Urban Traffic Noise of Heavy Vehicles in Octave Bands

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Abstract

In this paper same results of heavy vehicles traffic measurements were used to simulate the noise measurands by the CNOSSOS-EU method for this purpose. The heavy vehicles traffic volume and velocity were recorded by permanent automatic monitoring station. The noise was calculated in octave bands according to the CNOSSOS-EU method. The positional and not positional measures of traffic noise were proposed for data scattering. The results was described using parameters such as the median, average peak noise, average maximum noise, average background level, first and third quartiles and relative measures of noise. Analyzes carried out for the tested section of the road showed that the traffic of heavy vehicles is not always the main source of road noise. It has been shown that maximum values of the acoustic pressure occur for the frequency of f_0 = 500 Hz. The dispersion of noise and type A uncertainty of the results were evaluated.

Keywords: urban noise, CNOSSOS-EU method, heavy vehicles

1. Introduction

A common noise prediction model was adopted by the member states of EU and is specified in Directive 2015/996/EC. The ultimate scope is to enhance the reliability and comparability of noise data in EU [1, 2]. Traffic noise and vehicle monitoring systems using permanent monitoring terminals were installed in some cities e.g. Lisbon to record the values of the measurands throughout the year. Such systems were constructed in Kielce - an example of a medium-size town (a population of approximately 200,000) located in the southern part of central Poland. Kielce has more than ten such stations, both in the centre and on the outskirts. The measurements results of heavy vehicle traffic flow from two vehicular lanes running towards the town and two lanes running towards Kraków were analysed. Computer simulation of the acoustic pressure in octave bands, in accordance with the CNOSSOS-EU model were carried out.

2. Traffic volume and noise measurements

Traffic noise and volumes analyzed in this study were measured by the permanent station recording traffic volume and sound pressure levels, located in Krakowska Street in Kielce. This street is the main part of the outward route from the center of Kielce towards Kraków, and carries both urban, suburban and transit traffic. The measurements from two vehicular lanes running towards the town (lane 1-2) and two lanes running towards Kraków (lane 3-4) were analysed. The station includes a road radar box, a sound level meter and a weather station. The traffic volume and speed were measured by WAVETRONIX digital radar with an operating frequency of 245 MHz. The acoustic microphone was positioned at a distance of 4 m from the edge of the lane 1-2 at a height of 4 m.

The measurements were documented at one hour intervals throughout the entire 24 hours of the day (1:00-24:00) throughout the year 2013. The traffic volume and speed data were recorded every 1 minute (buffer) and the averaged results were reported every 1 hour. The counts were used to calculate the traffic flow (understood as the sum of the number of vehicles recorded within a time interval) and speed, split into hours.

Detailed analyzes were carried out for the day sub-interval (date registered from 6.00 to 18.00) of a 24-hour period because it is the most burdensome time interval of the whole day. The results analyzed contained heavy vehicle traffic flow together with vehicle average speeds measurements. In this work analysis was based on the measurements in working days. The study showed that measurements carried out only on one working day (e.g. Wednesday), may not be representative.

3. Simulation of traffic noise measurands according with CNOSSOS-EU Method calculations

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 and rolling noise [3]. Propulsion sound power level is given by:

$$L_{WP,i,m}(v_m) = A_{P,i,m} + B_{P,i,m} \cdot \left(\frac{v_m - v_{ref}}{v_{ref}} \right) + \Delta L_{WP,i,m} \quad (1)$$

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,

v_{ref} – reference speed equal to 70 km/h,

$A_{P,i,m}$, $B_{P,i,m}$ – coefficient for each octave band and for each vehicle category at the reference conditions,

$\Delta L_{WP,i,m}$ – sum of correction coefficients for deviations from reference conditions.

