Research Article

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Measurements of urban traffic parameters before and after road reconstruction

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Abstract: The study analyzed the parameters of vehicle traffic and noise on the national road in the section in the city from 2011 to 2016. In 2013-2014 this road was reconstructed. It was found that in most cases, the distribution of the tested variable was not normal. The median and selected percentiles of vehicle traffic parameters and noise were examined. The variability and type A uncertainty of the results were described and evaluated. The results obtained for the data recorded on working and non-working days were compared. The vehicle cumulative speed distributions, for two-way four-lane road segments in both directions were analyzed. A mathematical model of normalized traffic flow has been proposed. Fit factor $R^2$ of the proposed equations to the experimental data for passenger vehicles ranges from 0.93 to 0.99. It has been shown that two years after the road reconstruction, the median noise level did not increase even though traffic volumes and vehicle speeds increased. The Cnossos noise model was validated for data recorded over a period of 6 years. A very good agreement of the medians determined according to the Cnossos-EU model and the measured ones was obtained. It should be noted, however, that for the other analyzed percentiles, e.g. 95%, the discrepancies are larger.

Keywords: urban traffic flow equations, urban noise, monitoring station, vehicle speed distribution, Cnossos-EU model validation

1 Introduction

The problem of the harmful impact of urban transport means on the environment is analyzed in the literature in numerous publications [1–4]. Vehicle traffic parameters such as: traffic 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 [5–7]. The problem of environmental pollution with noise is no less important than with chemical agents or particulate matter [8]. A new pattern for a workplace located in the down town has been created, while the residential areas are mainly in peripheral regions. As a result, a large number of passenger vehicles enter the city in the morning and a similar number leave the city in the afternoon. This phenomenon called traffic tidal increases the environmental pollution [9, 10]. People living near roads expect the owner of the road infrastructure to bear the responsibility and costs of managing environmental pollution. The road administration should have knowledge about the current values of vehicle traffic parameters resulting, for example, from implementation of intelligent transport systems. This knowledge will also reduce the costs of verifying noise maps. Changes in traffic regulations may render the databases used to develop pollution models obsolete. Therefore, checking up-to-date databases is also justified [11].

For this reason, it is necessary to permanently monitor over a long period of time vehicle traffic and analyze the recorded data [12–14]. This will allow for a more precise analysis and a more objective assessment of the phenomena taking place as well as the values of their parameters. Traffic volume can be recorded by optical, magnetic, electromagnetic and pneumatic methods or GIS-based system [8, 15–17]. Stationary monitoring station or low-cost wireless sensor systems and citizenship participative initiatives are used to measure urban noise [6, 18, 19].

The article analyzes selected parameters of vehicle traffic on the national road on the basis of data recorded in 2011-2016. In the years 2013-2014 this road was thoroughly reconstructed. This project was entirely located within the administrative boundaries of the city of Kielce, on the sec-
tion from Popiełuszki Avenue to the city limits. Popiełuszki Av. is a road with four lanes of traffic. The road is part of the national road No. 73, which is directly connected with the Trans-European Transport Networks. It is also the major part of the Tarnow-bound thoroughfare functioning as both the transit route and the city street. As part of the project, the road was widened and the surface was strengthened by making a bituminous overlay of the existing western roadway. Another roadway presented on Figure 1 – 7.0 m wide, 4.7 km long, 10 bus bays, 5 km of pedestrian and bicycle routes and 3 bridges were built along the modernized road (Ściegiennego street). The implementation of this project contributed to the increase in safety, but also caused a lot of nuisance during construction, e.g. noise for local residents and road users [20].

The research reported here, aims at:

- analyzing the traffic volume of vehicles (taking into account the division into four groups of vehicles) on the section of the national road in the city, their speed and noise over several years
- determination of normalized traffic flow equations during the day from 5.00 to 23.00 in order to facilitate the comparison of the road load in individual years of its operation
- using the bootstrap method to determine the values of the tested traffic parameters for the years for which there were significant data gaps
- study the long-term impact of road reconstruction on vehicle traffic performance and noise
- analyzing the variability of traffic intensity in the analyzed period
- Cnossos-EU model validation in the analyzed period.

