Assessment of traffic noise for medium heavy vehicles in octave bands

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Abstract. The paper presents the analysis results of medium heavy vehicle traffic measurements which were used to simulate the noise measurands. The Cnossos-EU model was used for this purpose. The medium heavy vehicle traffic volume and velocity were recorded by permanent automatic sound and traffic monitoring station. The noise was calculated in octave bands according to the Cnossos-EU model. The results were described using parameters such as the median, average peak level $-C_{90}$, average background noise level $-C_{10}$, percentiles $C_{25}$ and $C_{75}$. Analyzes carried out for the tested section of the road showed that the traffic of medium heavy vehicles is one of the main source of road noise. It has been shown that maximum values of the equivalent sound level occur for the frequency of $f_0 = 1$ kHz. The positional measures of traffic noise were proposed for data scattering. The dispersion of noise and type A uncertainty of the results were evaluated. It was found that in most cases, the distribution of the tested variable was not normal. It was notice a lack of symmetry between the time distribution of traffic flow of vehicles entering and leaving the city.

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]. Noise assessment relies on various measurands, including short- or long-term noise indicators. Determining long-term indicators, which should be representative of the whole calendar year, is especially difficult. To this end, 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 and installed in Kielce. Kielce was chosen as 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 medium heavy vehicle traffic flow from two vehicular lanes running towards the town (lane 1-2) and two lanes running towards Kraków (lane 3-4) were analysed. Computer simulation of the equivalent sound level 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 analyzed. The traffic monitoring station is located between two intersections at a distance of about 500 m. 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 volume (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 (data registered from 6.00 to 18.00) of a 24-hour period because it is the most onerous time interval of the whole day. The results analyzed contained vehicle traffic measurements (split into groups of vehicles) together with vehicle average speeds. In this work analysis was based on the measurements in working days and Wednesdays as an example of a typical such working day.

3. CNOSSOS-EU method calculation of traffic noise measurands

In the Cnossos-EU model emission values are not A-weighted. In this method 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 [4]. The sound power level emitted by one of the vehicle category $m$ and in octave band number $i$ is:

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

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:

$$L_{eq,i,m} = L_{i,m}(v_m) + 10 \log \left( \frac{Q_m}{1000 v_m} \right)$$

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:

$$P_{i,m}^2 = \sum_{j=1}^{Q_t} p_0^2 \cdot 10^{L_{eq,i,m} + 10 \log (L_j/Q_t) - 20 \log (R_j) - 9.5}$$

where $L_s$ – length of a source line with homogeneous traffic, $Q_t$ – amount of source line segments, $p_0$ – reference sound pressure $2 \cdot 10^{-5}$ Pa, $j$ – index of source line segments, $R_j$ – distance of the center of the $j$ source line segments from the measuring microphone.

The acoustic pressure to the second power, measured by microphone in octave band $i$, generated by all vehicles on the test section of the road is:

$$P_i^2 = \sum_{m=1}^{4} P_{i,m}^2$$

Equivalent sound pressure level in octave band $i$ from 125 Hz up to 4 kHz:

$$L_{eq,T,i} = 10 \cdot \log (P_i^2/P_0^2)$$
The A-weighted equivalent sound pressure level is computed by summation in the frequency range from 125 Hz to 4 kHz:

$$L_{Aeq,T} = 10 \log \sum_{i=2}^{i=7} 10^{(L_{eq,T,i} + A_i)/10}$$

where $A_i$ denotes the A-weighting correction according to IEC 61672-1 and $i$ is the frequency band index. A complete implementation of these noise emission models in non-commercial software R were developed [8]. It was assumed in this paper that the acoustic source are:

- entry traffic on two lanes, that leads towards Kielce from Kraków – 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 for two acoustic models using measurements of relevant parameters of road vehicles.

