals, such as every 5 or 15 minutes [7-9], which complicates the analysis and increases the costs of monitoring.

Current noise hazard indices, typically expressed as a Euclidean measure of the difference between measurement result and accepted normative values on a decibel scale, often make it difficult to fully assess the harmfulness of noise. The indices also present challenges in interpreting the results obtained [10-12]. As such, transforming the comparisons of measurement results, expressed in decibel scale, into a scalar space is a more practical solution. This transformation should also allow for the reverse process, enabling the reduction of scalar results back to the decibel space. The adopted scalar indicator, when integrated with traditional legal descriptors could enhance public awareness of the harmful effects of noise [13,14]. Some efforts to address this issue have been made, such as in the work of Sahu [15], which introduced a parameter called the "noise exposure index" as an alternative measure for assessing acoustic hazards. Another study [16] proposed using a pollution modelling techniques and a parameter known as the "pollution standard index". This approach considers the values of individual noise parameters, which are then compared to a single quality standard. Additionally, the work in [17] used normalization, where recorded hourly noise values were divided by the maximum value, using Euclidean division.

Similarly, in the works [18, 19], the proportion of acoustic energy in each frequency band was calculated as a percentage of the total acoustic energy emitted by the studied vehicle. A key advantage of these models is that the result is a dimensionless number. However, a significant drawback of these approaches is the incompatibility of the transformations used with the formalism of decibel algebra [20]. Many publications have shown that human perception of the acoustic environment is influenced not only by the physical properties of the sound but also by psychological, social, cultural, meteorological, and geographical factors [4, 21]. Existing standards often fail to account for these subjective factors. Therefore, this work focuses on objective noise measures. The commonly used method of assessing changes in noise hazard status based on Euclidean differences in sound levels is inconsistent with human perception. To eliminate this limitation, the authors propose linking noise assessments to decibel algebra relations grounded in the psychoacoustic Weber-Fechner law. For this purpose, they suggest using an operation that divides two decibel values to determine human reaction to changes in sound levels. This relation offers a scalar dimension of decibel space, providing a more accurate representation of human perception of acoustic phenomena. Its use opens up new possibilities of assessing environmental noise, such as analyzing human perception of the sound decay curves and estimating the acoustic parameters of rooms – an approach not previously explored in research.

The article investigates noise hazards and changes in selected noise parameters two years after the completion of the road rebuilding. This assessment is based on a novel measure of exceedance of recommended sound levels, developed using decibel algebra relations. The work analyzes noise, vehicle speed, and traffic volume data recorded by monitoring stations to gain insights into traffic patterns and the associated measurement uncertainties. The analysis focuses on variations in these parameters based on the time of day, traffic direction (entrance or exit lanes from the city) and their variability for the whole year and on Fridays (the day with the highest traffic volumes) and Sundays (the day with the lowest traffic volumes). To further explore the relationships between traffic parameters and noise, simulations were conducted using the Cnossos-EU noise model. These simulations examine the impact of changes in vehicle speed and traffic volume on noise levels, offering a comprehensive understanding of how traffic patterns influence environmental noise.

Traffic Measurements and simulation procedures

Traffic volume and noise were recorded by a stationary monitoring station located on Popiełuszki Avenue in Kielce [22]. This avenue forms part of the eastern bypass of Kielce and the national road No. 73, connecting Warszawa/Łódź, Kielce, and Tarnów. It is also directly connected to the Trans-European Transport Network (TEN-T). Popiełuszki Avenue serves as the main exit route from the center of Kielce towards Tarnów, accommodating a mix of urban, suburban, and transit traffic. In 2013-2014, the road underwent significant upgrades, including widening and strengthening of the western section (R_{12}) with an SMA11 bituminous overlay, and the

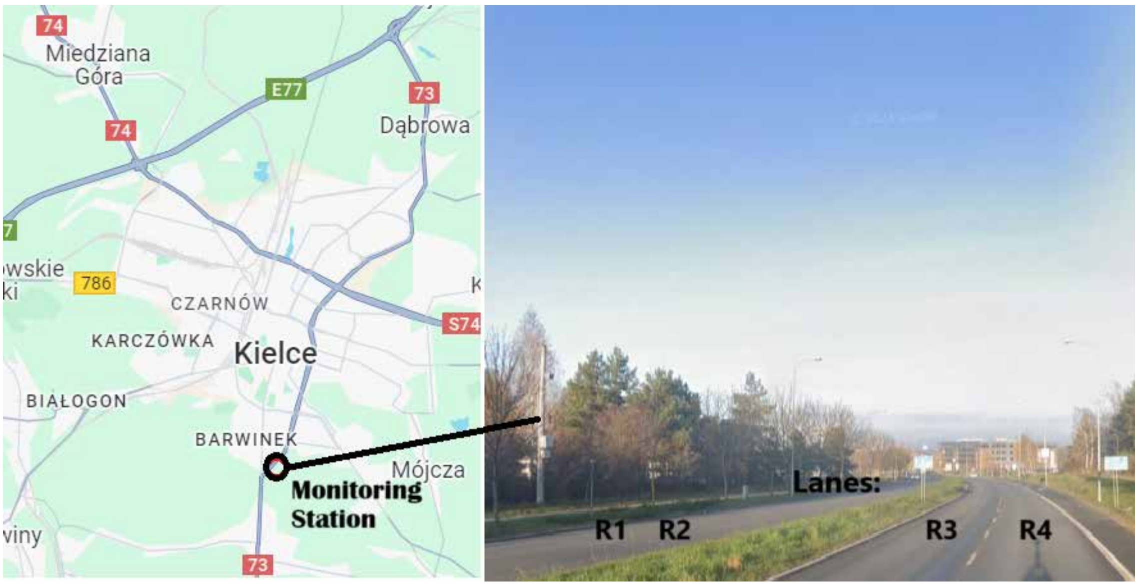

Figure 1. Layout of streets and location of the monitoring station in the communication system of the city of Kielce [Google Maps].

construction of a new eastern road (R_{34}). Currently, it is a four-lane road. The monitoring station presented in Fig.1 is located approximately 500 meters between two intersections, ensuring accurate measurement of traffic parameters under typical flow conditions.

The monitoring station is equipped with a road radar, a sound level meter, and a meteorological station. Traffic parameters were measured using the WAVETRONIX digital radar operating at a frequency of 245 MHz. The measurement results presented in this paper were conducted 24 hours a day from 2011 to 2016. Traffic volume and speed data were recorded every 1 minute (buffer) and subsequently averaged to provide hourly results. Traffic volume was defined as the total number of vehicles, including light motor vehicles, medium-heavy vehicles, heavy vehicles, and two-wheelers, recorded on all four lanes within a given time interval. The data were categorized by day of the week and hour of the day. Only days with complete 24-hour traffic data were included in the analysis, as some days had missing records. Procedures for calculating traffic volume, measurement uncertainty (u_A), and the coefficient of variation for traffic volume (V_{Q31}) are presented in [22]. The relative traffic volume was calculated using the formula:

$$VOL_{rel}\left(h_i, d_j, R\right) = VOL\left(h_i, d_j, R\right)/VOL_{max}\left(d_j, R\right) \quad (1)$$

where $VOL(h_i,d_j,R)$ is the average annual median of the traffic volume, $VOL_{max}(d, R)$ is the maximum value of median traffic volume of the analyzed set of vehicles on exit lanes (R_{12}) and entrance lanes (R_{34}) to the city, is day of the week, j= 1,2,…,7, h_i – hour of the day, i= 1,2,…,24. The maximum value of the median traffic volume of the analyzed set of vehicles was determined separately for each day of the week from 2011 to 2016.