Rolling sound power level:

$$L_{WR,i,m}(v_m) = A_{R,i,m} + B_{R,i,m}\log\left(\frac{v_m}{v_{ref}}\right) + \Delta L_{WR,i,m} \tag{2}$$

where:

$A_{R,i,m}$, $B_{R,i,m}$ – coefficient for each octave band and for each vehicle category at the reference conditions,

$\Delta L_{WR,i,m}$ – sum of correction coefficients for deviations from reference conditions.

Correction coefficients were not taken into account in the paper. The sound power level emitted by one of the vehicle category *m* and in octave band number *i* is:

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

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 meter length 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.

The acoustic pressure to the second power, measured by microphone, generated by vehicles category *m* in octave band *i* we can calculate according to formula:

$$p_{i,m}{}^2 = \sum_{j=1}^{Q_t} p_0^2\cdot 10^{\left(L_{Weq,i,m} + 10\cdot\log\left(\frac{l_S}{Q_t}\right) - 20\log(R_j) - 8\right)\cdot 0.1} \tag{5}$$

where:

l_S – length of a source line with homogeneous traffic,

Q_t – amount of source line segments,

p_0 – reference sound pressure equal to $2\cdot10^{-5}$ Pa,

j – index of source line segments,

R_j – distance of the center of the *j* source line segments from the measuring microphone.

In the paper, the tests for the variable components contained in the signals were based on measures [4]:

- median C_{50} – defined as the sound pressure value exceeded by the signal in 50% of the measurement period,
- the percentile C_{10} – defined as sound pressure value exceeded by the signal in 90% of the measurement period was used to assess average background noise level,
- the percentiles C_{25} and C_{75} are defined as the values of sound pressure value exceeded by the signal respectively in 75% or 25 % of the measurement period,

- to assess the average peak level the percentile C_{90}, defined as sound pressure value exceeded by the signal in 10% of the measurement period was used,
- to assess the average maximum noise the percentile C_{99}, defined as sound pressure value exceeded by the signal in 1% of the measurement period was used,
- range between 10 and 90 percentile, in which 80% of all data is included

$$C_{[10,90]} = [C_{10}(p_i), C_{90}(p_i)] \tag{6}$$

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

$$u_A = \sqrt{\frac{1}{n(n-1)}\sum_{1}^{n}(p_i - \overline{p_i})^2} \tag{7}$$

where n is the amount of data.

In this study, the authors analysed acoustic pressure values p_i expressed in terms of pascals to be able to easily compare the fixed components (median) and variable components of the acoustic pressure signals. The tests for the variable components contained in the signals were based on the measures: coefficient of variation [5], quartile deviation (Q_{31}), quartile variation coefficient ($V_{Q_{31}}$), and quartile coefficient of dispersion (V_{Q1Q3}). The influence by atypical data, taken into account in the analyses is less significant when positional measures are used. The measure of dispersion of the variable is the average quartile deviation:

$$Q_{31} = 0.5 \cdot [C_{75}(p_i) - C_{25}(p_i)] \tag{8}$$

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). By relating it to the median, the positional coefficient of variation is calculated from (9):

$$V_{Q_{31}} = \frac{Q_{31}}{Med} \cdot 100\% \tag{9}$$

It is a dimensionless relative measure that can be used to directly compare the variable components in its several realisations.

The quartile coefficient of dispersion is a relative measure of variance, that can be calculated from (10):

$$V_{Q1Q3} = \frac{Q_3 - Q_1}{Q_1 + Q_3} \cdot 100\% \tag{10}$$

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. Those measures determine the variability of acoustic pressure. It was assumed in this paper that the acoustic source are:

- entry traffic on two lanes, that leads from Kraków towards Kielce– denoted as lanes 1-2,
- exit traffic on two lanes, that leads from Kielce towards Kraków – denoted as lanes 3-4.

