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:

\[
L_{WP,i,m}(v_m) = A_{P,i,m} + B_{P,i,m} \cdot \left( v_m - v_{ref} \right) + \Delta L_{WP,i,m}
\]

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 \((m = 1\text{-light motor vehicles, } m = 2\text{-medium heavy vehicles, } m = 3\text{-heavy vehicles, } m = 4\text{-powered two-wheelers})\),
- \( v_m \) – 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:

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

(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:

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

(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:

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

(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:

\[ p_{i,m}^2 = \sum_{j=1}^{Q_r} P_0^3 \left( L_{Weq,i,m} + 10 \cdot \log \left( \frac{Q_m}{Q_j} \right) + 20 \log(R_j) + 8 \right) 0.1 \]  

(5)

where:

- \( l_S \) – length of a source line with homogeneous traffic,
- \( Q_i \) – amount of source line segments,
- \( P_0 \) – reference sound pressure equal to \( 2 \cdot 10^{-5} \) Pa,
- \( j \) – index of source line segments,
- \( R_j \) – distance of the center of the \( j \) source line segments from the measuring microphone.

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

$$C_{[10,90]} = [C_{10}(p_i), C_{90}(p_i)]$$  \hspace{1cm} (6)

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

$$u_A = \sqrt{\frac{1}{n(n-1)} \sum_{i=1}^{n} (p_i - \bar{p}_i)^2}$$  \hspace{1cm} (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 ($V_{Q_{31}}$), quartile deviation ($Q_{31}$), quartile variation coefficient ($V_{Q_{31}}$), and quartile coefficient of dispersion ($V_{Q_{1Q3}}$). 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:

$$Q_{31} = 0.5 \cdot [C_{75}(p_i) - C_{25}(p_i)]$$  \hspace{1cm} (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):

$$V_{Q_{31}} = \frac{Q_{31}}{Med} \cdot 100\%$$  \hspace{1cm} (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):

$$V_{Q_{1Q3}} = \frac{Q_3 - Q_1}{Q_1 + Q_3} \cdot 100\%$$  \hspace{1cm} (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](image.png)

**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](image)

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](image)

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

<table>
<thead>
<tr>
<th>Central frequency band $f_0$ [Hz]</th>
<th>Med. [mPa]</th>
<th>$Q_{31}$ [mPa]</th>
<th>$V_q$ [%]</th>
<th>$V_{Q103}$ [%]</th>
<th>$u_A$ [mPa]</th>
<th>$C_{10}$ [mPa]</th>
<th>$C_{90}$ [mPa]</th>
<th>$C_{99}$ [mPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>values of sound pressure parameters generated by all vehicles on lanes 1-2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>125</td>
<td>27.98</td>
<td>1.26</td>
<td>4.50</td>
<td>4.49</td>
<td>0.10</td>
<td>25.36</td>
<td>31.19</td>
<td>55.76</td>
</tr>
<tr>
<td>500</td>
<td>31.69</td>
<td>1.38</td>
<td>4.36</td>
<td>4.36</td>
<td>0.07</td>
<td>28.67</td>
<td>34.66</td>
<td>47.23</td>
</tr>
<tr>
<td>1000</td>
<td>42.85</td>
<td>1.23</td>
<td>2.88</td>
<td>2.88</td>
<td>0.06</td>
<td>39.49</td>
<td>45.14</td>
<td>47.47</td>
</tr>
<tr>
<td>values of sound pressure parameters generated by all vehicles on lanes 3-4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>125</td>
<td>21.63</td>
<td>1.30</td>
<td>6.01</td>
<td>5.96</td>
<td>0.05</td>
<td>18.82</td>
<td>24.66</td>
<td>26.97</td>
</tr>
<tr>
<td>500</td>
<td>25.78</td>
<td>1.41</td>
<td>5.46</td>
<td>5.43</td>
<td>0.06</td>
<td>22.34</td>
<td>28.90</td>
<td>31.16</td>
</tr>
<tr>
<td>1000</td>
<td>32.43</td>
<td>1.49</td>
<td>4.58</td>
<td>4.57</td>
<td>0.06</td>
<td>28.58</td>
<td>35.61</td>
<td>37.45</td>
</tr>
<tr>
<td>values of sound pressure parameters generated by all vehicles on lanes 1-2 and 3-4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>125</td>
<td>35.48</td>
<td>1.59</td>
<td>4.48</td>
<td>4.47</td>
<td>0.10</td>
<td>32.23</td>
<td>39.45</td>
<td>60.81</td>
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<tr>
<td>500</td>
<td>40.99</td>
<td>1.76</td>
<td>4.30</td>
<td>4.31</td>
<td>0.09</td>
<td>37.14</td>
<td>44.74</td>
<td>55.23</td>
</tr>
<tr>
<td>1000</td>
<td>53.88</td>
<td>1.72</td>
<td>3.19</td>
<td>3.20</td>
<td>0.08</td>
<td>49.62</td>
<td>56.94</td>
<td>59.25</td>
</tr>
</tbody>
</table>