Acoustic measurements were conducted using the SVAN 958A, a four-channel Class 1 digital vibration and sound level meter. The measuring microphone was positioned 4 m from lanes R_{12} and at a height of 4 m. A MIKROTECH GEFELL MK 250 pre-polarized 1/2” condenser microphone, Class 1, with a sensitivity of 50 mV/Pa and an SV12L preamplifier, was used. The measurement frequency range was 3.5 Hz to 20 kHz, with an RMS signal parameter detector resolution of 0.1 dB. During the tests, the RMS value of the A-weighted sound level was recorded every 1 s in the buffer, and the results were saved every 1 min. Based on these recordings, equivalent sound levels were calculated for three sub-periods [24]: L_{D_i} (6 a.m. to 6 p.m.), L_{E_i}, (6 p.m. to 10 p.m.), and L_{N_i} (10 p.m. to 6 a.m.).

Computer simulations of sound levels were conducted using the CNOSSOS-EU noise model, based on measured road vehicle parameters [4, 22]. The study assumed that noise is generated by vehicles entering the city in lanes 3 and 4 (marked R_{34}) and vehicles leaving the city in lanes 1 and 2 (marked R_{12}). The linear acoustic source was modeled along the the symmetry axis of each lane. Experimentally measured and simulated equivalent sound levels (for all vehicles) were compared by calculating the RMSE parameter, following the standard [23]. The calculated value of this parameter was approximately 1 dB. However, using the RMSE parameter for decibel-scale data may be problematic. RMSE analysis is typically performed in a probabilistic space, which raises concerns about the substantive correctness of applying it directly in the decibel domain. To address this, the normality of the data distributions was analyzed using the Shapiro-Wilk and Jarque-Bera tests. The Shapiro-Wilk test, based on positional statistics, rejected the null hypothesis (H0) of normal distribution compliance at a 0.05 significance level. In cases of uncertainty, the Jarque-Bera test was also applied, using sample moments to assess distribution shape through skewness and kurtosis. For normality, skewness and kurtosis values should be close to zero and three, respectively. The Jarque-Bera test results further supported rejecting the H0 hypothesis of normality. Histograms, Q-Q plots, skewness, and kurtosis parameters were analyzed. The obtained results indicate that there are grounds for rejecting hypothesis H0 about the normality of these distributions. However, statistical tests showed that for specific days, such as Fridays in 2012, Saturdays and Sundays in 2013, and Mondays in 2014, there were no grounds for rejecting H0 hypotheses.

The European Union Directive 2002/49/EC [24] introduced noise indicators based on equivalent sound levels assessed over an entire year. These indicators are used to develop acoustic maps and environmental noise protection programs [6, 25-27]. The indicator for overall annoyance L_{DEN} (day-evening-night noise level) in decibels can be calculated as follows:

$$L_{DEN} = 10 \lg \left[\frac{1}{365}\sum_{i=1}^{i=365} 10^{0.1 L_{DEN_i}}\right] \quad (2)$$

The L_{DEN_i} parameter is a daily indicator and is defined by the following formula:

$$L_{DEN_i} = 10 \lg \left[\frac{12}{24}10^{0.1\,L_{D_i}} + \frac{4}{24}10^{0.1\,(L_{E_i}+5)} + \frac{8}{24}10^{0.1(\,L_{N_i}+10)}\right] \quad (3)$$

L_{D_i}, L_{E_i}, and L_{N_i} are the A-weighted sound levels determined for specific sub-periods of the day on the *i-th* day [11]. The nonlinear nature of the logarithm function, along with certain paradoxes in decibel algebra [10], imposes limitations on these parameters. These limitations hinder comparative analyses, such as determining standard deviation or measurement uncertainty, studying variability, and may affect the results of statistical tests [12].

The authors propose replacing the analysis of noise levels L_{DEN_i} expressed on the dB scale, with an analysis of their exceedance multiplicities (marked k_i) relative to a reference value. This approach is based on the division operation in decibel algebra, which aligns with human perception of acoustic disturbances as described by sound levels L_{DEN_i} and L_{ref}

$$k_i = \frac{10^{0.1 L_{DEN_i}}}{10^{0.1 L_{ref}}} = 10^{0.1\left(L_{DEN_i} - L_{ref}\right)} \quad (4)$$

L_{DEN_i} is the designated noise level on the *i-th* day, and L_{ref} is the reference noise level value. According to the Polish standard, L_{ref} = 70 dB(A), and according to the World Health Organization (WHO) L_{ref} = 53 dB(A) for daytime or L_{ref} = 45 dB(A) for nighttime [28]. The result obtained from this operation is a scalar quantity, which reduces the perception of acoustic phenomena to the space of scalar numbers. As a result, further operations on the obtained result can be performed as operations on Euclidean numbers. The normalization presented in equation (4) ensures the proper implementation of subsequent steps in the identification process within the Euclidean space. The reverse transformation, from the space of scalar numbers back to the space of decibel numbers, is achieved by multiplying the sound level by the determined scalar k_i [10]. We can transform equation (4) as follows:

$$L_{DEN_i} = L_{ref} + 10 \lg (k_i) \tag{5}$$

The possibility of performing such a reverse operation significantly distinguishes the method proposed by the authors for determining the scalar exceedance coefficient from other methods presented in the works [15 - 19].

The arithmetic mean of the sound level can be determined from the relationship:

$$\overline{L_{DEN}} = L_{ref} + 10\lg \bar{k} \tag{6}$$

where $\bar{k}$ is the mean value of the permissible sound level exceedances, e.g., $\bar{k} = \frac{1}{n}\sum_1^n k_i$ or the median.

After performing simple transformations, we can determine:
- standard deviation of the L_{DEN}

$$\sigma_{L_{DEN}} = \sqrt{\frac{1}{N-1}\sum_{i=1}^{i=N}\left(L_{DEN_i} - L_{ref} - 10\lg \bar{k}\right)^2} \tag{7}$$

- positional coefficient of variation

$$V_{Q_{31}} = \frac{0.5\cdot[Q_3 - Q_1]}{Q_2} \cdot 100\% \tag{8}$$

where Q_1, Q_2 *and* Q_3 are first, second, and third quartiles, respectively
- dispersion coefficient of quarter deviation

$$V_{Q_1Q_3} = \frac{Q_3 - Q_1}{Q_1 + Q_3} \cdot 100\% \tag{9}$$

The positional coefficient of variation and the coefficient of dispersion of quarterly deviation are positional measures that focus on data between the first and third quartiles. Therefore, these coefficients' values are less influenced by atypical data.

Equation (4), based on the analysis of the variability of the k_i coefficient, provides a framework for estimating noise hazard assessment. The authors used the k_i parameter to assess road transport noise for these reasons. Analysing the k_i coefficient enables the comparison of constant components (such as the expected value or median) with the variable components of the analyzed signals.