It has been assumed in accordance with the CNOSSOS-EU noise model that the linear acoustic source is located along the symmetry axis of the respective lanes. Thus, the work analyzed the results of computer simulations of acoustic pressure in the place where the measuring microphone is located, i.e. at a distance of 4 m from lanes 1-2 and at a height of 4 m for two incoherent acoustic sources using measurements of relevant parameters of road vehicles. The acoustic pressures generated by these sources were also added up, which allows to assess the total noise generated by the examined road section. In [6], the values of the equivalent sound level (for all vehicles) experimentally measured and calculated according to the CNOSSOS-EU method were compared by calculating the root mean square error (RMSE) parameter. The calculated value of this parameter is about 1 dB.

4. Results

Figure 1 presents the averaged results of traffic volume measurements for heavy vehicles in subsequent hours of working days. Comparing figure 1a with 1b, there are some significant differences. In both drawings there is a local maximum of traffic volume at 9.00 (the so-called morning peak). In contrast, the afternoon peak occurs only in figure 1b (at 17.00).

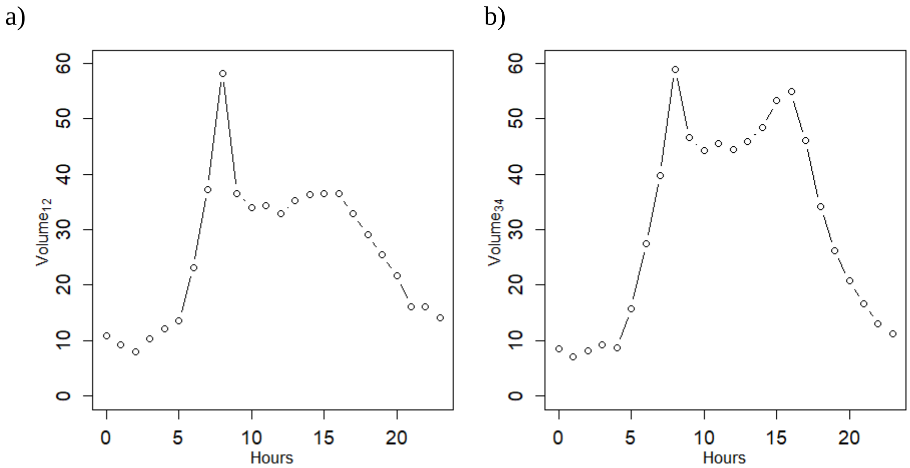

Figure 1. Average values of traffic flow (on working days in 2013) for heavy vehicles: a) on lanes 1-2, b) on lanes 3-4

Heavy vehicles traffic flow graphs on arbitrarily selected two Wednesdays in 2013 are shown in Figure 2. The graphs show that the measured traffic flow over the 24 hours may not be representative of the entire year. This conclusion justifies the need for long-term monitoring of heavy vehicles traffic.

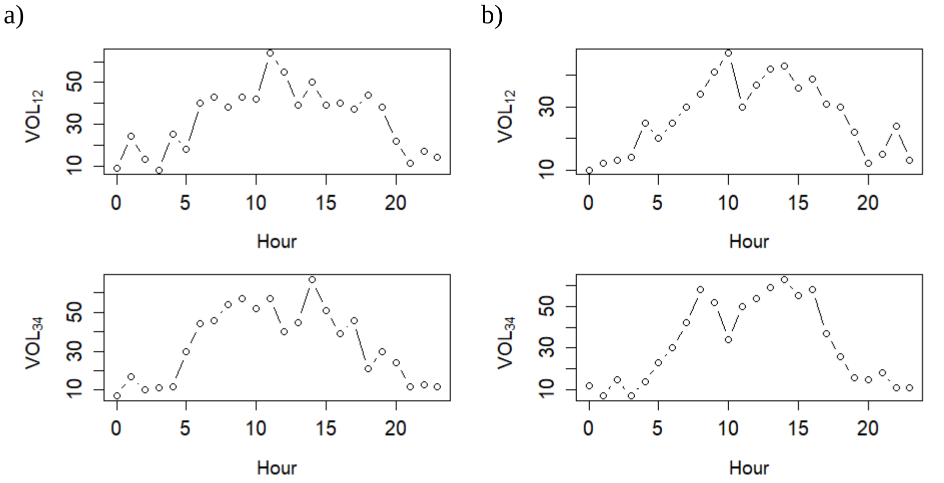

Figure 2. Traffic flow for heavy vehicles on lanes 1-2 or 3-4:
a) on Wednesday - 26 06.13, b) on Wednesday - 03.07.13

