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Urban tidal flow noise – case study

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Abstract The study carried out an analysis of the urban traffic noise from 2011 to 2016 at Kielce (Poland). The results of noise simulations according to the Cnossos-EU model were compared with the sound level calculated by monitoring station and a very good agreement was obtained. The mean absolute error was smaller than 1 dB(A). For weekdays the charts shape at individual hours of the day were shown to be similar. However, one can notice a different shape of this charts from the morning peak on Friday to the end of the weekend and especially on Saturday and Sunday.

Keywords: urban noise, traffic flow, monitoring station data.

1. Introduction

In the 21st century, a new pattern for a workplace located in the down town has been created, and as a result, in the morning a large number of vehicles enter and in the afternoon a similar number leave the city. This phenomenon called traffic tidal increases the environmental pollution with exhaust emissions, particulate matter, noise and vibrations [1]. For this reason, it is necessary to permanently monitor over a long period of time vehicle traffic and analyse the recorded data [2]. This knowledge is important for example for successfully implementation of intelligent transport systems and will also reduce the costs of verifying noise maps [3, 4]. The paper analyses selected parameters of traffic noise on the national road No 73 on the section from Popiełuszki Avenue to the city of Kielce (Poland) limits using six-year follow-up data recorded in 2011-2016. In the years 2013-2014 this road was thoroughly reconstructed. The pavement structure with SMA11 wearing layers was made. The research reported here, aims at:

- the comparison of the traffic noise in individual days and years of its operation
- study the long-term impact of road reconstruction on traffic noise
- Cnossos-EU model validation in the analysed period.

2. Related works

Studies of the harmful impact of transport means on the environment are presented in the literature in numerous publications [5-7] but mainly for weekdays. Long-term health effects such as cardiovascular diseases, annoyance and sleep disturbance have been related to traffic noise [8]. To assess urban noise cities regularly produce noise maps. The paper [9] presents seasonal and weekday influence on noise indicators based on noise map. Vehicle traffic parameters such as: flow, speed, structure have a significant impact on the air and ground pollution with exhaust emissions, noise and vibrations and other phenomena that create environmental hazards. Maintenance of vehicles, e.g. air pressure in tires, also affects noise and ambient pollution with particulate matter [10]. An additional factor influencing the acoustic climate are the modifications to the road infrastructure, the aim of which may also be to reduce the emission of traffic noise to the environment [11]. That is while it is necessary to permanently monitor over a long period of time vehicle traffic and analyse the recorded data [12]. The variations in traffic volume and noise are of interest e.g. in dynamic traffic management systems and navigation services, assessing the environmental effects of traffic. Stationary monitoring station or low-cost wireless sensor systems, mobile and stationary nodes and citizenship participative initiatives are used to measure urban noise [13]. Determining the models describing the acoustic field caused by road noise forces the solution of many practical engineering problems [14]. Increasingly, in noise modelling, attention is paid to the variability and computational intelligence [15]. Traffic noise in urbanized areas can be analysed depending on the adopted time interval and location of the road in the communication system [16]. Within one week, the traffic noise variability on weekdays differs significantly from the variability on weekends and holidays. The period of one day can be divided into 24 hours. In each subsequent hour of the day, traffic noise parameters may be different. The problem of traffic noise at weekends has been analysed much less frequently in the literature, which is mainly due to the lower traffic intensity, especially of heavy vehicles. However, as the authors' research has shown, it does not cause significant changes in the sound pressure level [2]. The goal of this research was to obtain an insight into the traffic noise profiles according to the day of the week, accuracy of noise measurements and Cnossos-EU model validation.

3. Measurements and calculations results

The data under analysis were recorded by automatic sound and traffic volume permanent monitoring station located in Popiełuszki Avenue in Kielce and is presented on Fig. 1. 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, which is directly connected with the Trans-European Transport Networks. The measurements of traffic flow in four lanes were documented at one hour intervals throughout the entire 24 hours of the day. The results of acoustic measurements performed during the period from 25/03/2011 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-weighted equivalent continuous sound pressure level were registered in the buffer every 1 s and the results were recorded every 1 minute. The data collected formed the basis for A-weighted equivalent continuous sound pressure 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 lane 1at a height of 4 m. Traffic volume was measured with a digital radar 245 MHz by WAVETRONIX.