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
The minimum values of these parameters were obtained in an octave with frequency \( f_0 = 4000 \text{ Hz} \). The values of the parameter \( C_{99} \) in relation to the value of \( C_{90} \) for lanes 1-2: in an octave with frequency \( f_0 = 125 \text{ Hz} \) and for frequency \( f_0 = 500 \text{ Hz} \) or \( f_0 = 1000 \text{ Hz} \) about 100 %. For the frequency \( f_0 = 2000 \text{ Hz} \) 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 \( f_0 = 1000 \text{ Hz} \) they are about 4 mPa. Values of coefficients of variation for lanes 3-4 are about 9 %.

### 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

<table>
<thead>
<tr>
<th>Central frequency band ( f_0 ) [Hz]</th>
<th>Med. ( Q_{31} ) [mPa]</th>
<th>( V_q ) [%]</th>
<th>( V_{Q103} ) [%]</th>
<th>( u_A ) [mPa]</th>
<th>( C_{10} ) [mPa]</th>
<th>( C_{90} ) [mPa]</th>
<th>( C_{99} ) [mPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>125</td>
<td>13.21</td>
<td>1.21</td>
<td>9.16</td>
<td>9.11</td>
<td>0.10</td>
<td>10.96</td>
<td>16.35</td>
</tr>
<tr>
<td>500</td>
<td>16.28</td>
<td>1.44</td>
<td>8.87</td>
<td>8.86</td>
<td>0.08</td>
<td>13.51</td>
<td>19.63</td>
</tr>
<tr>
<td>1000</td>
<td>14.88</td>
<td>1.30</td>
<td>8.76</td>
<td>8.74</td>
<td>0.07</td>
<td>12.34</td>
<td>17.82</td>
</tr>
<tr>
<td>125</td>
<td>10.24</td>
<td>0.97</td>
<td>9.45</td>
<td>9.46</td>
<td>0.04</td>
<td>8.29</td>
<td>12.43</td>
</tr>
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<td>500</td>
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<td>1.15</td>
<td>8.96</td>
<td>8.99</td>
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<td>10.40</td>
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<td>1000</td>
<td>11.85</td>
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<td>8.93</td>
<td>0.04</td>
<td>9.57</td>
<td>14.01</td>
</tr>
<tr>
<td>125</td>
<td>16.73</td>
<td>1.33</td>
<td>7.97</td>
<td>7.94</td>
<td>0.10</td>
<td>14.24</td>
<td>20.04</td>
</tr>
<tr>
<td>500</td>
<td>20.75</td>
<td>1.58</td>
<td>7.62</td>
<td>7.61</td>
<td>0.09</td>
<td>17.71</td>
<td>24.56</td>
</tr>
<tr>
<td>1000</td>
<td>19.04</td>
<td>1.44</td>
<td>7.54</td>
<td>7.54</td>
<td>0.08</td>
<td>16.23</td>
<td>22.16</td>
</tr>
</tbody>
</table>

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

\[
p_{hv}(f_0, C_X) \cdot 100 \% = R(f_0, C_X)
\]  \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 (\( f_0 = 125, 250, \ldots 4000 \text{ Hz} \)) 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

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

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 $C_{90}$ 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 $C_{90}$ percentile of acoustic pressure.
References