Results of measurements and calculations of traffic parameters

The deteriorating condition of the road, along with the nuisance caused by its rebuilding, led to a 12% decrease in the average annual daily traffic flow of all vehicles between 2011 and 2014. During this period, heavy vehicle traffic decreased by 36%, medium-heavy vehicles by 10%, and light-motor vehicles by 8%. However, two years after the road rebuilding, traffic volumes increased compared to 2011. Total vehicle traffic rose by about 13%, light-motor vehicles by 19%, and medium-heavy vehicles by 12%, as shown in Table 1.

Examples of traffic volume measurement results for all vehicles, aggregated for 24-hour intervals, are shown in Figure 2a. Statistical tests reject the null hypothesis H0, which assumes that the distribution of the measurement data complies with the normal distribution, at a significance level of 0.05 [22].

The Q-Q plots presented in Figure 2b confirm these conclusions. Deviations from the normal distribution can lead to incorrect calculations of certain parameters, such as the standard deviation and measurement uncertainty [22]. For this reason, the authors divided the results into seven groups, distinguishing measurements taken on weekdays and weekends, as shown in Figure 3.

The graphs indicate that traffic volumes remain relatively stable from Monday to Thursday, increase on Friday and decrease on weekends, consistent with findings in the literature [29]. An analysis of road traffic measurements recorded from 2011 to 2016 (Figure 3 and Table 1) confirms that traffic intensity from Monday to Thursday is similar. These days are often considered typical weekdays, making them preferred for noise level measurements, especially for legislative purposes such as noise map preparation. These measurements are generally conducted from Tuesday to Thursday, avoiding holidays, and are focused on peak traffic hours. Notably, traffic volume peaks on Fridays and drops to its lowest on Sundays. For this reason, the subsequent sections of this article will include detailed analyses of traffic and noise parameters for these two days. One objective of these analyses is to identify similarities and differences in acoustic threats between Fridays and Sundays.

The median average speed of vehicles during the analyzed period shows slight variations, as shown in Figures 4 and 5. However, the construction of road intersections with traffic lights and speed cameras as part of the modernization contributed to a decrease in speed, particularly during peak traffic hours. Notably, the speed charts for lanes entering (R_{12}) and exiting (R_{34}) the city have different shapes. On the R_{12} lanes

Table 1. Median of the annual daily traffic (ADT) flow in 2011 - 2016

	2011	2012	2013	2014	2015	2016
Median of ADT flow [vehicles/24 h]						
All vehicles	17691	17237	16187	15611	15977	20012
Passenger vehicles	11840	11725	11240	10921	11446	14129
Medium heavy vehicles	3194	3027	3015	2887	2851	3579
Heavy vehicles	2011	1744	1462	1296	1133	1598

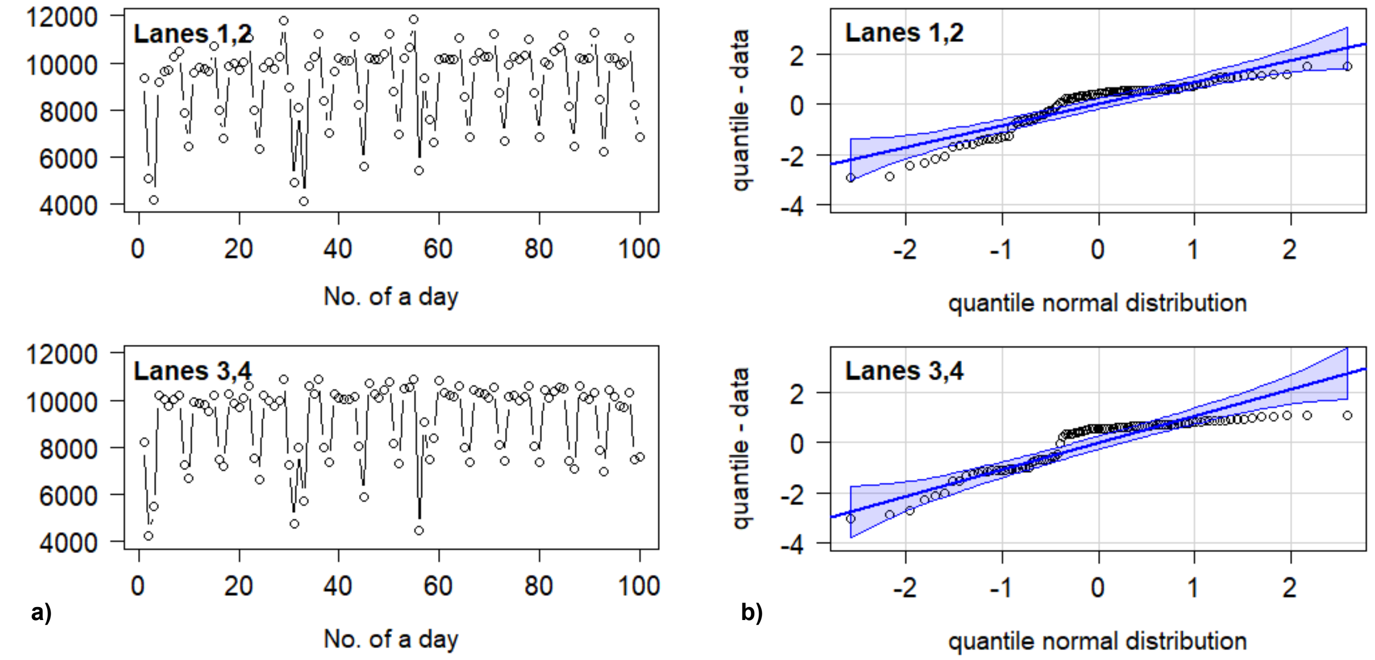

Figure 2. Traffic volume for all vehicles on a section of the road under study in 2016
a) values on individual days (data from March 25 to July 10), b) Q-Q quantile plot

(Figure 4), the median speed decreases between midnight and 4 a.m., then increases until 7 a.m., remaining relatively stable throughout the day before peaking at 8 p.m. In turn, on the R_{34} lanes, the speed graph shows a different pattern, with distinct values and variations during peak traffic hours.

Figure 5 shows speed charts for the tested road section on Sundays, broken down by individual lanes. While some differences are observed between the speed values on lanes R_{12} and R_{34}, these differences are much smaller than those seen on Fridays. An analysis of the graphs in Figures 4 and 5 shows that vehicle speeds frequently exceed not only the commonly recommended limit of 50 km/h in urban areas but also the permitted speed of 70 km/h on the tested section. Additionally, vehicle speeds on lanes R_{34} are generally higher than those on lanes R_{12}.

The speed below which 85% of vehicles in the traffic stream travel on lanes 2 and 3 was 85 km/h in 2011, 83 km/h in 2012, and 81 km/h in 2016. In contrast, the speed on lanes 1 and 4 remained constant at around 72 km/h during the analyzed period. The 15th percentile speed for lanes 2 and 3 decreased from 78 km/h to 73 km/h; while for lanes 1 and 4, it remained at approximately 65 km/h. The median traffic volume on lanes R_{12} and R_{34} shows only slight differences, as shown in Table 2, with significant differences occurring primarily on Fridays and weekends. The coefficients of variation V_{Q31} and measurement uncertainty for both directions of movement also show minor differences. The V_{Q31} coefficient ranges from 1.0% to 4.4%, with the highest values occurring on weekends on the R_{34} lanes. The uncertainty in traffic volume on the R_{34} lane (Tape A) ranges from 91 to 422 vehicles/24h (0.9% to 4.2%), varying depending on the day of the week.