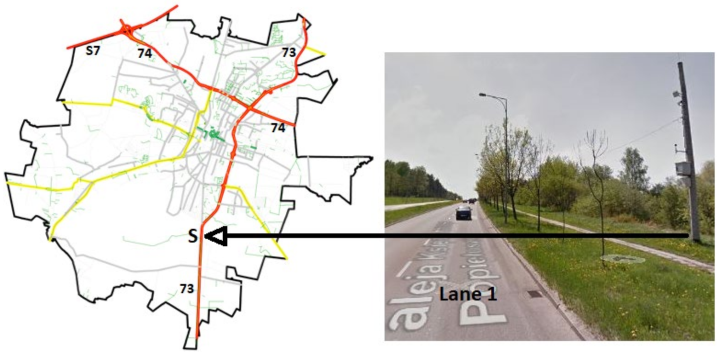

Figure 1. Layout of streets in Kielce and position of monitoring station [12].

The most common noise indicator used is the A-weighted equivalent continuous sound pressure level (L_{Aeq}), expressed in dB(A), defined as:

$$L_{Aeq} = 10 \cdot \log\left[\frac{1}{T}\int_{0}^{T}\left(\frac{p_A(t)}{p_0}\right)^2 dt\right] = 10 \cdot \log\left[\left(\frac{p_{A_{\mathrm{RMS}}}}{p_0}\right)^2\right], \tag{1}$$

where: T – represents the overall measurement time, [s]; $p_A(t)$ – A-weighted sound pressure [Pa]; p_0 – is the standardized reference sound pressure of 20 [μPa], $p_{A_{\mathrm{RMS}}}$ – represents the effective sound pressure [Pa]. The knowledge only of the value of traffic noise is not sufficient to analyse this problem. Having additional information about the uncertainty u_A and the Root Mean Square Error (RMSE) or Mean Absolute Error (MAE) of results significantly extends the knowledge about the tested phenomenon. Standard uncertainty of the A-weighted equivalent continuous sound pressure level, determined in the Type A evaluation, can be calculated from the following relationship:

$$u_A(L_{\text{Aeq}}) = \sqrt{\frac{\sum_{t=1}^{n}(L_{\text{Aeq},t} - \overline{L_{\text{Aeq}}})^2}{n(n-1)}}, \tag{2}$$

where n is the amount of data, and $\overline{L_{Aeq}}$ is median from n observations of L_{Aeq}.

In many cities, traffic measurement systems only record traffic volume and speed. To make full use of the data obtained in this way to assess environmental pollution, a noise model is still needed. In the Cnossos-EU model the sound power level was divided on two parts – propulsion ($L_{WP,i,m}(v_m)$) and rolling ($L_{WR,i,m}(v_m)$) noise [2]. The sound power level emitted by one of the vehicle category m and in octave band number i is:

$$L_{W,i,m}(v_m) = 10 \cdot \log(10^{\frac{L_{WR,i,m}(v_m)}{10}} + 10^{\frac{L_{WP,i,m}(v_m)}{10}}, \tag{3}$$

where: i – number of octave bands, from i=2 for f_0=125 Hz up to i=7 for f_0=4000 Hz, m – vehicle categories (m=1-light motor vehicles, m=2-medium heavy vehicles, m=3-heavy vehicles, m = 4-powered two-wheelers), v_m –rolling speed of vehicle category m. If a steady traffic flow of vehicles of category m per hour is assumed with an average speed v_m the directional sound power level per 1 m per frequency band i of the source line determined by the vehicle flow is defined by:

$$L_{Weq,i,m} = L_{W,i,m}(v_m) + 10 \cdot \log\left(\frac{Q_m}{1000 \cdot v_m}\right), \tag{4}$$

where: Q_m– traffic flow of vehicles of category m per hour with an average speed v_m.

In urban areas the distribution of values of traffic flow and rolling speed may differ from normal [2]. Therefore, the median was used in the calculations and not the average value. The slope of the road also has a certain impact on the noise level values and a correction related to this has been included in the model. The values of the other parameters of the model were assumed to be in accordance with the nominal ones. The conditions of deteriorating road quality were not taken into account.