2 Recorded data analysis procedure

This paper analyses the results of traffic flow and noise measurements recorded by stationary monitoring station [21–24]. This station was located close to the city limits, at Popiełuszki Av. (at a distance of 4 m from the edge of the lane 1). The measurements in four lanes were documented at one hour intervals throughout the entire 24 hours of the day. The construction of the station and the measurement procedure are presented in the paper [21]. Due to technical problems such as hardware or software malfunctioning on data collection equipment or loss of data packages during transmission to processing centers [25], in the 6-year operation period of the traffic parameters monitoring station, there were interruptions in its operation. The authors concluded that the correct periods of operation of the station can be considered only those days for which the station recorded the results of traffic intensity for each hour of the day. This means that in further calculations only those days were used for which the station registered the analyzed traffic parameters 24 times a day. The traffic flow was calculated according to following equation:

\[
FLOW_{N,p} = \sum_{i=1}^{N} \sum_{h=1}^{p} VOL_{p,d}
\]

where \(VOL_{p,d}\) is the traffic volume for \(d\) – day of week \((d = 1, 2, 3, 4, 5, 6, 7)\) and \(p\) is the time interval, \(N\) is the number of measurement data during year. The time sub-interval \(p\) can be equal to 1 hour or 24 hours (denoted as 24h, from 0.00 to 23.00) [21].

The average daily traffic flow was calculated from equation:

\[
FLOW = \frac{1}{N}FLOW_{N,p}
\]

The variability of traffic flow can be evaluated by the coefficient of variation:

\[
COV_{FLOW} = COV = \frac{\sigma_{FLOW}}{FLOW} \cdot 100\% = \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} (FLOW_{N,p} - FLOW)^2} \cdot \frac{FLOW}{FLOW} \cdot 100\%
\]
as well as by the positional variation [22]:

\[
V_q = \frac{Q_{31}}{Med} \cdot 100% = 0.5 \cdot \left( Q_3 (FLOW_{N,p}) - Q_1 (FLOW_{N,p}) \right) \cdot \frac{100}{Med}
\] (4)

where \( Q_1 (FLOW_{N,p}) \) – first quartile, \( Q_3 (FLOW_{N,p}) \) – third quartile of traffic flow [17].

Standard uncertainty of the parameter \( FLOW_{p,d} \), determined in the type A evaluation, was calculated from the following relationship:

\[
u_A = \sqrt{\frac{1}{N(N-1)} \sum_{i=1}^{N} (FLOW_{p,d} - FLOW)^2}
\] (5)

In order to compare the results obtained in different years, the authors proposed the use of the normalized traffic flow [22, 26–29] determined from:

\[
FLOW_{norm} (p, d, G(i), L) = \frac{FLOW(p, d, G(i), L)}{FLOW_{max} (p, d, G(i), L)}
\] (6)

where \( G(i) \) - vehicle sets, \( i = \) passenger vehicles, heavy vehicles, medium heavy vehicles, two wheelers, \( FLOW(p, d, G(i), L) \) – median of traffic flow, \( FLOW_{max} (p, d, G(i), L) \) – the maximum median of traffic flow of the vehicle set.

The most common noise indicator used to assess annoyance is the equivalent sound level (\( L_{Aeq,T} \)), expressed in dB(A), defined as:

\[
L_{Aeq,T} = 10 \cdot \log \left[ \frac{1}{T} \int_{0}^{T} \left( \frac{p_A(t)}{p_0} \right)^2 dt \right] = 10 \cdot \log \left( \frac{P_{A_{rms}}}{P_0} \right)^2
\] (7)

where:
- \( T \) – represents the overall measurement time, s
- \( p_A(t) \) – \( A \)-weighted sound pressure level, Pa
- \( P_{A_{rms}} \) – is the standardized reference sound pressure of 20 \( \mu \)Pa
- \( p_0 \) – represents the effective sound pressure.