Shapiro-Wilk and Jarque-Bera tests showed that the acoustic pressure distributions generated by heavy vehicles are not compatible with the normal distribution. Histograms of acoustic pressure distributions on working days of 2013 for heavy vehicles including a 1-2 or 3-4 lane confirmed deviations from the normal distribution. Examples of histograms in the octave band f_0 = 500 Hz are shown in figure 3. Values of selected data distribution parameters are: for figure 3a: skewness is 2.6 and kurtosis is 15.7, for figure 3b: skewness is 0.03 and kurtosis is 6.5. Note the diverse forms of these distributions on each lane.

Table 1 summarizes the results of the data analysis for values of acoustic pressure parameters in selected octave bands, on working days for the day sub-interval , generated by vehicles of all categories calculated by the CNOSSOS-EU method. Maximum values of median as well as percentiles C_{10} and C_{90} were obtained in an octave with a central frequency of f_0 = 1000 Hz. The minimum values of these parameters were obtained in an octave with frequency f_0 = 4000 Hz. The values of the parameter C_{99} in relation to the value of C_{90}, for lanes 1-2: in an octave with frequency f_0 = 125 Hz are 80% higher. In other octave bands these differences are not so significant. For the frequency f_0 = 1000 Hz they are about 5%. Values of coefficients of variation are in the range from 3% to 5% and uncertainty u_A is less than 0.10 mPa. Differences in the values of the same parameters (C_{90} and C_{99}) but for lanes 3-4 are smaller and for the octave band f_0 = 1000 Hz they are about 6 %. Values of coefficients of variation for lanes 3-4 are from 4.5% to 6%. The value of the C_{99} parameter is greater than C_{90} by about 6% to 8%. The maximum values of the parameters of the sum of the acoustic pressure generated by lanes 1-2 and 3-4 occur in the octave band f_0 = 1000 Hz. Only the maximum value of the C_{99} parameter in the f_0 = 125 Hz band is higher than C_{90} by about 50 %.

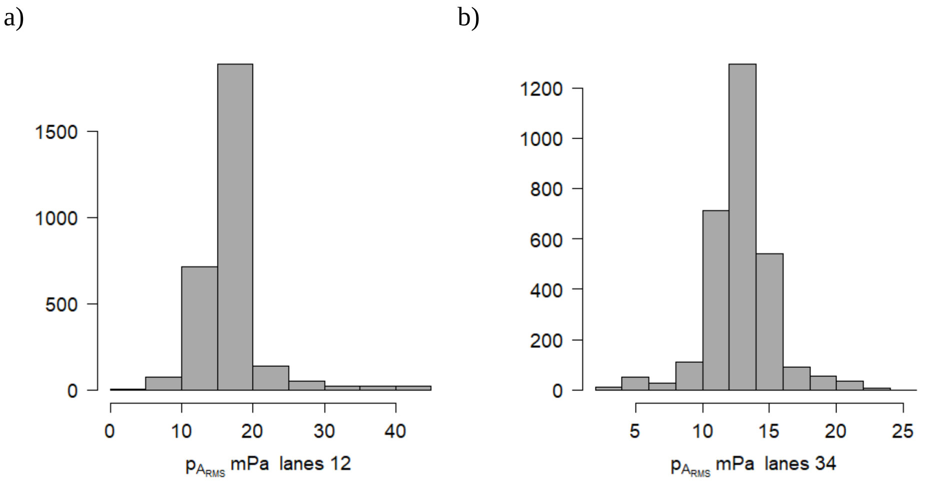

Figure 3. Acoustic pressure distribution in octave band f_0 = 500 Hz in working days 2013: a) on lanes 1-2, b) on lanes 3-4