The non-linear character of A-weighted equivalent sound pressure level 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 [5]. Therefore in the paper, further analysis were based on the positional measures [6]:

- $C_{50}$ – median, defined as the sound pressure level exceeded by the signal in 50% of the measurement period,
- $C_{[25,75]}$ – range between 25 and 75 percentile, in which 50% of all data is included:

$$C_{[25,75]} = [C_{25}(L_{Aeq,T}), C_{75}(L_{Aeq,T})]$$

- $C_{[10,90]}$ – range between 10 and 90 percentile, in which 80% of all data is included:

$$C_{[10,90]} = [C_{10}(L_{Aeq,T}), C_{90}(L_{Aeq,T})]$$

The percentile $C_{10}$, defined as sound pressure level 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 level exceeded by the signal respectively in 75% or 25% of the measurement period. To assess the av. peak level the percentile $C_{90}$, defined as sound pressure level exceeded by the signal in 10% of the measurement period was used. Those measures determine the dispersion of noise.

The extended uncertainty $U$ of measurements was determined according to the following procedure [7]:

$$U = \pm \sqrt{\frac{\sigma^2}{n} + \frac{0.026\sigma^4}{n-1}} t_{\alpha;n-1}$$

where the coefficient $t_{\alpha;n-1}$ is the quantile of the t Student distribution. In this article, expanded uncertainty was determined for the assumed confidence level $\alpha = 0.05$.

4. Measurements and calculations results
Dependences of traffic volume and the noise value but generated independently on the two center lines between the lanes 1-2 and 3-4 (according to the Cnossos –EU model) in subsequent hours for all vehicle categories are shown in figure 1.
Figure 1. For arbitrarily chosen day (26.06.2013 Wednesday) and for all vehicle categories traffic volume (VOL<br>MEA) and velocity (Vm) measurements in subsequent hours and the corresponding simulated A-weighted equivalent sound level (L<sub>eqMOD</sub>) determined according to Cnossos-EU model (generated by line source located along center line of lanes 1-2 or lanes 3-4) for: a) lanes 1-2, b) lanes 3-4

It can be seen in figure 1a especially from 4.00 am to 8.00 am that the increase in noise level from approximately 60 dB to 70 dB is related to the increase of traffic intensity by 1400 vol h<sup>-1</sup>. Next, despite the traffic dropping by about 400 vol h<sup>-1</sup> between 8.00 and 13.00 hours, the noise level is reduced up to 68 dB. However, it should be noted that the average vehicle speed is increased by approximately 5 km h<sup>-1</sup>. This phenomenon occurs on all working days of the analyzed road. When comparing figures 1a and 1b, it can be noticed that during the morning traffic peak hours, until about 9.00, the flow of the vehicles on lanes 1-2 is about 1400 vol h<sup>-1</sup> and is much larger than on lanes 3-4. From 12.00 to 17.00 the flow of vehicles on lanes 3-4 (leaving Kielce) increases to a maximum value of approximately 1400 vol h<sup>-1</sup>. We have to notice a lack of symmetry between the time distribution of traffic flow and velocity of vehicles entering and leaving the city. Analyzing the equivalent sound levels generated on lanes 1-2 and 3-4, shown in figure 1, we can see the quality similarity and some quantitative differences. For example at 8.00 L<sub>AeqMOD</sub> on lanes 1-2 is approximately 71 dB and for lanes 3-4 approximately 68 dB. The computer simulation values of the measures of the dispersion of the equivalent sound level determined for the day time subinterval, for all Wednesdays in the year 2013 are presented in table 1.

Table 1. The computer simulation values of the measures of the dispersion of the L<sub>AeqMOD</sub> determined for the day time subinterval in the year 2013.

| Cnossos-EU noise model | C<sub>[2,5,75]</sub> dB | Median dB | C<sub>[10,90]</sub> dB | U dB |
|------------------------|--------------------------|------------|------------------------|-----|
| for all Weekdays       |                          |            |                        |     |
| for lanes 1-2          | [69.44, 69.98]           | 69.73      | [69.06, 70.19]         | 0.053 |
| for lanes 3-4          | [66.88, 67.75]           | 67.29      | [66.20, 68.18]         | 0.070 |
| for all Working Days   |                          |            |                        |     |
| for lanes 1-2          | [69.48, 70.00]           | 69.75      | [69.03, 70.23]         | 0.031 |
| for lanes 3-4          | [66.94, 67.76]           | 67.33      | [66.21, 68.17]         | 0.037 |
| in octave band f<sub>0</sub>= 1 kHz |          |            |                        |     |
| for lanes 1-2          | [66.36, 66.86]           | 66.62      | [65.91, 67.07]         | 0.029 |
| for lanes 3-4          | [63.81, 64.61]           | 64.20      | [63.10, 65.01]         | 0.037 |
For lanes 1-2, the $C_{10}$ percentile value is around 69 dB and $C_{90}$ 70 dB. However, for lanes 3-4 $C_{10}$ is about 66 dB and $C_{90}$ 68 dB. Analyzing the reasons for the above differences in the $L_{AeqMOD}$ parameter values, it should be noted that the acoustic source for lanes 1-2 is 8 m from the measuring microphone and for lanes 3-4 this length is 15.5 m. Calculations showed that this causes differences in the calculated sound level of about 1 dB. The purpose of the calculations was to show that the parameters of vehicle traffic and noise generated on Wednesdays are typical for all working days.