The non-linear character of logarithmic function changes is a limitation to the use of the \( L_{Aeq,T} \) parameter. This impedes both the determination of standard deviation or measurement uncertainty and the performance of a comparative analysis [30]. It is possible to determine from the equation (7) the sound pressure \( p_{A_{rms}} \) and use this parameter expressed in mPa in further analysis of standard uncertainty and the coefficients of variation \( COV \) or \( V_q \) [21].

\[
p_{A_{rms}} = p_A = \sqrt{10^{0.1L_{Aeq,T}} \cdot p_0^2}
\] (8)

The analysis carried out in these units allows easier comparison of the constant (median, percentiles e.g. C95 and C99) and variable (e.g. coefficient of variation) components of the analyzed sound pressure signal. The study of the variable components contained in the analyzed signals was based on the analysis of positional coefficient of variation \( (V_q) \).

### 3 Measurements and calculations results

Examples of the measurement results of the daily traffic flow before and after the road reconstruction are shown in Figure 2. The data for 2012 show a tendency to decrease the value of traffic flow. Drawings of histograms and Q-Q quantile plots show that the probability distributions of the tested data deviate from the normal distribution. The conducted statistical tests of Shapiro-Wilk and the Jarque-Bera confirm this hypothesis [22].

The calculated values of the skewness and kurtosis of the probability distributions also confirms the deviation from the normal distribution. The traffic volume in the years 2011–2015 decreased by 9.7%, which was caused by the deteriorating condition of the road and the nuisance associated with its renovation. The decrease in traffic flow was – for heavy vehicles 43.7%, for medium heavy vehicles 10.7% and for passenger vehicles 3.3%. These data partly explain the downward trend seen in 2012 in Figure 2. In 2016, there was

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</tr>
</thead>
<tbody>
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<td>17691</td>
<td>17237</td>
<td>16187</td>
<td>15611</td>
<td>15977</td>
<td>20012</td>
</tr>
<tr>
<td>Passenger vehicles</td>
<td>11840</td>
<td>11725</td>
<td>11240</td>
<td>10921</td>
<td>11446</td>
<td>14129</td>
</tr>
<tr>
<td>Heavy vehicles</td>
<td>2011</td>
<td>1744</td>
<td>1462</td>
<td>1296</td>
<td>1133</td>
<td>1598</td>
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<td>Medium heavy vehicles</td>
<td>3194</td>
<td>3027</td>
<td>3015</td>
<td>2887</td>
<td>2851</td>
<td>3579</td>
</tr>
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</table>
an increase in traffic (compared to 2011) for all vehicles by 13.1%, passenger vehicles by 19.3%, medium heavy vehicles by 12%, and heavy vehicles by – 20%. Table 1 shows the median of the annual daily traffic flow (ADT) in the years 2011–2016.

The analysis of the share of individual groups of vehicles in the traffic structure showed that the dominant group are passenger vehicles, for which the share in the traffic flow for 2011 was 67% and 80% on Sundays. This share in 2016 increased to 71% and on Sundays to 84%. The next group were medium heavy vehicles, for which the share in the analyzed period did not change much and amounted to 18%, and on Sundays to 11%. The share of heavy vehicles decreased from 11% in 2011 to 8% in 2016 and on Sundays to 2%. For this reason, in the further part of the work, the traffic of mainly passenger and medium heavy vehicles will be analyzed. Figure 3 presents traffic flow box plots for individual days of the week for passenger vehicles before and after road reconstruction [31].
Measurements of urban traffic parameters before and after road reconstruction

Table 2: A comparison of basic statistical measures of traffic volumes, determined by descriptive statistics and bootstrap method (boot) for all vehicles and for each day of the week in 2016

