Modelling of road traffic noise

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Abstract. Effective implementation of the EC Communication relating to urban mobility is dependent on adopting relevant indicators that will allow comprehensive assessment of the measures undertaken under the urban mobility plan. One of the fundamental parameters for this assessment is the equivalent sound level indicator, measured over the 24-hour period, used to evaluate the annoyance of the road traffic noise. Not only is its value important but also its variability. This paper reports the results of the analysis of traffic noise along a major road, performed using various descriptors. The data recorded continuously throughout the year by the traffic rate and noise monitoring terminal were used to construct the measurement database. Analysis of the results was performed for the period between March and June in 2011 and 2016. The road was renovated between 2013 and 2015. The noise variability assessment was conducted using classical and positional indicators. Measurement uncertainties were evaluated.

Keywords: traffic noise, traffic noise variability, noise measurement uncertainty

1 Introduction

The Communication of the European Commission on urban mobility [1] promotes "...cooperation across different policy areas and sectors (transport, land use and spatial planning, environment, economic development, social policy, health, road safety, etc.); across different levels of government and administration; as well as with authorities in neighbouring areas – both urban and rural." For these guidelines to be effectively and broadly deployed, it is necessary to adopt the solutions available within the so-called urban intelligent transport system regulations, concerning urban access, road safety issues, citizen and stakeholder engagement as well as fostering changes in mobility behaviour. The EC recommends solutions that will encourage inhabitants to use multimodal transport, choose transit over car, shift towards cycling and walking, and combine different modes within one travel chain. As for the urban road traffic management, public transport should be given priority over private transport and the speed of the vehicles should be controlled. Enhancing the traffic flow and discouraging drivers from speeding, thus reducing brake/acceleration cycles, will contribute to increased road safety for all citizens and to reduced air pollution and noise [2]. The mobility plans will be effective provided that subsequent stages of the

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plan implementation are monitored and assessed, with the assessment results adapted to the changing conditions. The measures undertaken under the mobility plans are evaluated using common descriptors. There are fixed indicators, on which the evaluation is based, and supplementary indicators determined when the need arises. The fixed indicators include:

- travel speed of cars and collective transport vehicles,
- fine particulate matter concentration, PM2.5, PM10, BaP at each assessment point,
- the number of inhabitants and dwellings exposed to road traffic noise, assessed using the L_{DWN} and L_N descriptors. Average values of some of these descriptors are determined periodically, once in five years, during noise mapping [3], but this is insufficient for the purpose of mobility change analysis. Several cities, including Kielce, have stationary monitoring systems constructed to register noise and traffic rates for 24 hours throughout the year [4]. These systems, e.g., Enviro 151, are able to remotely configure and program measurement sessions. Measurement results, available on the internet in real time, illustrate the variations in the structure and rate of traffic in the city and allow the implementation of the digital acoustic mapping project. Kielce has more than ten such stations, both in the centre and on the outskirts of the city. This paper analyses the results from the equivalent sound level measurements recorded by one of these stations in 2011 and 2016.

2 Measuring station

The data under analysis were recorded by automatic sound and traffic volume continuous monitoring station located in Popiełuszki Avenue in Kielce. Kielce is a medium-size town located in south-central Poland (the Świętokrzyskie Mountains) within the moderate climate zone. Temperatures within a year range approximately from -5°C in January to +17°C in July. Average monthly precipitation is from 34 mm in October to 96 mm in July. The wind, predominantly from the south and west, reaches an average speed of about 3 m/s over a year. Kielce gets on average 70 days a year of snow on the ground.

Popiełuszki Avenue is a road with four lanes of traffic separated by a 3m grass median. One side of the road is comprised of compact residential development, about 200m from the measuring station. The other side is the edge of a woods area. The road is part of the eastern bypass around Kielce and part of the national road No. 73 (Warszawa/Łódź – Kielce - Tarnów - Krosno), which is directly connected with the Trans-European Transport Networks (TEN-T). It is also the major part of the Tarnów-bound thoroughfare functioning as both the transit route and the city street.