Knowledge of the statistical values of traffic intensity measures, determined for each annual average day and hour, is essential for tasks such as road design and public transport planning. Figure 6 presents the experimentally obtained median annual traffic volume for each hour of the day.

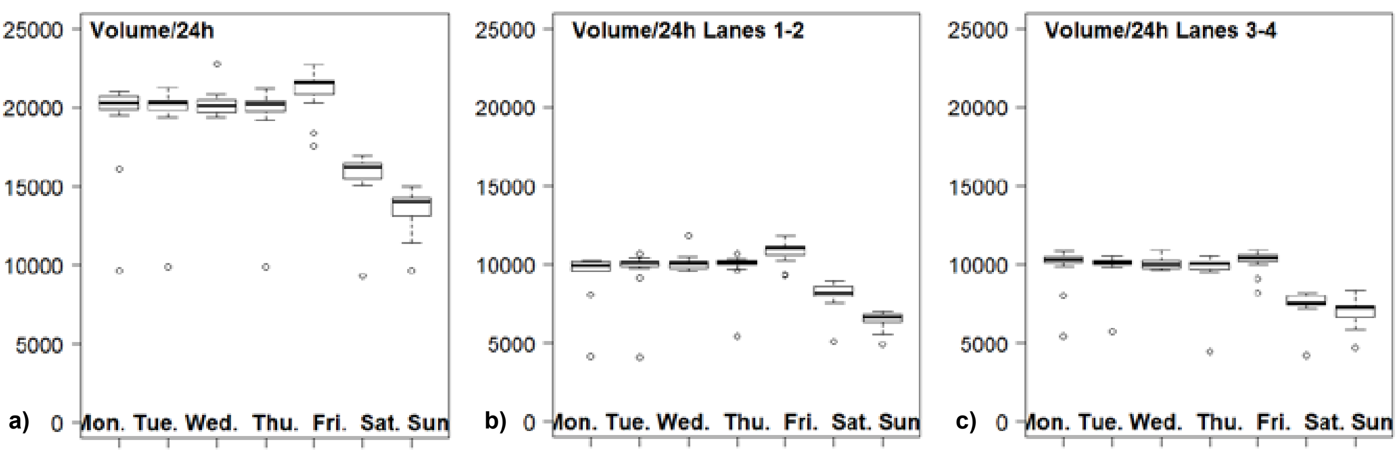

Figure 3. Box plots for annual daily traffic volume determined
a) on a section of the road under study, b) on lanes R_{12}, and c) on lanes R_{34}.

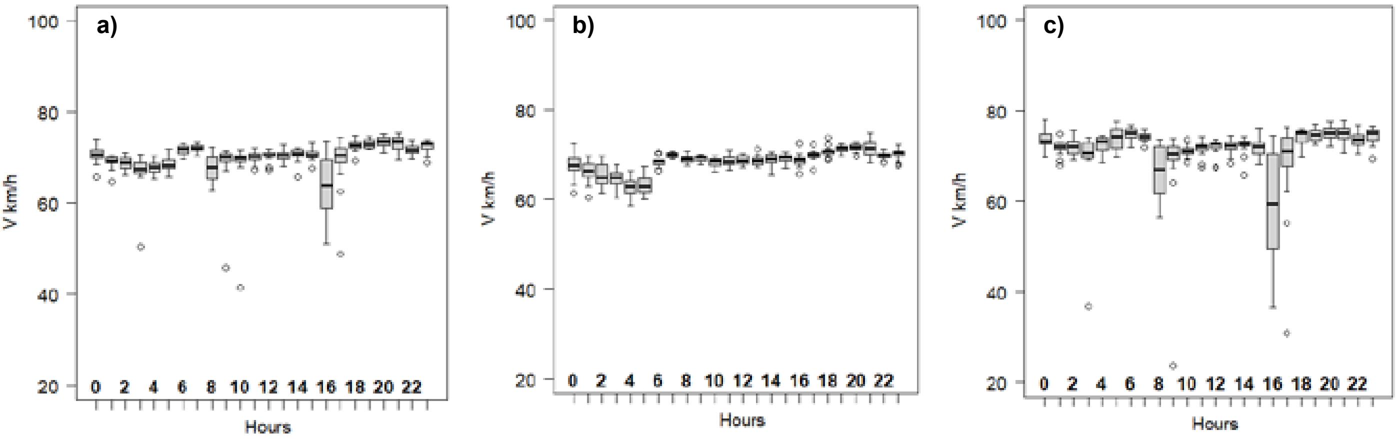

Figure 4. Box plots for Fridays of the relation between annual hourly traffic speed and time for 24-hour periods a) on a section of the road under study, b) on lanes R_{12}, c) on lanes R_{34}.

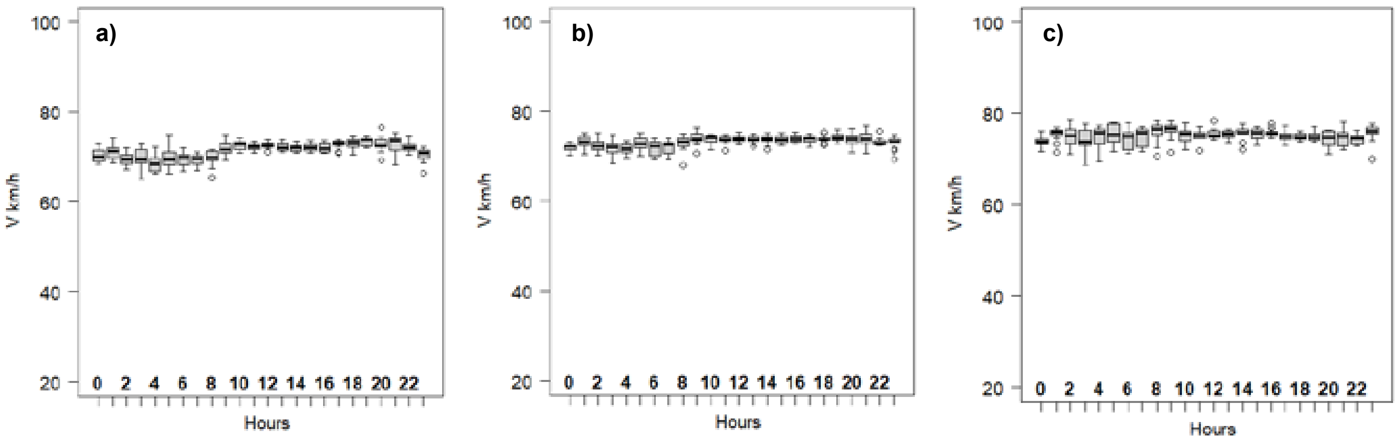

Figure 5. Box plots for Sundays of the relation between annual hourly traffic speed and time for 24-hour periods a) on a section of the road under study, b) on lanes R12, c) on lanes R34.

It should be noted that the graphs in Figure 6 differ in both values and shape (hourly distribution). Fridays are characterized by traffic peaks at 8 a.m. and 4 p.m., with high traffic volumes and minimal changes in the V_{Q31} coefficient. The morning peak shows rapid increases and decreases, while the afternoon peak exhibits slower changes in traffic volume. In contrast, on Sundays, there is only one prolonged traffic peak from 2 p.m. to 4 p.m., and the overall traffic volume is much lower [22].