<table>
<thead>
<tr>
<th>Day</th>
<th>Med. veh/24h</th>
<th>Med. (boot) veh/24h</th>
<th>( \sigma_{med(boot)} ) veh/24h</th>
<th>( C_{95} ) veh/24h</th>
<th>( C_{Q95(boot)} ) veh/24h</th>
<th>( u_a ) veh/24h</th>
<th>( u_a(boot) ) veh/24h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mon.</td>
<td>20287</td>
<td>20286</td>
<td>250</td>
<td>20970</td>
<td>20911</td>
<td>97</td>
<td>783</td>
</tr>
<tr>
<td>Tue.</td>
<td>20311</td>
<td>20224</td>
<td>156</td>
<td>20923</td>
<td>20863</td>
<td>254</td>
<td>725</td>
</tr>
<tr>
<td>Wed.</td>
<td>20157</td>
<td>20123</td>
<td>212</td>
<td>21526</td>
<td>21526</td>
<td>836</td>
<td>220</td>
</tr>
<tr>
<td>Thu.</td>
<td>20238</td>
<td>20192</td>
<td>178</td>
<td>20974</td>
<td>20885</td>
<td>247</td>
<td>777</td>
</tr>
<tr>
<td>Fri.</td>
<td>21614</td>
<td>21495</td>
<td>218</td>
<td>22261</td>
<td>22264</td>
<td>322</td>
<td>326</td>
</tr>
<tr>
<td>Sat.</td>
<td>16218</td>
<td>16003</td>
<td>327</td>
<td>16845</td>
<td>16809</td>
<td>136</td>
<td>459</td>
</tr>
<tr>
<td>Sun.</td>
<td>14045</td>
<td>13889</td>
<td>362</td>
<td>14635</td>
<td>14635</td>
<td>243</td>
<td>363</td>
</tr>
</tbody>
</table>

These figures show that the gap between the third and first quartiles \( Q_3 - Q_1 \) decreased after the road renovation. It is also visible that after the reconstruction, the changes in the median value on business days are small. Only on Fridays the median value increases, which is consistent with the literature [32].

Due to technical faults of the monitoring station (which is a problem for every station) [25], the total number of days examined in individual years was always less than 360 and, for example, in 2016 it was 100. This makes statistical analyzes difficult and may cause greater uncertainty of the obtained results. For this reason, the authors decided to check the correctness of the results obtained with the methods of descriptive statistics and also performed the bootstrap calculations [33, 34] for all results obtained from experimental measurements. The method is based on the Monte Carlo technique used for sampling with replacement \( n \) times from the \( n \)-element sample being the only known implementation of the random variable \( X \). The number of replications of the variable \( X^* \) in this paper was taken to be \( n = 1000 \). The bootstrap method can be used when the distribution of variables under investigation is unknown. A comparison of the results obtained with these methods is presented in Table 2.

The analysis of this table shows that there are slight differences in the values obtained with each of the methods. Nevertheless, the measurement uncertainty values for both methods are similar, which confirms the correctness of the adopted analysis of measurement data. One should also pay attention to the values of the traffic volume \( C_{95} \) percentile, which on some days are much higher than the median. It can then cause much greater nuisance by vehicle traffic than the median would suggest. Figures 2 and 3 allow to estimate the variability of traffic flow in an approximate...
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Figure 5: The annual hourly traffic flow box plots for all vehicle sets for period of 24h at business days: a) in 2012, b) in 2016

manner [35]. In order to carry out a more detailed analysis, the authors decided to investigate the annual hourly variability of traffic in the 24-hour interval.

Figure 4 shows the annual hourly traffic flow box plots for 2012 and 2016. The local extreme points of traffic flows occurred at about 8.00 and 16.00. There is a great similarity between the two figures and there is a visible increase in traffic in 2016, especially during peak traffic hours.