The results of acoustic measurements performed during the period from 25/03/2011 to 25/06/2011 and from 25/03/2016 to 25/06/2016 were split into three sub-intervals of a 24-hour interval: day time, evening time and night time. In the years 2013 - 2015, Popiełuszki Avenue was thoroughly renovated. The acoustic measurements were carried out with the SVAN 958A, a four-channel digital vibration analyser and a class 1 sound level meter, operating within the measuring frequency range 0.5 Hz to 20 kHz, depending on a microphone used. The frequency range is 3.5 Hz to 20 kHz when a Microtech Gefell MK250 free-field, prepolarised 1/2" condenser microphone with a sensitivity of 50 mV/Pa, SV 12L preamplifier is used. The temperature range within which the device is operable is from -10^{o} C to 50^{o} C. The resolution of the signal *RMS* detector is 0.1 dB. The measurements were carried out 24 hours a day. The *RMS* values of the A sound level were registered in the buffer every 1 s and the results were recorded every 1 minute. The data collected formed the basis for equivalent sound level calculation for three time intervals, i.e., from 6:00 to 18:00, from 18:00 to 22:00 and from 22:00 to 6:00. The microphone for the sound pressure measurements was mounted at a distance of 4 m from the edge of the road at a height of 4 m. Traffic volume was measured with a digital radar 245 MHz by

WAVETRONIX. Weather data were recorded by the VAISALA WTX 510 automatic meteorological station.

3 Analysis of measurement results

The most common noise indicator used to assess annoyance is the equivalent sound level ($L_{Aeq,T}$), expressed in (dB), defined as [5]:

$$L_{Aeq,T} = 10 \cdot log\left[\frac{1}{T}\int_0^T \left(\frac{p_A(t)}{p_0}\right)^2 dt\right] = \quad 10 \cdot log\left[\left(\frac{p_{A_{RMS}}}{p_0}\right)^2\right] \tag{1}$$

where:

T - represents the overall measurement time, s
$p_A(t)$ - A-weighted sound pressure level, Pa
p_0 - is the standardized reference sound pressure of 20 µPa
$p_{A_{RMS}}$ - represents the effective sound pressure.

Figure 1a compiles the measurement results for the equivalent sound level expressed as dB for T= 86400 s, recorded in 2011 and 2016. Figure 1b shows quantile plots and histograms with the function of probability density distribution for the standardized values of the data under analysis. The graphical representation of the spread of variables is shown on the box plots in Fig. 1c.

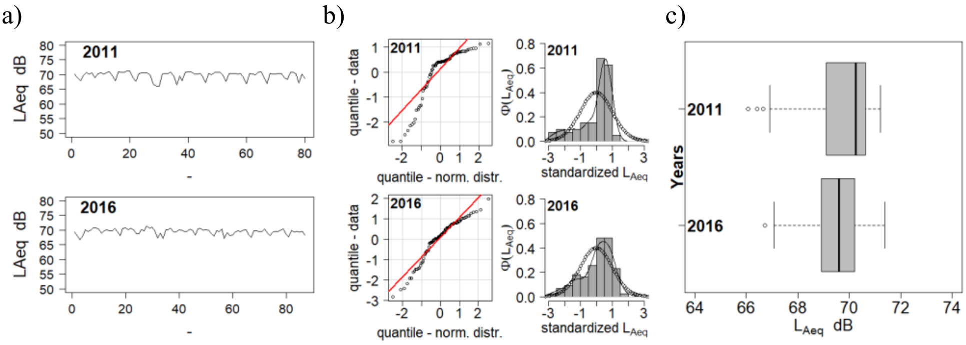

Fig. 1. Equivalent sound level results from the terminal in Popiełuszki Avenue recorded in 2011 and 2016 for all 24-hour measurement periods; a) equivalent sound level variations and the corresponding: b) quantile plots and histograms with the function of probability density distribution for the standardized data, c) box plots.

