

Assessment of variability of acoustic power generated by traffic volume

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Abstract. The concept of energy harvesting is a mechanism of deriving energy from the sources present in the environment. Using this energy will enable wireless and portable electronic devices to be completely self-sustaining. A variety of sources are available for energy harvesting, including electromagnetic radiation, vibration-, sound -, and wind- energy. The output power levels from these sources and the mechanisms involved in energy conversion determine its possible applications. The paper analyses the variability of the acoustic power generated by traffic volume. The equivalent sound level was calculated by permanent automatic sound and traffic volume monitoring stations for three time intervals. The measurements were carried out 24 hours a day. In this study, the authors analysed the acoustic power to be able to compare the fixed and variable components. Standard deviation, coefficient of variation, the positional coefficient of variation, and the quartile deviation were proposed for performing a comparative analysis of the acoustic power scattering. The coefficient of variation is a parameter that satisfactorily describes a variable component of acoustic power. Uncertainties of the acoustic power calculation were compared within the periods under analysis.

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1 Sound and traffic volume measurements

The data under analysis were recorded by the automatic permanent traffic volume and sound pressure levels monitoring stations located in Krakowska Road in Kielce [1]. The acoustic measurements were carried out using SVAN 958A device, which is 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 microphone for the acoustic pressure measurements was mounted at a distance of 4 m from the edge of the road at a height of 4 m. The resolution of the RMS detector was 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 equivalent sound level was calculated for three sub-intervals of a 24-hour interval, i.e., from 6:00 to 18:00 (day time), from 18:00 to 22:00 (evening time) and from 22:00 to 6:00 (night time).

The recorded set of data in the form of calculated values of the equivalent sound level comprises 905 records. Due to technical difficulties, the data set is not complete and covers only the period between 8 January and 6 December 2013.

The station includes a road radar box, a sound level meter and a weather station. The traffic volume was measured by WAVETRONIX digital radar with an operating frequency of 245 MHz. The traffic volume and speed data were recorded every 1 minute (buffer) and the averaged results were reported every 1 hour. Owing to some technical problems, the data set was incomplete and comprised 8,375 counts.

Figure 1a shows a box plot of traffic volumes by day of the week.

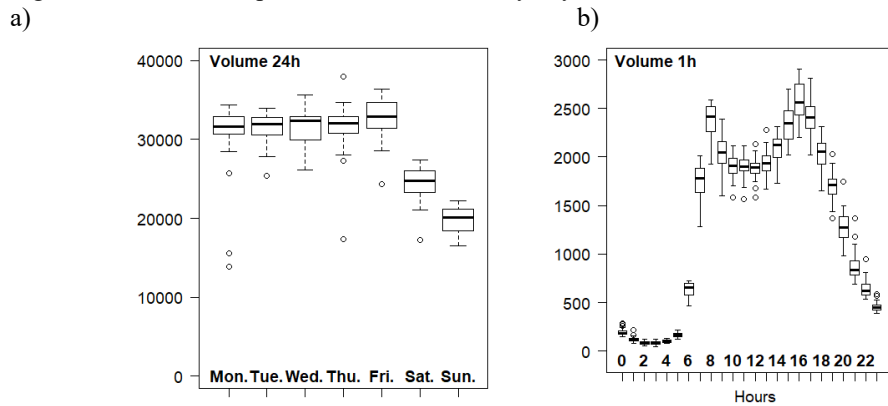


Fig. 1. The box plots of traffic volume a) day-to-day average traffic volume, b) plots of a 24h period for Wednesdays [2]

The plots show that from Monday to Thursday the volumes change slightly, increase on Friday by about 2% and decrease on Sunday by about 37%. The nature of these changes is consistent with the literature of the subject. The calculated average daily traffic volume is 28,906 vehicles and increases by 9% to 31,940 vehicles on working days from Tuesday to Thursday. Passenger cars constitute 76% of the total number of vehicles on a working day. The number of lorries expressed as a percentage is 4% [2]. On Sundays, however, the share of lorries drops to 2% and that of passenger cars increases to 87%. Figure 1b shows time-dependent graphs of selected hourly traffic volume parameters for all vehicles on Wednesdays as a representative of the results obtained for the entire week. Figure 1b shows two local extreme points of traffic volumes occurring at 8.00 and 16.00. The median of the maximum traffic volume is 2560 vehicles/hour.