Table 1. The values of sound pressure parameters on working days for the day sub-interval, generated by vehicles of all categories calculated by the CNOSSOS-EU method, in selected octave bands

Central frequency band f_0 [Hz]	Med. [mPa]	Q_{31} [mPa]	Vq [%]	V_{Q1Q3} [%]	u_A [mPa]	C_{10} [mPa]	C_{90} [mPa]	C_{99} [mPa]
values of sound pressure parameters generated by all vehicles on lanes 1-2								
125	27.98	1.26	4.50	4.49	0.10	25.36	31.19	55.76
500	31.69	1.38	4.36	4.36	0.07	28.67	34.66	47.23
1000	42.85	1.23	2.88	2.88	0.06	39.49	45.14	47.47
values of sound pressure parameters generated by all vehicles on lanes 3-4								
125	21.63	1.30	6.01	5.96	0.05	18.82	24.66	26.97
500	25.78	1.41	5.46	5.43	0.06	22.34	28.90	31.16
1000	32.43	1.49	4.58	4.57	0.06	28.58	35.61	37.45
values of sound pressure parameters generated by all vehicles on lanes 1-2 and 3-4								
125	35.48	1.59	4.48	4.47	0.10	32.23	39.45	60.81
500	40.99	1.76	4.30	4.31	0.09	37.14	44.74	55.23
1000	53.88	1.72	3.19	3.20	0.08	49.62	56.94	59.25

Table 2 compiles the analysis results for acoustic pressure parameters in selected octave bands, on working days for the day sub-interval, generated by heavy vehicles calculated by the CNOSSOS-EU method. The calculations show that maximum values of median as well as percentiles C_{10} and C_{90} were obtained in an octave with a central frequency of

f_0 = 500 Hz. The minimum values of these parameters were obtained in an octave with frequency f_0 = 4000 Hz. The values of the parameter C_{99} in relation to the value of C_{90}, for lanes 1-2: in an octave with frequency f_0 = 125 Hz are 172 % higher and for frequency f_0 = 500 Hz or f_0 = 1000 Hz about 100 %. For the frequency f_0 = 2000 Hz they are about 110 %. Values of coefficients of variation are about 9 % and uncertainty u_A is less than 0.10 mPa. Differences in the values of the same parameters (C_{90} and C_{99}) but for lanes 3-4 are smaller and for the octave band f_0 = 1000 Hz they are about 4 mPa. Values of coefficients of variation for lanes 3-4 are about 9 %. The value of the C_{99} parameter is greater than C_{90} by about 30%. The maximum values of the parameters of the sum of the acoustic pressure generated by lanes 1-2 and 3-4 occur in the octave band f_0 = 500 Hz. Only the maximum value of the C_{99} parameter in the f_0 = 125 Hz band is higher than C_{90} by about 135%. Statistical analysis of the acoustic pressure values shows that the values of Q_{31} for heavy vehicles fall within the range 1.0 mPa to 1.6 mPa.

Table 2. The values of sound pressure parameters on working days for the day sub-interval, generated by heavy vehicles calculated by the CNOSSOS-EU method, in selected octave bands

Central frequency band f_0 [Hz]	Med. [mPa]	Q_{31} [mPa]	Vq [%]	V_{Q1Q3} [%]	u_A [mPa]	C_{10} [mPa]	C_{90} [mPa]	C_{99} [mPa]
values of sound pressure parameters generated by heavy vehicles on lanes 1-2								
125	13.21	1.21	9.16	9.11	0.10	10.96	16.35	44.58
500	16.28	1.44	8.87	8.86	0.08	13.51	19.63	38.90
1000	14.88	1.30	8.76	8.74	0.07	12.34	17.82	34.80
values of sound pressure parameters generated by heavy vehicles on lanes 3-4								
125	10.24	0.97	9.45	9.46	0.04	8.29	12.43	16.81
500	12.88	1.15	8.96	8.99	0.05	10.40	15.30	20.60
1000	11.85	1.06	8.90	8.93	0.04	9.57	14.01	18.76
values of sound pressure parameters generated by heavy vehicles on lanes 1-2 and 3-4								
125	16.73	1.33	7.97	7.94	0.10	14.24	20.04	47.67
500	20.75	1.58	7.62	7.61	0.09	17.71	24.36	43.52
1000	19.04	1.44	7.54	7.54	0.08	16.23	22.16	39.09