The data registered by the monitoring station allowed to determine the traffic and noise parameters for all working days in 2013. The noise parameters calculated on this basis are presented in Table 1. The type A uncertainty of the determined values is less than 0.1 dB. The discrepancies between the measurements and calculated results estimated as the values of RMSE parameter [8] are about 1 dB. Comparison of the values of the parameters appearing in table 1 confirms the correct assumption that Wednesday can be considered as a typical working day. Statistical analysis of the obtained values of traffic and noise parameters on working days, taking into account the specificity of lanes 1-2 and 3-4 showed not only different values but also different data distributions differing from the normal distribution. Figure 2 presents graphs of the distribution value of the equivalent sound level for a model of an acoustic source located in two different positions, for all vehicles during the day subinterval, for all working days.

Values of selected data distribution parameters are: for figure 2a: skewness is -4.35 and kurtosis is 37.10, for figure 2b: skewness is -3.30 and kurtosis is 24.76. Figure 2 and table 1 show that 80 % of the data is in the range [66 dB,70 dB].

Figure 2 shows that, despite large differences in vehicle traffic intensity values 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.
For arbitrarily chosen day (26.06.2013 Wednesday) and for all vehicle categories the A-weighted equivalent sound level for \( f_0 = 1 \) kHz determined for one hour intervals and the corresponding volume of all vehicle categories, for acoustic source model in the middle of the; a) lanes 1-2, b) lanes 3-4.

The percentile values for the \( L_{A_{eq}} \) parameter in the octave band with a center frequency \( f_0 = 1 \) kHz for all vehicles on working days are presented in table 1.

Analyzing the values of the corresponding percentiles from table 1, e.g. for lane 3-4 the model shows that for the octave band with frequency \( f_0 = 1 \) kHz 80 \% of the data is contained in the range [63.1 dB, 65.01 dB] while 50 \% data in the range [63.81 dB, 64.61 dB]. The median value is 64.20 dB. The type A uncertainty of the parameter values shown in table 1 is less than 0.1 dB.

For arbitrarily chosen day (26.06.2013 Wednesday) and for medium heavy vehicle categories the A-weighted equivalent sound level determined for one hour intervals and the corresponding volume of vehicle; a) lanes 1-2, b) lanes 3-4.

Traffic volume analyzes carried out in [3] showed that after passenger vehicles, the second dominant category is medium heavy vehicle. Figure 4 presents traffic flow charts for medium heavy vehicle and the equivalent sound level that they generate on an arbitrarily chosen Wednesday. The course of the dependency changes shown in figure 4 is similar to those shown in figures 1 and 3. The main qualitative
difference between them is that traffic on lanes 3-4 (vehicles leaving the city) is greater than on lanes 1-2 (vehicles entering the city). The calculated values of the equivalent sound level generated by vehicles in lanes 1-2 from 9:00 systematically decrease from about 66 dB to 55 dB at 24:00.

Table 2 presents the percentiles of the $L_{Aeq}$ parameter for medium heavy vehicles, on Wednesday 2013, for the sub-interval day. For both directions of motion, the median value is about 64 dB and 80% of the data is in the range [62 dB, 65 dB].