The tests for the components contained in the acoustic signals were based on the percentiles: Q10, Q25, Q50, Q75, and Q90 defined as the values of noise exceeded by the signal respectively in: 90% (Q10 – average background noise level), 75%, 50% (median), 25%, or 10% (Q90 – av. peak level) of the measurement period. The discrepancies between measurement and model data can be estimated as follows:

– Mean Absolute Error (MAE)

$$\text{MAE} = \frac{1}{n}\sum_{t=1}^{n}\left|L_{Aeq,t(measurement)} - L_{Aeq,t(model)}\right|, \tag{5}$$

- Root Mean Square Error (RMSE)

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{t=1}^{n}\left(L_{Aeq,t(measurement)} - L_{Aeq,t(model)}\right)^2}. \tag{6}$$

The traffic parameters analysed in this study were measured by the permanent automatic monitoring station recording traffic volume, velocity and sound pressure levels with the difference that the noise in May and June 2016 was recorded every 1 hour. To compare the results of noise studies the authors used parameters such as: percentiles of L_{Aeq}, RMSE, MAE. The deteriorating condition of the road and the nuisance associated with its renovation contributed to a decrease in traffic volume in the years 2011 to 2016 by 9.7%. In 2016, there was an increase in traffic volume (compared to 2011) for all vehicles by 13.1% [12]. The intersections of the road with traffic lights and speed cameras built as part of the renovation contributed that the median average speed in the period studied slightly changed especially during traffic rush hours [12]. The reconstruction of the analysed section of road No. 73 was also aimed at reducing the acoustic nuisance of vehicle traffic [17]. Figures 2 and 3 contains the measurement results for the A-weighted equivalent continuous sound pressure level for two time intervals: 24h sub-interval and sub-interval day (from 6.00 to 18.00), recorded in 2011 and 2016. It can be noted that both before and after the reconstruction of the road, the medians on weekdays except Fridays are almost constant, but for each studied year and time interval they take different values. The box plots in Fig. 2 and Fig. 3 indicate that despite the reconstruction of the road, the values of noise level underwent only slight changes. The calculations of the A-weighted equivalent continuous sound pressure level values in 2011 showed that the median on weekdays in sub – intervals day range from 71.8 dB(A) to 72.0 dB(A) and decreases up to 68.9 dB(A) on Sundays. One should also pay attention to the values of the other traffic noise percentile e.g. Q90,

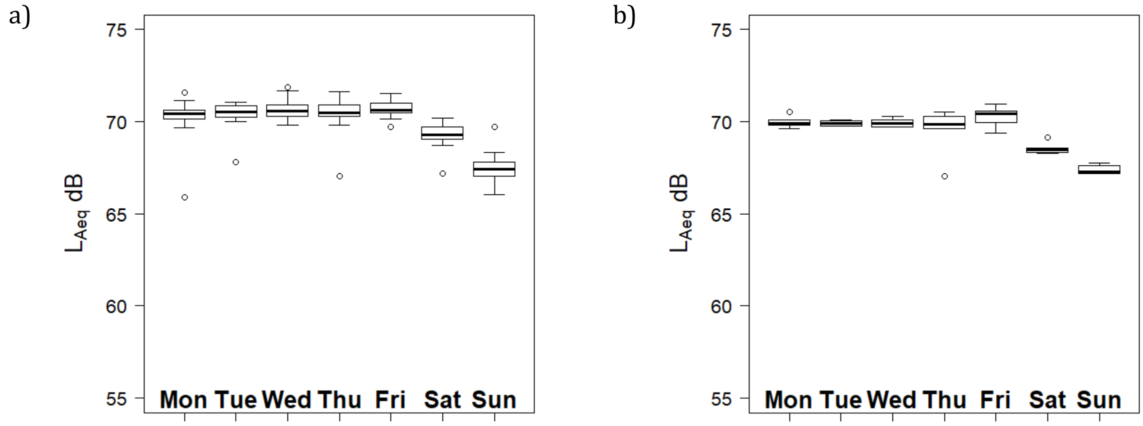

Figure 2. Box plots for A-weighted equivalent continuous sound pressure level measured for each average annual day of the week: for 24h sub-interval a) before road reconstruction in 2011, b) after road reconstruction in 2016.

which on some days are much higher than the median –e.g. on Fridays in 2014 (road works) Q50 – 67.8 dB(A) but Q90 – 77.5 dB(A). It can then cause much greater nuisance than the median value would suggest. But in 2011 percentile Q90 of L_{Aeq} range from 72.3 dB(A) to 72.8 dB(A) on weekdays and was equal to 69.2 dB(A) on Sundays. The median of L_{Aeq} values in 2016 on weekdays range from 71.4 dB(A) to71.5 dB(A) and decreases up to 68.3 dB(A) on Sundays. But percentile Q90 of $L_{Aeq,T}$ range from 72.4 dB(A) on weekdays to 68.8 dB(A) on Sundays. Measured noise levels far exceed the World Health Organization's recommended reduction of road traffic noise levels below 53 decibels. Road traffic noise above this level is associated with adverse health effects, increased drug use and traffic accidents [5].