Analysis of annual hours traffic flow for 24h sub-interval, at business days in 2012 and 2016 is presented in Figure 5. The analysis of Figure 5 shows that the value of the $Q_3 - Q_1$ quartile range is smaller than in Figure 4. It is particularly visible during the peak traffic hours. Figure 5 also shows a much smaller amount of outliers than in Figure 4. The median of the traffic flow maximum values in 2012 is 1,316 vehicles/hour at 16.00. The type A uncertainty is equal to 20 vehicle/24h and positional variation $V_q = 3\%$, $COV_{FLOW} = 13\%$.

Due to the large and varied amount of outliers visible in Figures 4 and 5, the knowledge of the median value of traffic flow in each hour of the day is not sufficient to analyze this parameter. Having additional information about the values of the uncertainty $u_a$ and the coefficient of variation $COV_{FLOW}$ or $V_q$ significantly extends the knowledge about the tested parameter [22].

The $V_q$ coefficient according to the equation (3) is a relative parameter with a value depending on the median and 50% of data symmetrically distributed in relation to it. $COV$ depends on all data, including outliers. Therefore, its value is much greater than $V_q$. Figure 6 shows the $V_q$ diagram of annual hourly traffic flow and time at business day in 2011–2016 for all vehicle sets. The analysis of this chart shows that in the tested time period from about 8.00 to 17.00, the value of this coefficient ranges from 3% to 7%. In the remaining periods of the day, these changes are much greater and reach 20%.

The median of annual hourly traffic speed in 2012 and 2016 underwent slight changes and ranges from 65 km/h to 74 km/h. The $V_q$ coefficient did not exceed 4% and the $u_a$ uncertainty was less than 0.7 km/h. Figure 7 shows the annual hourly traffic speed box plots at business day before and after road reconstruction. The speed analyzes car-
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Figure 7: Annual hourly traffic velocity box plots at business day a) in 2012, b) in 2016

Figure 8: Annual hourly traffic cumulative speed distribution curve on lanes 3 and 4 a) in 2012 b) in 2016

ried out show that in the traffic rush hours, the speed was around 73 km/h before and drop up to 70 km/h after the road reconstruction. During these hours, the speed range between the $Q_1$ and $Q_3$ quantiles is much larger than in the other times of the day and after the renovation it amounts to about 5 km/h. The traffic steering and control system launched after the road reconstruction undoubtedly contributed to the drop in speed. The maximum values of the median speed occurred in 2011 around 8.00 am and in 2016 from 6.00 am to 7.00 am. The cause of transport changes visible after the reconstruction of the road may be the increase in economic activity and sub-urbanization of the surrounding regions after Poland’s accession to the European Union.

Figure 8 shows sample histograms of the average hourly speed in 2012 and 2016 on the inner and outer lanes towards Kielce. Their analysis can be performed in accordance with the guidelines (recommendations) provided in the literature [36, 37].

The speed below which 85% percent of vehicles in the traffic stream travel in lane 3 was 85 km/h in 2011, 83 km/h in 2012 and 81 km/h in 2016. On the other hand, the speed
of vehicles in the analyzed period in lane 4 did not change and amounted to approximately 72 km/h. The 15 percentile for lane 3 changed from 78 km/h to 73 km/h and for lane 4 it was about 65 km/h. Similar relationships also exist for lanes 1 and 2.

The annual hourly traffic flow box plots presented in Figures 4 and 5 show the value and dispersion of traffic flow. They also allow for the assessment of the share of atypical data in the analyzed sample, which may facilitate their analysis. A large amount of information presented on a single graph may be difficult to analyze, especially for a reader analyzing the phenomenon presented for the first time. It is also difficult to compare several charts of this type. For these reasons, the authors proposed to use the relative parameter called normalized traffic flow calculated according to the equation (5).

Figure 9 shows relation between the normalized annual hourly traffic flow and time at business days a) in 2012, b) in 2016.

![Figure 9: Relation between the normalized annual hourly traffic flow for all set of vehicles and time at business days a) in 2012, b) in 2016](image)

Figure 9 shows relation between the normalized annual hourly traffic flow for all set of vehicles and time at business days a) in 2012, b) in 2016. Such charts were made for each year from 2011 to 2016 and for each group of vehicles. The similarity of the obtained curves allowed for further analysis and creation of a mathematical model.