The share of acoustic pressure generated by heavy vehicles in the total acoustic pressure generated by road vehicles of all categories can be calculated according to

$$\frac{p_{hv}(f_0, C_X)}{p_{av}(f_0, C_X)} \cdot\ 100\ \% = R(f_0, C_X) \quad (11)$$

where

p_{hv} – acoustic pressure of heavy vehicles,
p_{av} – acoustic pressure of all vehicles.

It depends on the center frequency of the octave band (f_0 = 125, 250, ... 4000 Hz) and the percentile number (X = 10, 50, 90, 99). The calculations show that this value varies from 28 % to 80 %, as shown in the table 3.

Table 3. The share of acoustic pressure generated by heavy vehicles in the total acoustic pressure generated by road vehicles of all categories

f_0	$R(f_0, C_{10})$ [%]	$R(f_0, C_{50})$ [%]	$R(f_0, C_{90})$ [%]	$R(f_0, C_{99})$ [%]
125 Hz	43	49	50	79
250 Hz	47	50	52	77
500 Hz	49	51	53	80
1000 Hz	32	35	39	66
2000 Hz	28	30	31	61
4000 Hz	33	38	39	70

The highest values of the $R(f_0, C_X)$ parameter occur in the octave band f_0 = 500 Hz and for the C_{99} percentile, i.e. the average maximum acoustic pressure.

5. Conclusions

The traffic volume analysis carried out on lanes 1-2 and 3-4 shows that for all vehicles and heavy vehicles there are differences in the flow of cars entering and leaving the city. These differences indicate that some drivers treat Krakowska Street as a transit road despite the existing Kielce bypasses.

The study showed that measurements carried out only on one working day (e.g. Wednesday), may not be representative.

Despite differences in the value of vehicle traffic intensity on lanes 1-2 and 3-4, there is a similarity in noise changes (calculated according to the CNOSSOS-EU model) as a function of time. The octave bands in which the greatest acoustic pressure is generated are the f_0 = 500 Hz and f_0 = 1000 Hz band. The values of acoustic pressure parameters in this bands dominate both for heavy and all vehicles.

It has been shown that for working days and in octave band f_0 = 1000 Hz 80% of the data are in the range of limit values: for all vehicles (50 mPa, 57 mPa) while for heavy vehicles in the range of limit values (16 mPa, 22 mPa). But in octave band f_0 = 500 Hz 80% of the data are in the range of limit values: for all vehicles (37 mPa, 45 mPa) while for heavy vehicles in the range of limit values (18 mPa, 24 mPa).

For heavy vehicles, the maximum values for median and percentiles C_{10} and C_{90} were obtained in octave band with a center frequency of f_0 = 500 Hz. The minimum values of these parameters were obtained in the octave band with center frequency f_0 = 4000 Hz. The values of the parameter C_{99} in relation to the value of C_{90} (for lanes 1-2): in the octave band with frequency f_0 = 125 Hz are higher by about 170% and for the frequency f_0 = 500 Hz or f_0 = 1000 Hz by about 100%.

The values of the coefficients of variation V_q and V_{Q1Q3} are similar in all octave bands but depend on the vehicle category and the central frequency f_0.

The share of acoustic pressure generated by heavy vehicles in the total acoustic pressure generated by road vehicles of all categories depends on the center frequency of the octave band and the percentile number and ranges from 28% to 80%. The highest values occur in the band f_0 = 500 Hz and for the C_{99} percentile of acoustic pressure.

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