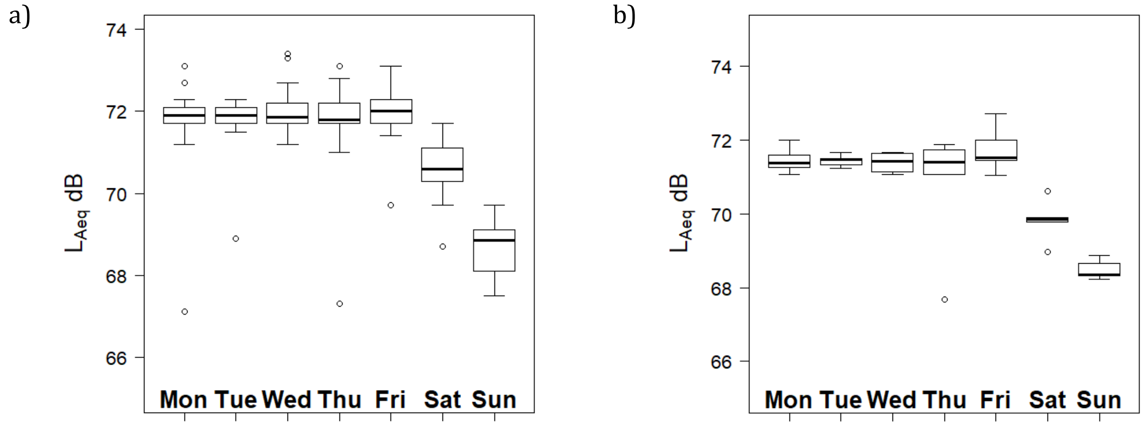

Figure 3 . Box plots for A-weighted equivalent continuous sound pressure level-measured for each average annual day of the week for sub-interval from 6.00 to18.00: a) before road reconstruction in 2011, b) after road reconstruction in 2016.

Noise values greater than percentiles Q25 and less than Q75 measured in 2011 are included in a wider range than the measured ones in 2016. The type A uncertainty of the results of these noise measurements is less than 0.60 dB(A). Figures 2 and 3 allow to estimate the variability of traffic noise in an approximate manner [18].

In order to carry out a more detailed analysis, the authors decided to investigate the hourly variability of traffic noise in the 24-hour interval. The recording of noise levels values every 1 hour was carried out in May and June 2016. In order to validate the model, the values of the L_{Aeq} (based on vehicle traffic parameters) were determined using the Cnossos-EU model for those days for which we had measured noise values. This approach allows direct comparison of the calculated values with the measured ones. Due to various technical problems, the recorded values of vehicle traffic and noise parameters were complete for 39 days. Figure 4 shows, as examples, the recorded results of noise measurements in June 13 - 19.06.2016, in order to compare with the noise values calculated according to the Cnossos-EU model during this period. Figure 4a shows the results of calculations according to the Cnossos-EU model and Fig. 4b shows the results recorded by the noise monitoring station. It can be noticed the satisfactory similarity of these drawings, especially on weekdays. However, during the morning to afternoon rush hour, there are some differences. The local extreme points of traffic noise on weekdays occurred at about 8.00 and 16.00. During these hours, the values of both decreases and increases in noise levels for measurement data are greater than for model ones. This may be due to anomalous noise events [19] and the fact that the Cnossos-EU model is a static-dynamic model but the traffic parameters of vehicles changes dynamically. On Saturdays and Sundays there are differences in both shapes and values of noise charts.