An analysis of the relative annual traffic volume recorded each hour was also carried out using the equation (1). Figure 7 shows the median annual average relative hourly traffic volume by time of day for Sundays in 2016 and 2014. Between 5 a.m. and 3 p.m., the relative traffic intensity graphs for 2014 and 2016 are similar, with the peak occurring at 3 p.m. In the remaining hours of the day, the relative traffic intensity was higher in 2016 than in 2014.

Results of measurements and calculations of traffic noise

The calculation results for the median equivalent sound level L_{Aeq} and the corresponding multiplicity coefficients k_i for Sundays in 2016 and 2014 are presented in Figure 8. Analyzing the L_{Aeq} results on the decibel scale, a notable similarity between the two graphs can be observed. In 2016, the noise level increased more rapidly during the day until 3 p.m., then decreased more slowly than in 2014. The minimum L_{Aeq} value in both charts occurs at 5 a.m., and the maximum at 3 p.m., corresponding to peak traffic hours. However, examining the changes in the multiplicity coefficients k_i in the examined years reveals more pronounced similarities and differences between these charts. From midnight to 6 a.m. the values of k_i in 2016 were approximately twice as high as those in 2014. A similar trend is observed from 3 p.m. until 10 p.m. Between 7 a.m. until 3 p.m the k_i values are similar for both years. It is evident that the sensitivity of k_i on the Euclidean scale is more pronounced than that of L_{Aeq} on the decibel scale. The values of the V_{Q31} and V_{Q1Q3} parameters for L_{Aeq} and k_i coefficients are the same. However, the coefficient of variation (COV), defined as the ratio of the standard deviation to the mean value, and the uncertainty of the L_{Aeq} or k_i coefficient, differ substantially. For example, on Sundays in 2016 at 3 p.m., $u_A(L_{Aeq})$ = 0.2% and $u_A(k_i)$ = 3.5%. These discrepancies may result from the adopted procedure used to calculate the standard deviation on the decibel scale. On Sundays in 2016, the noise level exceeded the administrative recommendations of 70 dBA from 2 p.m. to 6 p.m. On Fridays in 2016, the noise level did not exceed the recommended 65 dBA from midnight to 5 a.m.

The results of the calculations for selected noise parameters, two years after the completion of the road rebuilding are

Table 2. Values of statistical measures of traffic volume on lanes R_{12} and R_{34} were determined for each average annual day of 2016.

Day	*Median* [veh/24h]	V_{Q31} [%]	$V_{Q_1Q_3}$ [%]	u_A [%]	*Median* [veh/24h]	V_{Q31} [%]	$V_{Q_1Q_3}$ [%]	u_A [%]
		R_{12}				R_{34}		
Monday	9966	2.5	2.5	4.2	10333	1.5	1.5	3.6
Tuesday	10146	1.3	1.3	4.1	10155	1.0	1.0	3.0
Wednesday	10100	2.0	2.1	1.4	10040	2.2	2.2	0.9
Thursday	10132	1.2	1.2	3.5	10063	2.1	2.0	4.2
Friday	11055	2.4	2.4	1.5	10412	2.0	2.0	1.6
Saturday	8221	3.8	3.8	2.8	7557	3.8	3.7	3.2
Sunday	6660	3.6	3.6	2.3	7253	4.4	4.5	3.1

presented in Table 3. It can be seen that the values of the L_{DEN} and L_N parameters exceed international recommendations, such as those from the WHO, as well as Polish standards. The coefficients of variation for night-time noise (L_N parameter) are approximately 8%, while for the 24-hour period (L_{DEN} parameter), they are approximately 9.5%. The standard deviation of these parameters is about 1 dB, and the type A uncertainty is around 0.3%. However, this small uncertainty value raises questions about the accuracy of the calculation procedure when using the decibel scale. These parameters can also be expressed in Euclidean numbers by calculating the multiplicity factor according to the formula (4). Using the multiplicity factor, the Type A uncertainty increases to approximately 4%, which is considered more reliable. Similar discrepancies occur for the coefficient of variation (COV). When using the decibel scale, the COV is approximately 1.6%,

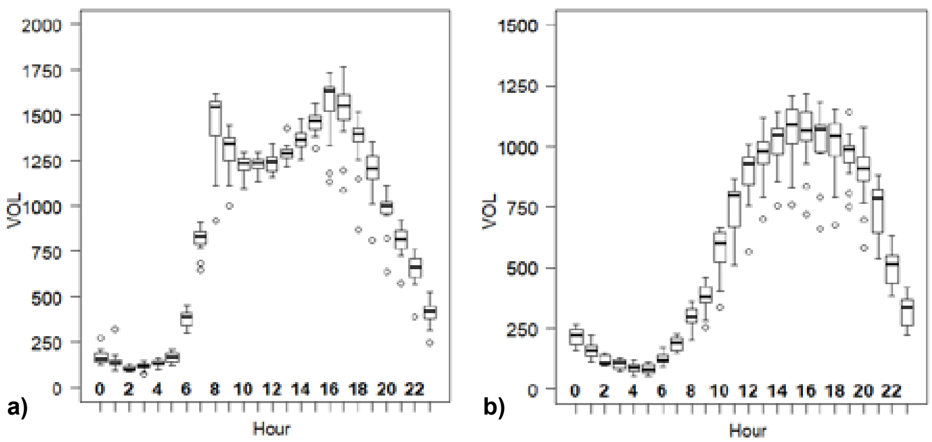

Figure 6. Box plots of the relation between the annual hourly traffic volume and time for 24 hours on a section of the road under study in 2016: a) for Fridays, b) for Sundays.

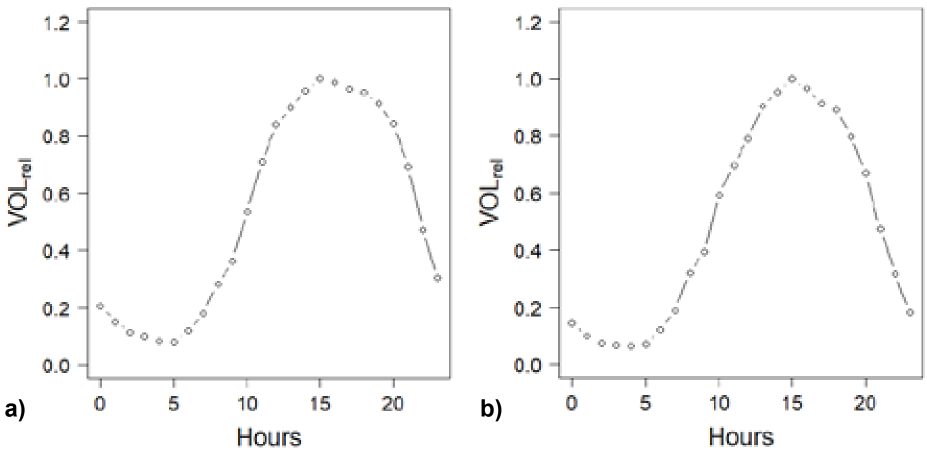

Figure 7. Relation between the relative annual hourly traffic volume and time for Sundays a) in 2016, b) in 2014