The graphs in Fig. 1a indicate that despite the thorough renovation of the road, the values of $L_{Aeq,T}$ underwent only slight changes. The range between the minimal values (Saturdays and Sundays) and the values recorded on the working days decreased. The quantile plots and histograms in Fig. 1b confirm that the data do not follow a normal distribution [6].

The non-linear character of logarithmic function changes is a limitation to the use of the $L_{Aeq,T}$ parameter. This impedes both the determination of standard deviation or measurement uncertainty and the performance of a comparative analysis. It may also affect the results of statistical tests for normal distribution of the data [5]. Therefore, the authors of this paper decided to determine the RMS sound pressure ($p_{A_{RMS}}$) in the T period from equation (1) and use this parameter in further analysis.

$$p_{A_{RMS}} = p_A = \sqrt{10^{(0.1*L_{Aeq,T})} * p_0^2} \tag{2}$$

Standard uncertainty of the parameter, determined in the Type A evaluation, can be calculated from the following relationship:

$$u_A = \sqrt{\frac{1}{n(n-1)} \sum_{i=1}^{n} \left(p_{A_{RMS_i}} - \overline{p_{A_{RMS}}} \right)^2} \tag{3}$$

In this study, the authors analysed $p_{A_{RMS}}$ from (2) expressed in terms of Pa to be able to easily compare the fixed components (the expected value and the median) and variable components (standard deviation, coefficient of variation – classical and positional) of the sound pressure signals recorded. The tests for the variable components contained in the signals were based on the classical and positional measures: standard deviation ($\sigma_{p_{A_{RMS}}}$), coefficient of variation (COV), quartile deviation Q_{31}, quartile variation coefficient ($V_{Q_{31}}$), and quartile coefficient of dispersion (V_{Q1Q3}). Standard deviation is an absolute measure commonly used for the analysis of sound pressure variable component. Standard deviation is estimated from (4), where *n* is the amount of data:

$$\sigma_{p_{A_{RMS}}} = \sqrt{\frac{1}{n-1} \sum_{i=1}^{i=n} \left(p_{A_{RMS_i}} - \overline{p_{A_{RMS}}} \right)^2} \tag{4}$$

This parameter defines the average variation in individual sound pressure values from the arithmetic mean. Standard deviation can be related to the expected value of the signal being analysed to obtain the coefficient of variation (*COV*). The *COV* is a dimensionless relative measure that can be used to directly compare the variable components in its several realisations. For the sound pressure tested, the *COV* can be expressed as [7]:

$$COV_{p_{A_{RMS}}} = COV = \frac{\sigma_{p_{A_{RMS}}}}{\overline{p_{A_{RMS}}}} \cdot 100\% \tag{5}$$

The value of the *COV* is greatly influenced by atypical data, taken into account in the analyses. This influence is less significant when positional measures are used. The measure of dispersion of the variable is the average quartile deviation:

$$Q_{31} = 0.5 \cdot \left[Q_3\left(p_{A_{RMS}}\right) - Q_1\left(p_{A_{RMS}}\right) \right] \tag{6}$$

Quartile deviation is an absolute measure that defines the average variance of half of the measurement data around the median (after rejecting 25% data with the lowest values and 25% data of the highest values of sound pressure), expressed in terms of pascal. By relating it to the median, the positional coefficient of variation is calculated from (7):

$$V_{Q_{31}} = \frac{Q_{31}}{Med} \cdot 100\% \tag{7}$$

The quartile coefficient of dispersion is a relative measure of variance, calculated from (8):

$$V_{Q1Q3} = \frac{Q_3 - Q_1}{Q_1 + Q_3} \cdot 100\% \tag{8}$$

The positional coefficient of variation and the quartile coefficient of dispersion are positional measures of the data between the first and third quartiles. Thus, atypical data exert less influence on these coefficients. It has to be noted, however, that the data under analysis represent the measurements collected within 24-hour periods, thereby atypical data cannot be regarded as erroneous measurements.