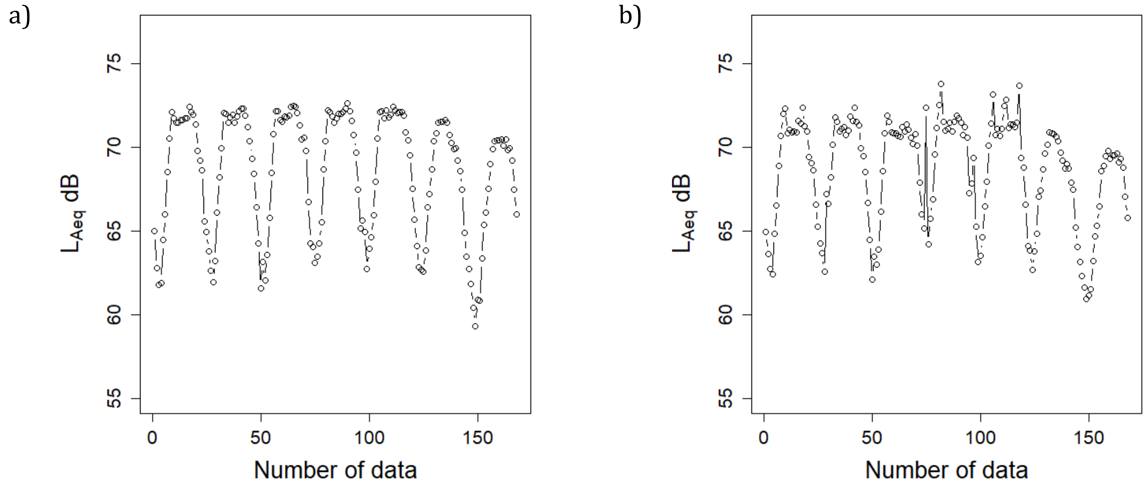

Figure 4. A-weighted equivalent continuous sound pressure level for week from 13.06.2016 to 19.06.2016: a) Cnossos-EU model calculations results, b) measurement data.

The largest discrepancies between the hourly median values occur at 16.00, for the model - 72.19 dB(A) and from the measurements - 71.37 dB(A). The knowledge only of the value of traffic noise in each hour of the day is not sufficient to analyse this problem. Additional information about the uncertainty u_A and the RMSE or MAE significantly extends the knowledge about the tested phenomenon [20]. The RMSE parameter for the noise values presented on Fig. 4 is equal to 0.94 dB(A). The type A uncertainty of the calculated and measured values of the A-weighted equivalent continuous sound pressure level is less than 0.5 dB(A) and occurs at 8.00.

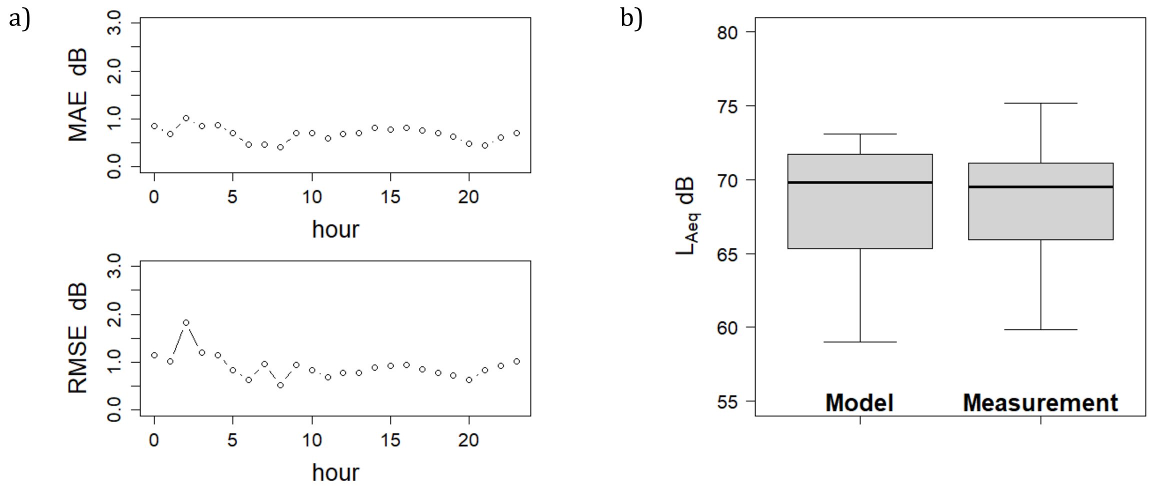

Figure 5. Assessment for model and measurement data for 2016: a) time-dependent values of MAE and RMSE parameters, b) boxplots of equivalent sound level.