The most commonly used noise indicators expressed in (dB) are the equivalent sound level ($L_{Aeq,T}$), represented mathematically by:

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

and sound exposure level defined as

$$L_{AE} = 10 \log \frac{1}{T_0} \int_0^T 10^{\frac{L_{pA}(t)}{10}} dt, T_0=1 \text{ s} \quad (2)$$

where:

T – represents the overall measurement time [s],

$p_A(t)$ – is the A -weighted instantaneous sound pressure level [Pa],

p_0 – is the standardized reference sound pressure of 20 μ Pa,

p_{ARMS} – represents the effective sound pressure,

$L_{pA}(t)$ – is the A -weighted sound pressure level.

The Nordic Prediction Method (NPM) [3] was used in this study to determine the equivalent sound pressure level by numerical modelling on the basis of the number of vehicles passing by and their speed. The source strength includes the reflection in the road surface, and assumes a source height of 0.5 m. Omni-directional sources are assumed. The ground surface is flat and acoustically hard. The sound exposure level for light vehicles at a 10 m distance from the road and for one vehicle per second can be calculated as follows:

$$L_{AE,10 \text{ m}}(\text{light}) = 73.5 + 25 \log \left(\frac{v}{50} \right) \text{ for } 40 \frac{\text{km}}{\text{h}} \leq v, \quad (3)$$

$$L_{AE,10 \text{ m}}(\text{light}) = 71.1 \text{ for } 30 \leq v < 40 \text{ km/h},$$

where v is the vehicle speed. For heavy vehicles the corresponding equation is:

$$L_{AE,10m}(heavy) = 80.5 + 30 \log\left(\frac{v}{50}\right) \text{ for } 50 \leq v \leq 90 \frac{km}{h},$$

$$L_{AE,10m}(heavy) = 80.5 \text{ for } 30 \leq v < 50 \frac{km}{h}.$$
(4)

The equivalent sound level for light or heavy vehicle groups and time interval T are as follows:

$$L_{Aeq,T,10m}(light) = L_{AE,10m}(light) + 10 \log\left(\frac{N_{light}}{T}\right)$$
(5)

$$L_{Aeq,T,10m}(heavy) = L_{AE,10m}(heavy) + 10 \log\left(\frac{N_{heavy}}{T}\right)$$
(6)

T – the number of seconds within the time interval for which $L_{Aeq,T}$ is calculated,
 N_{light}, N_{heavy} – the number of light or heavy vehicles recorded at time T .

The equivalent sound level generated by both groups for time interval T can be calculated from:

$$L_{Aeq,T,10m} = 10 \text{Log}(10^{0,1L_{Aeq,T,10m}(light)} + 10^{0,1L_{Aeq,T,10m}(heavy)})$$
(7)

Figure 2 shows the box plots of the equivalent sound level L_{Aeq} recorded at the monitoring station for particular days of the week divided into night, day and evening periods.

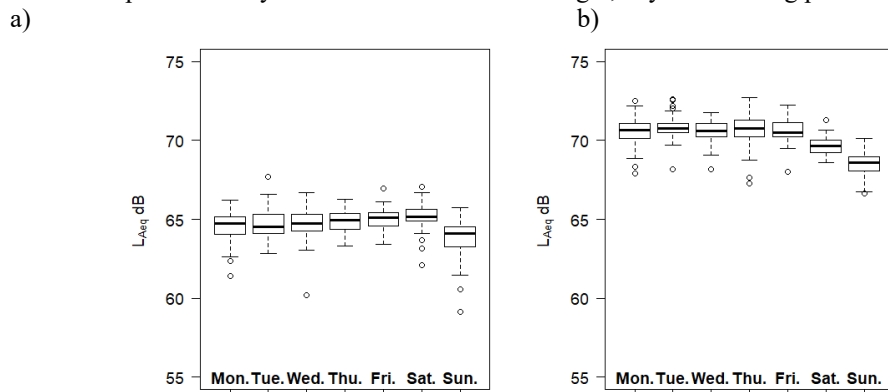


Fig. 2. The box plots of the equivalent sound level L_{Aeq} recorded at the monitoring station for particular days of the week divided into a) night period, b) day period

Between 22.00 and 6.00, the L_{Aeq} values increase slightly on Thursday, Friday and Saturday and then decrease on Sunday. Between 6.00 and 18.00 from Monday to Friday, L_{Aeq} fluctuates slightly and then decreases on Saturday and Sunday.

The acoustic power of the road can be approximated by: [4]

$$W_A = \frac{2\pi r^2 p_{A_{RMS}}^2}{\rho c}, \quad (8)$$

where:

$$p_{A_{RMS}}^2 = 10^{(0.1 * L_{Aeq,T})} \cdot p_0^2, \quad (9)$$

$\rho c = 406 \text{ Ns/m}^3$ – the impedance of air at 22°C ,

$r^2 = 10^2 + (3.5)^2 \text{ m}^2$ – the distance between the source and the microphone.