Table 1 summarizes the results of the data analysis for 2011, the *RMS* sound pressure values calculated according to relationship (2). The calculations show that the pressure increases on working days and decreases by 10 to 20 mPa on Saturdays and Sundays. Note large changes in the standard deviation values that range from 2 mPa to 8 mPa. The *COV* values range from 3% to 13%, and the highest value is obtained on Mondays. By contrast, the values of $V_{Q_{31}}$ and V_{Q1Q3} are in the range from 2% to 5%, with the highest values recorded on Sundays. The measurement uncertainty is the lowest on Wednesdays (0.56 mPa), with 1.20 mPa on Sundays which is a noticeably lower value than that recorded for Mondays (2.45 mPa).

Table 1. Values of basic statistical measures of $p_{A_{RMS}}$, determined for all 24h periods of the week in 2011

	Med. **mPa**	$\overline{p_{A_{RMS}}}$ **mPa**	$\sigma_{p_{A_{RMS}}}$ **mPa**	***COV*** **%**	Q_{31} **mPa**	$V_{Q_{31}}$ **%**	V_{Q1Q3} **%**	u_A **mPa**
Monday	65.41	63.18	8.13	12.86	1.11	1.70	1.72	2.45
Tuesday	65.31	64.60	5.45	8.44	1.54	2.35	2.33	1.72
Wednesday	65.89	66.55	1.95	2.94	1.72	2.61	2.58	0.56
Thursday	67.08	65.72	7.04	10.71	2.28	3.40	3.40	2.03
Friday	67.29	67.29	3.14	4.66	2.42	3.60	3.58	0.87
Saturday	56.25	56.05	4.58	8.18	1.34	2.39	2.36	1.32
Sunday	47.30	46.53	3.79	8.14	2.43	5.13	5.19	1.20

Table 2 compiles the analysis results for *RMS* sound pressure data collected in 2016. The calculations show that this value varies from about 60 mPa to 65 mPa on working days and decreases by 10 to 15 mPa on Saturdays and Sundays. Standard deviation values range from 4 mPa to 6 mPa. The *COV* is in the range 6% to 10%, with the highest value achieved on Tuesday. By contrast, $V_{Q_{31}}$ and V_{Q1Q3}values range from 3% to 6%, with the highest value recorded on Saturdays. The measurement uncertainty is 1.35 mPa on Saturdays and 1.04 mPa (the lowest) on Fridays.

Table 2. Values of basic statistical measures of $p_{A_{RMS}}$, determined for all 24h periods of the week in 2016

	Med. **mPa**	$\overline{p_{A_{RMS}}}$ **mPa**	$\sigma_{p_{A_{RMS}}}$ **mPa**	***COV*** **%**	Q_{31} **mPa**	$V_{Q_{31}}$ **%**	V_{Q1Q3} **%**	u_A **mPa**
Monday	61.90	61.01	4.66	7.63	2.59	4.18	4.21	1.34
Tuesday	61.73	61.34	5.87	9.57	2.41	3.91	3.87	1.69
Wednesday	60.61	62.56	4.26	6.80	2.28	3.76	3.68	1.23
Thursday	63.05	61.52	5.86	9.53	2.64	4.19	4.24	1.69
Friday	65.33	64.84	3.90	6.01	1.81	2.78	2.77	1.04
Saturday	55.60	56.26	4.86	8.64	3.38	6.08	6.04	1.35
Sunday	50.68	50.80	4.12	8.11	2.38	4.70	4.72	1.19

Analysis of the results in Tables 1 and 2 indicates that the renovation of Popiełuszki Avenue reduced the *RMS* sound pressure on working days. This value changed slightly on Saturdays, but on Sundays it increased by about 10%. The average value of coefficient $V_{Q_{31}}$increased from about 3% in 2011 to around 4% in 2016 while the *COV* did not change and remained at the level of about 8%. The lowest measurement uncertainty was 0.6 mPa in 2011 and 1.0 mPa in 2016. Figure 2 shows the box plots of the *RMS* sound pressures in 2011 and 2016

a) b)