**Table 2.** The computer simulation values of the measures of the dispersion of the $L_{Aeq}$ determined for the day time subinterval calculated for medium heavy vehicles.

| Cnossos-EU noise model | $C_{[25,75]}$ | Median | $C_{[10,90]}$ | $U$ |
|------------------------|---------------|--------|---------------|-----|
| for all Wednesdays     |               |        |               |     |
| for lane 1-2           | [63.24, 64.39] | 63.87  | [62.47, 64.96] | 0.124 |
| for lane 3-4           | [63.23, 64.28] | 63.73  | [62.38, 64.84] | 0.102 |
| for all working days   |               |        |               |     |
| for lane 1-2           | [63.26, 64.42] | 63.90  | [62.32, 65.01] | 0.071 |
| for lane 3-4           | [63.26, 64.28] | 63.76  | [62.47, 64.90] | 0.055 |
| in octave band $f_0 = 1$ kHz |           |        |               |     |
| for lane 1-2           | [60.07, 61.23] | 60.72  | [59.14, 61.80] | 0.070 |
| for lane 3-4           | [60.10, 61.11] | 60.60  | [59.31, 61.70] | 0.054 |

The percentiles of the $L_{Aeq}$ parameter for medium heavy vehicles, on business days for the sub-interval day shown in table 2 also confirm that Wednesday can be considered as a typical business day. Confirmation of this assumption is the convergence of the boundaries of the ranges in which 80% of the data falls, e.g. for lanes 3-4 for Wednesdays $C_{[10,90]} = [62.38 \text{ dB}, 64.84 \text{ dB}]$ and for working days $C_{[10,90]} = [62.47 \text{ dB}, 64.90 \text{ dB}]$. The uncertainty value of $L_{Aeq}$ is around 0.1 dB.

Figure 5 shows the A-weighted equivalent sound level in octave band $f_0 = 1$ kHz determined for one hour intervals and the corresponding volume of medium heavy vehicle categories in the Wednesday.

**Figure 5.** The A-weighted equivalent sound level in octave band $f_0 = 1$ kHz determined for one hour intervals and the corresponding volume for medium heavy vehicle categories in the Wednesday 26.06.13; a) lanes 1-2, b) lanes 3-4.

Figure 5 shows the A-weighted equivalent sound level in octave band $f_0 = 1$ kHz determined for one hour intervals and the corresponding volume of medium heavy vehicle categories in the Wednesday. It should be noted that the rate of change in noise value shown in figure 5 for each of the proposed models is different. When comparing figure 4 of 5, it can also be seen that the rate of noise change in
the 1 kHz octave band, e.g. in figure 4 b, is lower than in figure 5 b. The percentiles of the $L_{Aeq,MOD}$ parameter for delivery vehicles, on working days, for the sub-interval day in the octave band with a center frequency of $f_0 = 1$ kHz are shown in table 2. Values of percentiles of the equivalent sound level presented in table 2 are smaller than in table 1. For example, the values of parameter range $C_{[10, 90]}$ for lanes 3-4 for $f_0 = 1$ kHz are: in table 2 [59.31 dB, 61.70 dB] and in table 1 [63.10 dB, 65.01 dB].

5. Conclusion
This paper showed that the parameters of vehicle traffic and noise generated on Wednesdays are typical for all working days.

The traffic volume analysis carried out on lanes 1-2 and 3-4 (entry to and exit from the city) shows that for all vehicles and medium 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.

Analyzing the equivalent sound levels generated on lanes 1-2 and 3-4, some qualitative similarity and some quantitative differences were found.

Despite the large 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 band in which the greatest noise is generated is the $f_0 = 1$ kHz band. The values of noise parameters in this band dominate both for medium heavy and all vehicles.

It has been shown that for medium heavy vehicles and working days 80 % of the data is in the range of limit values depending on the lane [62.3 dB, 65.0 dB] or [62.5 dB, 64.9 dB], while 50 % of the data is in the range [63.3 dB, 64.4 dB] or [63.3 dB, 64.3 dB]. Similar for medium heavy vehicles and for the octave band with a frequency of $f_0 = 1$ kHz, 80 % of the data are in the range of limit values, [59.1 dB, 61.8 dB] or [59.3 dB, 61.7 dB], while 50 % of the data is in the range [60.1 dB, 61.2 dB] or [60.1 dB, 61.1 dB]. The type A uncertainty of the $L_{Aeq,MOD}$ parameter is less than 0.1 dB.

6. References
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