Let us suppose that impedance and distance from the source are constant and that the acoustic power depends primarily on the square of the acoustic pressure. Figure 3 shows the road acoustic power variations for different sub-intervals of the 24-hour period over the whole year. The analysis of this figure indicates that the acoustic power values changes significantly depend to a large extent on the season of the year. In the summer months for the day time sub-interval, there are periods when these values are relatively low, but at irregular intervals in some weeks, they increase considerably. The changes may be due to the school break and holiday period in those months. The acoustic power variations for the evening sub-interval are similar to those for the day sub-interval. There are also large differences in the acoustic power values between the day and night sub-interval.

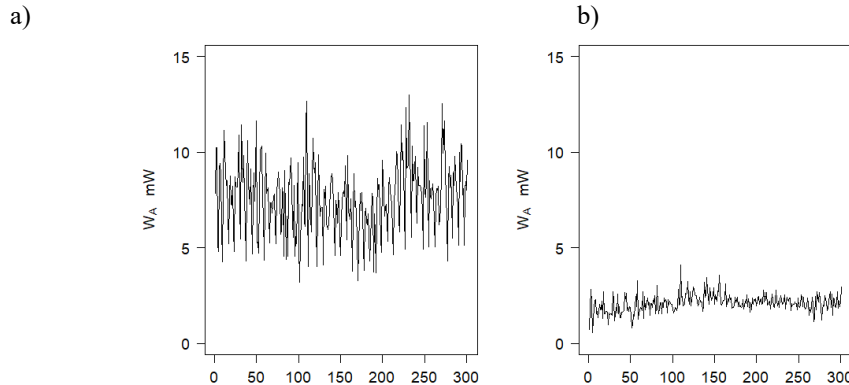


Fig. 3. Road acoustic power calculated from experimental noise data a) for day sub-interval, b) for night sub-interval

Figure 4 compiles the changes in acoustic power by day of the week split into 24-hour period sub-intervals. On working days, the acoustic power values vary slightly regardless of the sub-interval. On working days, variations in acoustic power are only minor, regardless of the sub-interval, with evening and night sub-intervals values being two times less than those for the day sub-interval.

This figure also shows a large amount of outliers with high values, especially for the day and night sub-intervals.

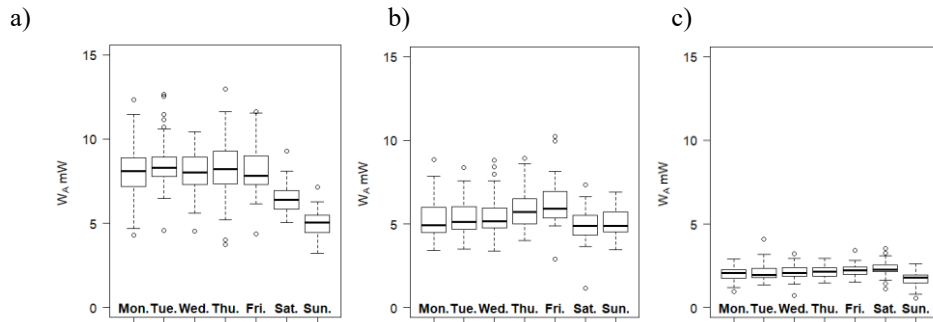


Fig. 4. Road acoustic power calculated from experimental noise data a) for the day sub-intervals, b) for the evening sub-interval, c) for the night sub-interval

2 Acoustic power measurands

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

$$u_A = \sqrt{\frac{1}{n(n-1)} \sum_{i=1}^n (W_{A_i} - \overline{W_A})^2} \quad (10)$$

Standard deviation is an absolute measure commonly used for the analysis of sound variable component. Standard deviation is estimated from (11), where n is the amount of data:

$$\sigma_{W_A} = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (W_{A_i} - \overline{W_A})^2} \quad (11)$$

This parameter defines the average variation in individual acoustic power 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_{W_A}). This coefficient is a dimensionless relative measure that can be used to directly compare the variable components in its several realisations. For the acoustic power tested, the COV_{W_A} can be expressed as:

$$COV_{W_A} = \frac{\sigma_{W_A}}{\overline{W_A}} \cdot 100\% \quad (12)$$

The value of the COV_{W_A} 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:

$$Q_{31} = 0.5 \cdot [Q_3(W_A) - Q_1(W_A)] \quad (13)$$

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 acoustic power). By relating it to the median, the positional coefficient of variation is calculated from (14):

$$V_{Q_{31}} = \frac{Q_{31}}{Med} \cdot 100\% \quad (14)$$

The quartile coefficient of dispersion is a relative measure of variance, calculated from (15):

$$V_{Q_{1Q3}} = \frac{Q_3 - Q_1}{Q_1 + Q_3} \cdot 100\% \quad (15)$$

The positional coefficient of variation and the quartile coefficient of dispersion are positional measures of the data between the first and third quartiles.