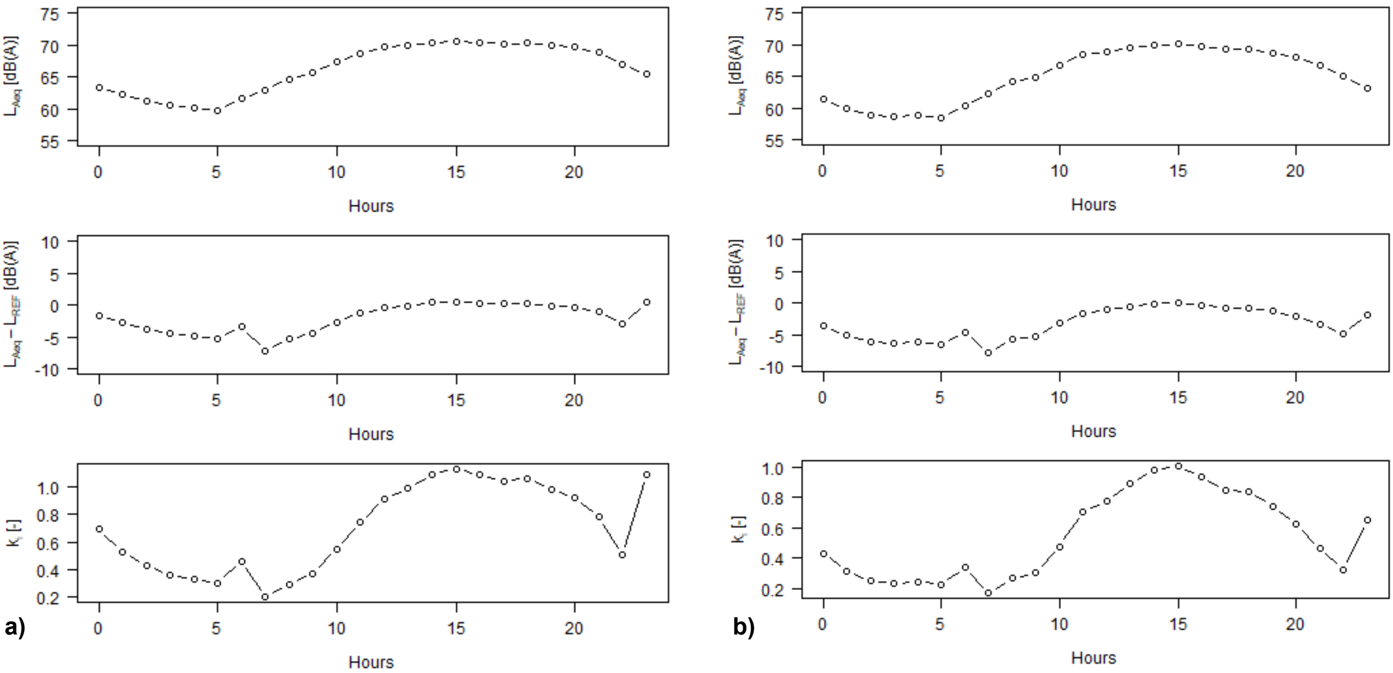

Figure 8. Equivalent sound level L_{Aeq}, exceeding the reference value $L_{Aeq} - L_{ref}$, and multiplicity factor k_i referenced to 70 dB(A) or 65 dB(A) for Sundays a) in 2016, b) in 2014

but with the multiplicity factor, it increases to about 23%. It is important to note that the decibel scale measures energy levels, while the multiplicity factor depends on the ratio of disturbance energy to reference energy, as shown in equations (4) and (5).

$$\bar{L}_{DEN} = 10\,log\left(\frac{1}{N}\sum_{i=1}^{i=N}10^{0.1L_{DEN_i}}\right)$$

– logarithmic mean of the L_{DEN},

$$\sigma_{L_{DEN}} = \sqrt{\frac{1}{N-1}\sum_{i=1}^{i=N}\left(L_{DEN_i} - \bar{L}_{DEN}\right)^2}$$

– standard deviation of the L_{DEN},

$$\sigma_k = \sqrt{\frac{1}{N-1}\sum_{i=1}^{i=N}\left(k_i - \bar{k}\right)^2}$$

– standard deviation of the k,

$$u_A = \sqrt{\frac{1}{n(n-1)}\sum_{i=1}^{n}\left(L_{DEN_i} - \bar{L}_{DEN}\right)^2}$$

– the tape A uncertainty of the L_{DEN}.

The simulations were carried out using the Cnossos noise model, and the results are presented in Table 3. There is a significant convergence between the calculated and measured parameter values, as shown in Figure 9 and Figure 10. The boxplots for the L_{DEN_I} parameter in Figure 9 indicate that the data distribution deviates from the normal distribution, which was confirmed by the histogram analysis. Outlier data with small values are visible in these charts. The median value is approximately 73.8 dB(A), and the maximum noise level is approximately 75.3 dB(A). When comparing the maximum noise value to the median on the decibel scale, the difference may seem small. However, when assessing this difference using the multiplicity factor, it corresponds to a change of approximately 42%, which is significant.

The boxplot of the k_i coefficient shown in Figure 10a indicates the extent to which the permissible energy of emitted noise was exceeded during the day. The median value is approximately 2.4, which indicates that the permissible energy of emitted noise (according to the Polish standard) was exceeded by 140%. The maximum multiplicity value is 3.4, which can be considered an outlier. This outlier is likely caused not only by the vehicles on the examined road section but also, for example, by noise generated by a nearby shopping centre. This possibility is supported by Figure 10b and calculations carried out using the Cnossos model (presented in Table 3), indicating that the maximum k_i value is 2.6.

The analysis of noise parameters before the road rebuilding began showed that the median value of $L_{DEN(i)}$ was 74.6 dB(A) in 2011 and 72.2 dB(A) in 2014. This decrease in noise medians results from decreased traffic volume across all vehicle groups, particularly heavy vehicles. This downward trend in traffic flow is seen in Table 1. Noise calculations performed using the Cnossos model confirmed a slight decrease in noise medians. The calculated noise median was 73.4 dB in 2011 and 72.5 dB in 2014. After the road rebuilding was completed, the median noise level in 2016 was 73.8 dB(A), despite a 28% increase in traffic intensity compared to 2014. When comparing the parameters before and after road renovation using the decibel scale, such as $L_{DEN(i)}$, it is clear that although there was some reduction in their values, they still exceed the recommended standards. This cursory analysis suggests that the environmental conditions have only slightly improved despite the significant costs incurred for the rebuilding. The median exceedance coefficient for the $L_{DEN(i)}$ parameter was 2.9 in 2011 and 2.4 in 2016, reflecting a decrease of approximately 17%. The maximum values of the k_i coefficient for the $L_{DEN(i)}$ parameter were 4.4 in 2011 and 3.4 in 2016, indicating a decrease of approximately 15 %.

The qualitative assessment of noise emissions varies depending on the scale used. The sensitivity of the k_i

Table 3. Road noise statistics on decibel scale and values of multiples of recommended sound levels after road modernization in 2016.