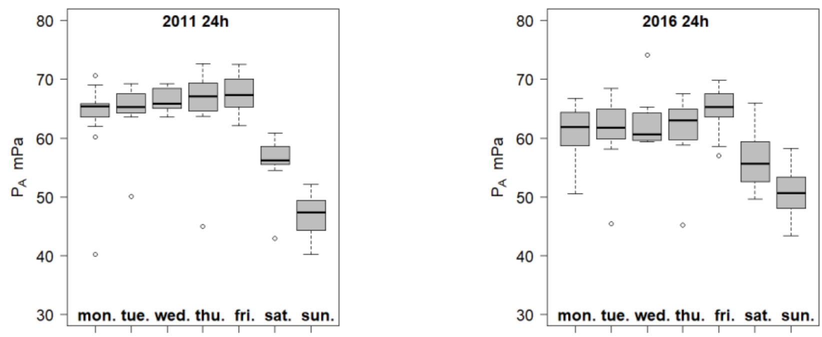

Fig. 2. Box plots of $p_{A_{RMS}}$ for each 24-hour period of the week: a) in 2011, b) in 2016.

The outliers visible in the graphs should be accounted for in the analysis because, in the authors' view, they do not represent measurement errors. Analysis of the measurement results database revealed the outliers on the following days of public holidays in 2011: Easter Monday – Monday, Constitution Day – Tuesday, Corpus Christi – Thursday, Easter Saturday – Saturday, and in 2016; Constitution Day – Tuesday, Corpus Christi – Thursday. The data confirmed a regularity between the box plots in Fig. 2a and in Fig. 2b, showing that the highest *RMS* sound pressure values occurred on Fridays. Figure 3 depicts the $V_{Q_{31}}$ values split into days of the week in 2011 and 2016. The nature of these changes in each year is different, but the coefficients are in the range of about 2% to 6%. The character of the V_{Q1Q3} changes is very similar to that shown in Fig. 3.

a) b)

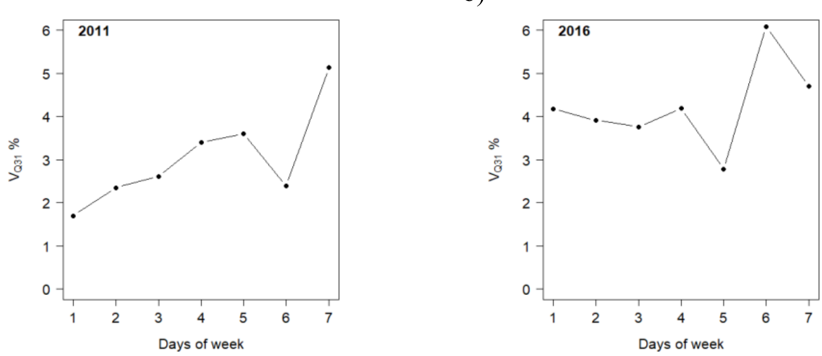

Fig. 3. Relationship between the value of $V_{Q_{31}}$ and particular days of the week a) in 2011, b) in 2016.

Figure 4 shows the changes in measurement uncertainty values of sound pressure u_A and *COV* on particular days of the week. The measurement uncertainty values of sound pressure vary with the year but remain lower than 2.5 mPa, and the differences on Saturdays and Sundays are minor. As for the *COV*, its values in the two years are different, but remain lower than 12.5%, with minor differences on Saturdays and Sundays.

a) b)