Additional information about the analysed phenomenon is provided by the box plot of the A-weighted equivalent continuous sound pressure level shown in Fig. 5. The box plots in Fig. 5b show that the median noise calculated according to the Cnossos-EU model is slightly higher than the measured one. Noise values greater than percentiles Q25 and less than Q75 calculated according to the model are included in a wider

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range than the measured ones. The values of the MAE parameter on Fig. 5a range from about 0.5 dB(A) to 1 dB(A). In contrast, RMSE values range from about 0.5 dB(A) to 2 dB(A). The largest discrepancies in the values of these two parameters occur at 2.00.

The discrepancies in the values of the measured and calculated noise levels are confirmed by graphs of the Q10 and Q90 percentile dependencies as a function of time. These discrepancies are greatest during the morning rush hour and the smallest during the afternoon rush hour, as shown in Fig. 6.

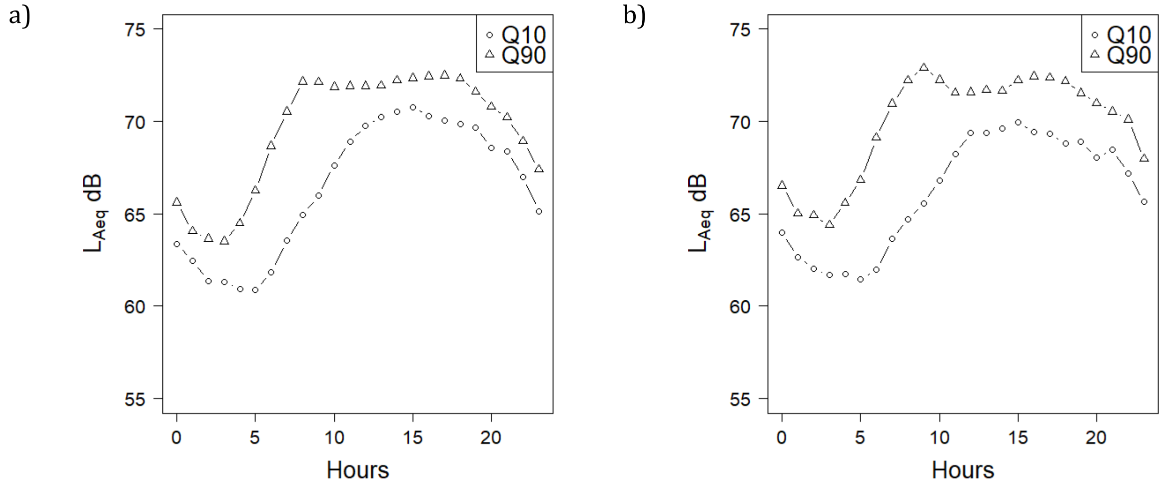

Figure 6. Percentiles Q10 and Q90 of equivalent sound level:
a) Cnossos – EU model calculation results, b) measurement results.