2016	L_{DEN}	$Q_2(L_{DEN(i)})$	$L_{DEN(i)}$ (max)	σ	u_A	u_A [%]	$V_{Q_{31}}$ [%]	$V(_{Q_1Q_3})$ [%]
Experiment								
$L_{DEN(i)}$ dB(A)	73.6	73.8	75.3	1.0	0.2	0.3	9.1	9.5
$k(L_{DEN})$ L_{ref} = 70 dB(A)	2.3	2.4	3.4	0.5	0.1	4.4	9.1	9.5
$k(L_{DEN})$ L_{ref} = 53 dB(A)	116	121	171	23	3.8	3.3	9.1	9.5
L_N dB(A)	65.5	65.6	68.0	1.2	0.2	0.3	7.9	7.9
$k(L_N)$ L_{ref} = 45 dB(A)	114	116	201	29	4.6	4.0	7.9	7.9
Cnossos model								
L_{DEN} dB(A)	73.1	73.4	74.2	1.1	0.1	0.15	10.1	10.6
$k(L_{DEN})$ L_{ref} = 70 dB(A)	2	2.2	2.6	0.4	0.1	5	10.1	10.6
$k(L_{DEN})$ L_{ref} = 53 dB(A)	102	111	131	21	2.2	2.2	10.1	10.6

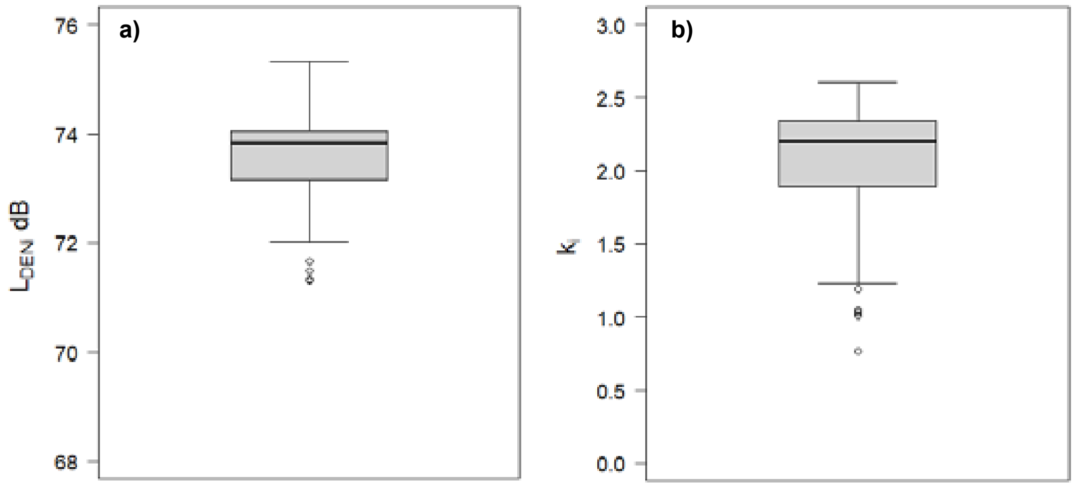

Figure 9. Boxplot of the $L_{DEN(i)}$ parameter for Popiełuszki Av. in 2016, for the data determined a) experimental results, b) simulation results according to the Cnossos model

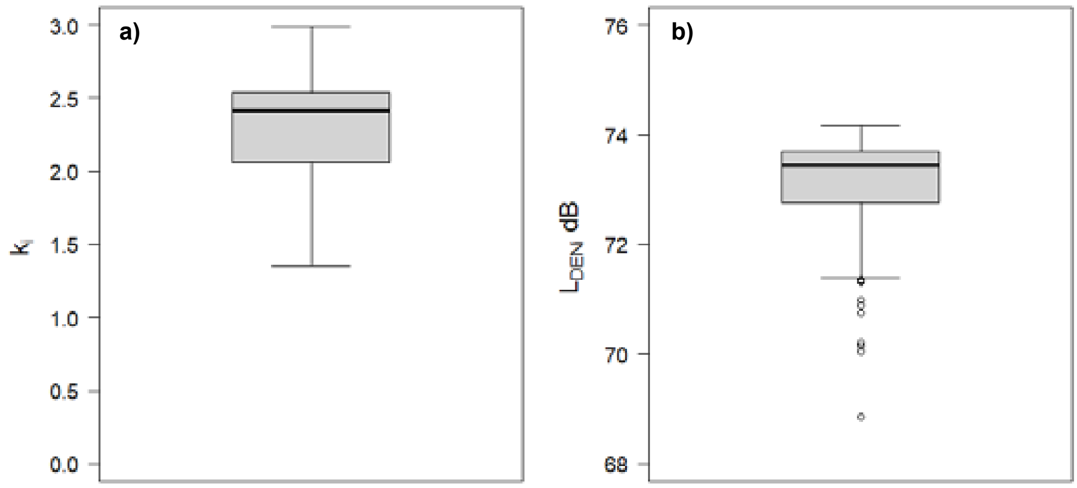

Figure 10. Boxplot of the k_i coefficient for Popieluszki Av. in 2016 for data $L_{DEN(i)}$ and L_{ref}=70 dB(A) determined a) experimentally, b) simulations according to the Cnossos model

coefficient on the Euclidean scale is greater than that of the L_{Aeq} parameter on the decibel scale. It is also worth noting the strong dependence of the k_i coefficient on the chosen reference level, which makes its interpretation challenging. For example, for L_{DEN} = 73.6 dB(A), the k_i value calculated at L_{ref} = 70 dB(A) is 2.3 while for L_{ref} = 53 dB(A) k_i = 116, as shown in Table 3. To analyze the variability of the $L_{DEN(i)}$ parameter, the coefficients V_{Q31} and V_{Q1Q3} calculated from the experimental database or determined using the Cnossos model, were selected. The values of these coefficients were approximately 15% in 2011 and 10% in 2016. This decrease suggests that road rebuilding resulted in the so-called calming of vehicle traffic, which contributes to increased road safety. During the rebuilding, in 2013 and 2014, the experimental values of these coefficients increased several times, reaching approximately 80%, while the values theoretically calculated according to the Cnossos model were about 15%. The discrepancies between these values confirm that construction works contribute to increased noise, especially in terms of maximum values. Additionally, it can be observed that the values of the noise coefficients of variation, such as V_{Q31}, are approximately twice as large as the traffic volume.