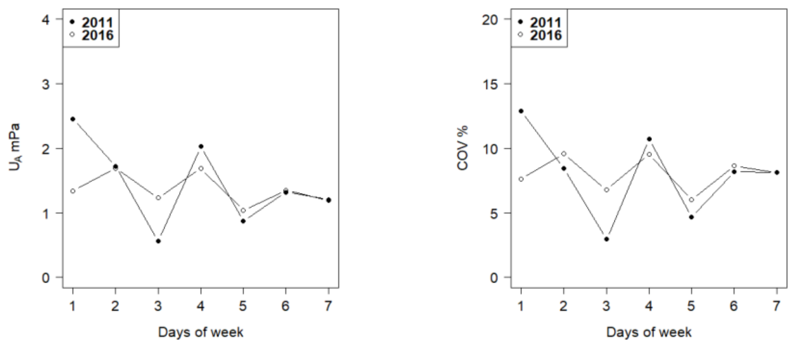

Fig. 4. Comparison of the values of a) sound pressure measurement uncertainty – Type *A* evaluation, b) the *COV*, recorded in 2011 and 2016.

The values of u_A and *COV* against the average value of *RMS* sound pressure are shown in Fig. 5a and 5b.

a) b)

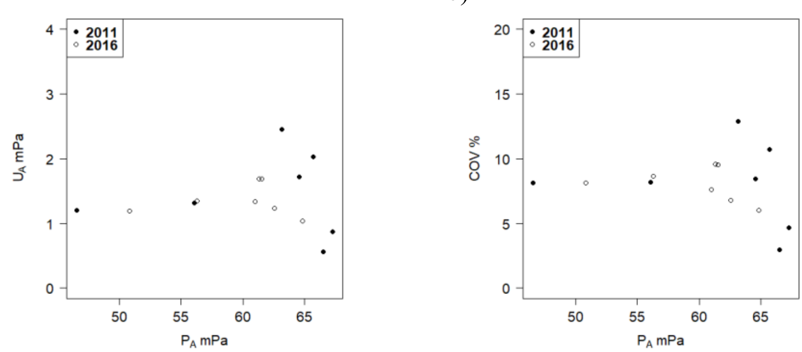

Fig. 5. Average value of the *RMS* sound pressure versus a) sound pressure measurement uncertainty – Type A evaluation, b) the *COV*, for the measurement data of 2011 and 2016.

Both drawings show some similarity despite the fact that they represent different physical quantities. For pressures up to about 60 mPa, the dependencies are close to linear. For higher pressure values, the dependency is difficult to indicate. Note that both parameters i.e., u_A and *COV* depend on the $\sigma_{p_{A_{RMS}}}$ standard deviation. The variability interval of standard deviation in 2011 is significantly higher than in 2016, which results in a large spread in Fig. 5. The $\sigma_{p_{A_{RMS}}}$ parameter values depend on the technical condition of the road and motor vehicles, which in 2011 was far worse than in 2016. As the use of roads causes their wear, the values of u_A, *COV*, $V_{Q_{31}}$ and V_{Q1Q3} will increase over time. This problem requires further analysis.

Conclusions

The data collected for the equivalent sound level, measured over the 24-hour period and generated by vehicles passing along Popiełuszki Avenue, Kielce between March and June in 2011, before road renovation and in the corresponding period of 2016 after the renovation, showed that the $L_{Aeq,T}$ values fluctuated slightly. Analysis of *RMS* sound pressure values revealed that compared with 2011, the *RMS* sound pressure decreased on working days in 2016. There was a minor change on Saturdays, while on Sundays the values increased by about 10%. The average value of the $V_{Q_{31}}$ coefficient of variation increased from about 3% in 2011 to about 4% in 2016 while the *COV* remained at the level of about 8%. The lowest measurement uncertainty was 0.6 mPa in 2011 and 1.0 mPa in 2016. The highest *RMS* sound pressure values were recorded on Fridays. The nature of changes in the sound pressure coefficient varies from day of the week, but is different in each year, but the values of the coefficients range from about 2% to 6%. The sound pressure measurement uncertainties in 2011 and in 2016 were different, but never exceeded 2.5 mPa, and on Saturdays and Sundays differed only slightly. Likewise, the *COV* values in 2011 and in 2016 were different, but never exceeded 12.5% and on Saturdays and Sundays only minor differences were recorded.

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