3 Results of calculation

Table 1 summarizes the calculation results of these parameters by day of the week and day sub-intervals.

Table 1. Values of basic statistical measures of acoustic power for the day sub-intervals

Day sub-interval	Med. mW	$\overline{W_A}$ mW	σ_{W_A} mW	COV_{W_A} %	Q_{31} mW	Vq %	$V_{Q_{1Q3}}$ %	UA mW
Monday	8.11	8.16	1.70	20.82	0.82	10.07	10.15	0.26
Tuesday	8.29	8.59	1.55	18.02	0.56	6.72	6.67	0.24
Wednesday	8.01	8.06	1.24	15.42	0.82	10.18	10.04	0.19
Thursday	8.24	8.27	1.75	21.11	0.93	11.31	11.18	0.26
Friday	7.81	8.19	1.46	17.77	0.86	11.02	10.56	0.22
Saturday	6.41	6.49	0.92	14.17	0.57	8.82	8.84	0.14
Sunday	5.04	4.98	0.84	16.93	0.51	10.21	10.37	0.13

The Shapiro-Wilk and the Jacob Berry statistical tests showed that there were no grounds to reject the null hypothesis that the acoustic power was consistent with normal. The calculated acoustic power values for working days are about 8 mW and on Sunday they decrease to 5 mW. The coefficient of variation COV_{W_A} is around 21% on Mondays and 14% on Saturdays.

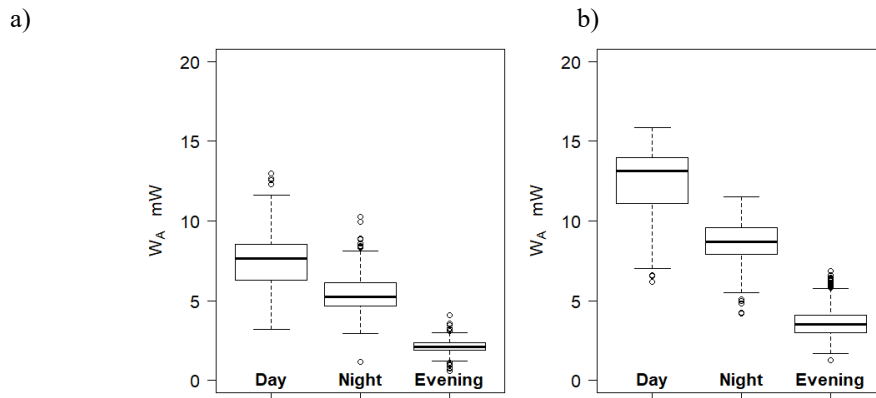


Fig. 5. The Box Plots of the road acoustic power for three sub-intervals of a 24-hour period, a) based on the measured acoustic pressure, b) determined according to the NPM

Figure 5 compares the acoustic power values calculated on the basis of the acoustic pressure determined experimentally and computed according to the NPM for different sub-intervals of the 24-hour period. The comparison of Fig. 5a and Fig. 5b shows the qualitative consistency of the results obtained. There are, however, discrepancies in the calculated power values.

4 Concluding remarks

Road vehicles travelling along Krakowska Road in Kielce are an acoustic source of acoustic power in the range of 2 mW to 8 mW. About 30,000 vehicles travel on this road daily, of which passenger cars amount to 76%. Other vehicles are vans, lorries and motorcycles. The equivalent sound level of these vehicles is about 70 dB. Changes in the values of traffic parameters (traffic rate, speed) cause the variability of acoustic power of this source. These changes are not periodic but dependent on the month of the year, the day of the week and the sub-interval of a 24-hour period. In this study, analysis of the acoustic power parameters by day of the week and sub-interval of the 24-hour period shows that on working days between 6.00 and 18.00, the acoustic power of this source is about 8 mW and decreases to 2 mW on Sundays at night time. The uncertainty of the acoustic power determination for the day sub-intervals ranges from 0.13 mW to 0.26 mW; standard deviation is in the range between 0.84 and 1.75 mW; the COV_{W_A} ranges from 14% to 21%, and V_q and V_{Q1Q3} from 7% to 11%. The NPM noise model used in this study ensures correct determination of acoustic power by 24-hour period sub-intervals. However, some simplifications adopted in this study and in the NPM model cause discrepancies between the acoustic power values calculated based on

experimentally determined noise and traffic parameters, especially noticeable in the case of the day sub-intervals.

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