Discussion

Based on the analyses, the road rebuilding has improved the acoustic condition of the environment. However, it still needs to comply with administrative recommendations. Therefore, it is justified to conduct computer simulations to determine what actions should be taken - without the need for further road modernization (e.g., construction of low-noise road surfaces) – to ensure that noise parameters remain within the existing administrative limits [30]. Simulations were carried out using the Cnossos model to assess the impact of reducing vehicle speed on the tested road section in 2016 and its effects on generated noise parameters. Traffic intensity was assumed to be based on data recorded in 2016. In the first simulation variant, it was assumed that the speed of each vehicle was 50 km/h, which resulted in L_{DEN} = 71.4 dB(A) and k_i = 1.4 and $L_{DEN(i)}(max)$ = 72.2 dB(A) and $k_i(max)$ = 1.7. In the second variant, it was assumed that the speed of each vehicle at night is 50 km/h, and during the day, the speed is consistent with the 2016 measurements. This resulted in L_{DEN} = 72.45 dB(A) and k_i = 1.9, with the maximum values being $L_{DEN(i)}(max)$ = 73.5 dB(A) and $k_i(max)$ = 2.3. For the third calculation variant, it was assumed that the vehicle speed at night is 50 km/h, and during the day, the speed is reduced to 30 km/h. This scenario produced L_{DEN} = 70.6 dB(A) and k_i = 1.1, with maximum values of $L_{DEN(i)}(max)$ = 71.4 dB(A) and $k_i(max)$ = 1.4. While these noise parameters still exceed the recommended values, the night-time noise levels were found to be in line with recommendations: L_N = 62.9 dB(A) and k_i = 0.6, with $L_{N1}(max)$ = 64 dB(A) and $k_i(max)$ = 0.8. In the fourth variant, where the speed of each vehicle was reduced to 30 km/h, the resulting noise parameters were L_{DEN} = 69.96 dB(A) and k_i = 0.8, with $L_{DEN(i)}(max)$ = 70.8 dB(A) and $k_i(max)$ = 1.2. These values do not exceed the recommended threshold, however, the noise coefficients of variation increased by approximately twice as much, which may be considered a disadvantage of this solution. The simulations show that modifying vehicle traffic parameters by limiting their speed to 30 km/h during the day and 50 km/h at night is essential to keep noise parameters at or below 70 dB(A) and in line with the recommendations. Finally, in the fifth calculation variant, it was assumed that the traffic intensity for all vehicle groups would be reduced by 50%, while vehicle speeds would remain as recorded in 2016. Under these conditions, L_{DEN} = 70.1 dB(A) and k_i = 1.0. Considering the uncertainty in these values, it can be assumed that the normative values will not be exceeded, though, they will still need to align with WHO recommendations.

Conclusions

Two years after the road was reconstructed, traffic increased by approximately 28%. Significant differences in traffic volume are observed on Fridays and weekends. On Fridays, traffic peaks in the morning at 8 a.m. and in the afternoon at 4 p.m., with high traffic volumes and minimal changes in the V_{Q31} coefficient. On Sundays, however, there is only one prolong traffic peak from 2 p.m. to 4 p.m., and the overall traffic volume is much lower. Studies of annual hourly traffic volume distributions on lanes R_{12} and R_{34} as a function of time reveal asymmetry between the number of vehicles entering and leaving the city. Both the shape of the graphs and the timing of peak traffic are different for individual lanes. Similarly, speed patterns on the city's entry and exit lanes have different patterns. The traffic volume variability, defined by the V_{Q31} coefficient, ranges from 1.0% to 4.4%, with the highest values occurring on weekends on lanes R_{34}. The type A uncertainty for the traffic volume on lane R_{34} ranges from 0.9% to 4.2%, depending on the day of the week and the measurement time.

The analysis of noise parameters before the road reconstruction showed that the median $L_{DEN(i)}$ value was 74.6 dB(A) in 2011, decreasing to 72.2 dB(A) in 2014. This decrease in noise medians results from decreased traffic intensity of all vehicle groups, especially heavy vehicles, and decreased speed. After the road reconstruction was completed, the median noise level in 2016 increased to 73.8 dB(A), despite a 28% increase in traffic intensity compared to 2014. When comparing $L_{DEN(i)}$ values on the decibel scale before and after the road reconstruction, the results show a slight reduction, though the values still exceed the recommended standards. This suggests that, despite the substantial rebuilding costs, the environmental benefits in terms of noise reduction have been modest. The median exceedance coefficient k_i for the $L_{DEN(i)}$ parameter dropped from 2.7 in 2014 to 2.3 in 2016, a decrease of about 15%. Maximum k_i values were 4.4 in 2011, 27 in 2014, and 3.4 in 2016. The qualitative assessment of noise emission changes varies depending on the scale used. Using the decibel scale to determine absolute noise values does not cause significant doubts. However, the expression of relative noise values may cause ambiguity in the assessment. The sensitivity of the k_i coefficient measured on the Euclidean scale, demonstrates greater sensitivity to changes compared to $L_{DEN(i)}$ on the decibel scale. To evaluate the variability of $L_{DEN(i)}$ parameter, coefficients V_{Q31} and V_{Q1Q3} derived from experimental data or the Cnossos model, were analyzed. These coefficients were approximately 15% in 2011 and 10% in 2016. This decline indicates that road rebuilding contributed to the so-called calming of vehicle traffic, enhancing road user safety.

Simulations carried out using the Cnossos model show that limiting vehicle speed to 30 km/h during the day and 50 km/h at night, without altering traffic intensity parameters, would result in noise levels not exceeding 70 dB(A), aligning with the recommendations. In another scenario, it was assumed that traffic intensity for each vehicle group would be reduced by 50%, while vehicle speeds would remain consistent with data recorded in 2016. For such traffic parameters, the values of L_{DEN}=70.1 dB(A) and k_i = 1 were calculated, suggesting compliance with normative noise values. These analyses show that road modernization is essential to achieve noise parameters that meet WHO recommendations.

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Additional information

The author(s) declare no competing financial interests, confirm that all material drawn from other sources (including their own published works) has been properly cited, and state that all necessary permits have been obtained.

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Ocena zmian zanieczyszczenia środowiska hałasem drogowym za pomocą miary skalarnej

Streszczenie: Artykuł porusza kwestię oceny wpływu przebudowy dróg na zanieczyszczenie hałasem drogowym. Do oceny zagrożeń hałasem wykorzystano parametry wyrażone w skali decybelowej oraz zaproponowano nową skalarną miarę, która porównuje wartość poziomu dźwięku z poziomem dopuszczalnym. Miara ta opiera się na prawie Webera Fechnera, które odnosi się do ludzkiego postrzegania zmian poziomu dźwięku. Została ona wyprowadzona z wykorzystaniem algebry decybelowej zastosowanej do wyników pomiarów i jest nazywana „współczynnikiem przekroczenia zalecanego poziomu dźwięku". Jej przydatność zweryfikowano analizując wyniki pomiarów parametrów ruchu i hałasu przed i dwa lata po przebudowie odcinka drogi krajowej w Kielcach. Dokonano oceny natężenia ruchu, prędkości pojazdów i hałasu pojazdów drogowych. W analizie oceniono wartości bezwzględne, zmienność oraz niepewność wyników uzyskanych dla całego roku, piątków i niedziel. Zaobserwowano znaczące różnice w wartościach parametrów ruchu pomiędzy pasami wjazdowymi i wyjazdowymi z miasta w dni powszednie i weekendy. Analiza wykazała 28% wzrost natężenia ruchu po przebudowie drogi. Obecna miara, która porównuje różnicę w poziomach hałasu przed i po przebudowie drogi, wskazuje, że chociaż poziomy hałasu zmniejszyły się, nadal przekraczają wartości normatywne. Dla tych samych parametrów mediana współczynnika przekroczeń zmniejszyła się o około 17%, a maksymalny współczynnik przekroczenia zmniejszył się o około 15%. Przydatność diagnostyczna współczynnika przekroczenia została dodatkowo oceniona przy użyciu symulacji hałasu opartych na modelu Cnossos-EU. Symulacje te wykazały wysoką wrażliwość proponowanej skalarnej miary hałasu na zmiany prędkości pojazdów i natężenia ruchu. Symulacje wykazały również, że w celu spełnienia polskich wartości normatywnych hałasu w Polsce, natężenie ruchu musiałoby zostać zmniejszone o 50%, a prędkość pojazdów musiałaby zostać ograniczona do 50 km/h.