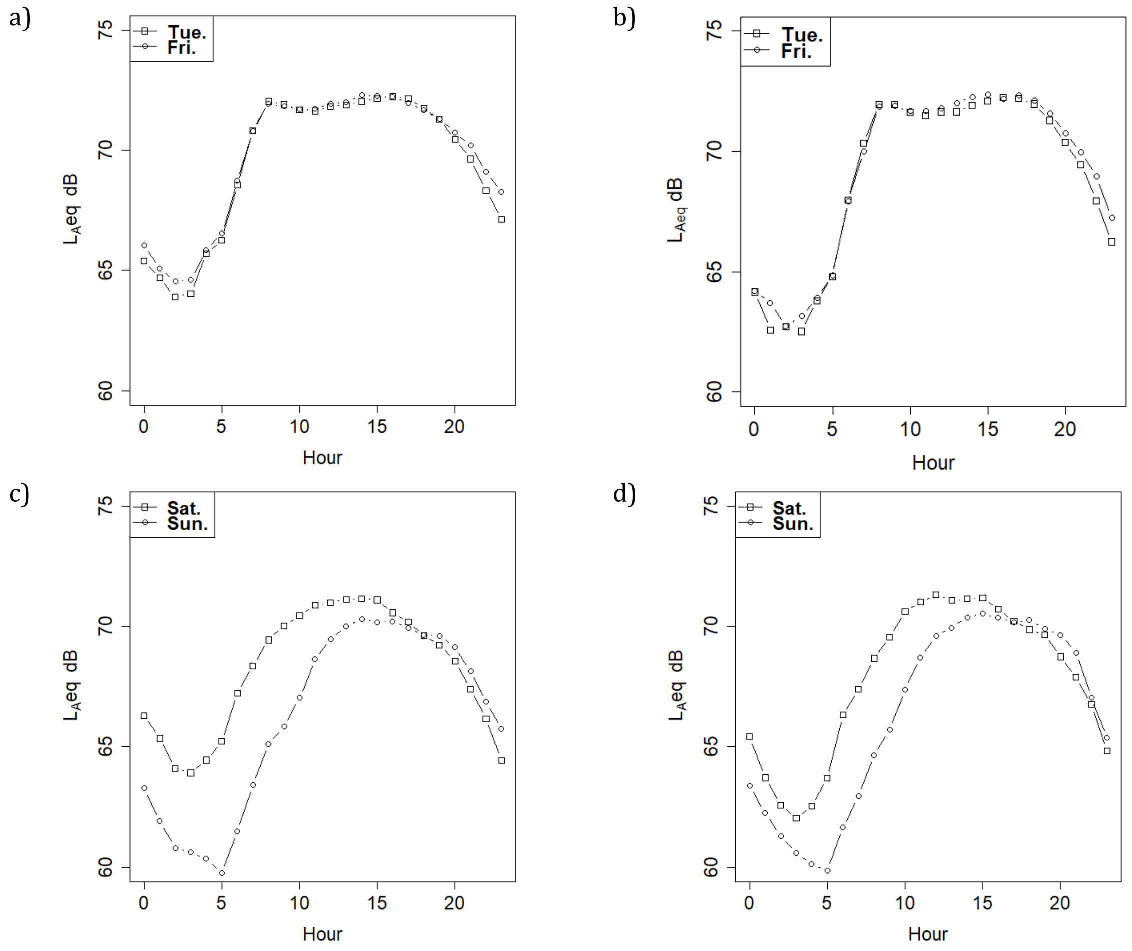

Figure 7. Median of A-weighted equivalent continuous sound pressure level calculated with Cnossos – EU model for: a) Tuesdays and Fridays in 2011, b) Tuesdays and Fridays in 2016, c) Saturdays and Sundays in 2011, d) Saturdays and Sundays in 2016.

The maximum values of percentiles Q90 in the morning peak according to the model are at 8.00 and from measurements at 9.00 (between 8.00 and 10.00). During morning peak hours, experimental values decrease to a greater extent than model ones, which justifies aggregating the results in shorter time intervals, e.g. every 15 minutes or 30 minutes. Noise values in the afternoon peak according to measurements are lower than in the morning peak. The values of the RMSE parameters for both graphs in Figure 6 are approximately equal to 0.62 dB(A).

The comparison of simulations results carried out according to the Cnossos-EU model are presented in Fig. 7. The charts of traffic noise shown in Figs 7 indicate both similarities of variability on weekdays and some differences particularly on weekends. It can be noticed in these graphs the similarity of curves showing changes in noise values regardless of the weekday and the year under study. It can also be noted that in 2016 there was a decrease in noise values at night and in the morning, except for Sundays. But, the noise curve slope rate (in the morning) in 2016 is higher than in 2011.The time distributions of noise values on Saturdays and Sundays are varied.

4. Conclusions

Two years after the reconstruction of the road, the values of noise level underwent only slight changes. The median of A-weighted equivalent continuous sound pressure level as well as maximum sound pressure level decreased about 1 dB(A) despite the fact that in 2016, there was an increase in traffic volume (compared to 2011) for all vehicles by 13.1%.

There is a satisfactory similarity of noise graphs on weekdays however, during in the early hours of the morning and in the late evening hours, there are some differences. The local extreme points of traffic noise on weekdays occurred at about 8.00 and 16.00. On Saturdays and Sundays there are differences in both shapes and values of noise charts.

During rush hours, the values of both decreases and increases in noise levels for measurement data are greater than for model ones. This may be due to acoustic events and the fact that the Cnossos-EU model is a static-dynamic but traffic flow parameters changes dynamically. The type A uncertainty of the calculated and measured values of the equivalent sound level is less than 0.6 dB(A). The RMSE values range from about 0.5 dB(A) to 2 dB(A)

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Additional information

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

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