The traffic flow charts shown in Figure 9 can be divided into four phases. The first one is from 0.00 to 5.00 with the traffic flow in the range 0.05 - 0.15 FLOW_{max}. During these hours passenger vehicles (in 2011) account for approximately 40%, medium heavy vehicles 20%, and heavy vehicles 37% of the total number of all vehicles. The second phase, from 5.00 to the morning peak around 8.00, is characterized by a very high rate of traffic increase, which can be described by a linear relationship FLOW_{norm} = 0.29x + B. The third phase between the morning and afternoon peak around 16:00 can be described by a second order polynomial FLOW_{norm} = 0.012x^2 + Ex + F. The share of passenger vehicles in the traffic rush hours is about 71%, medium heavy vehicles 16% and heavy vehicles 8%. The fourth phase from the afternoon peak to 23.00 can be described by the linear relationship FLOW_{norm} = -0.12x + H. At 23:00 passenger vehicles account for approximately 63%, medium heavy 13%, and heavy 19% of the total number of all vehicles (in 2011). The values of the B, E, F, H coefficients appearing in these equations depend on the year for which we conduct the analysis and are presented in Table 3. The R^2 coefficients of fitting model curves to experimental data are in the range from 0.93 to 0.99. The second phase before the morning peak and the fourth after the afternoon peak is also well described by higher-order polynomials, but their coefficients take positive or negative values depending on the year and are not always significant.

The analyzes show that passenger, medium heavy and heavy vehicles dominate the traffic structure. For this reason, it is interesting how the presented traffic flow test procedure should be modified for these groups of vehicles. Figure 10 shows relation between the normalized annual hourly traffic flow versus time for passenger, medium heavy and heavy vehicles.

Similarly to Figure 9, the presented waveforms for passenger and medium heavy vehicles can be divided into four phases and each of them can be described with appropriate equations.
Table 3: Values of the B, E, F, H coefficients in the equations describing the phases of the model of the normalized annual hourly traffic flow of various groups of vehicles

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<tbody>
<tr>
<td>All vehicles</td>
<td></td>
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</tr>
<tr>
<td>B</td>
<td>-1.20</td>
<td>-1.35</td>
<td>-1.34</td>
<td>-1.33</td>
<td>-1.41</td>
<td>-1.44</td>
</tr>
<tr>
<td>E</td>
<td>-0.21</td>
<td>-0.26</td>
<td>-0.29</td>
<td>-0.28</td>
<td>-0.29</td>
<td>-0.37</td>
</tr>
<tr>
<td>F</td>
<td>2.00</td>
<td>2.32</td>
<td>2.45</td>
<td>2.37</td>
<td>2.47</td>
<td>2.93</td>
</tr>
<tr>
<td>H</td>
<td>2.89</td>
<td>3.04</td>
<td>3.02</td>
<td>3.04</td>
<td>3.06</td>
<td>2.99</td>
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<td></td>
<td></td>
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<tr>
<td>B</td>
<td>-1.46</td>
<td>-1.56</td>
<td>-1.53</td>
<td>-1.48</td>
<td>-1.52</td>
<td>-1.55</td>
</tr>
<tr>
<td>E</td>
<td>-0.33</td>
<td>-0.38</td>
<td>-0.41</td>
<td>-0.39</td>
<td>-0.39</td>
<td>-0.41</td>
</tr>
<tr>
<td>F</td>
<td>2.68</td>
<td>2.93</td>
<td>3.05</td>
<td>2.91</td>
<td>2.95</td>
<td>3.11</td>
</tr>
<tr>
<td>H</td>
<td>2.98</td>
<td>3.12</td>
<td>3.11</td>
<td>3.11</td>
<td>3.13</td>
<td>3.00</td>
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<tr>
<td>Medium heavy vehicles</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>B</td>
<td>-0.93</td>
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<td>-1.04</td>
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</tr>
<tr>
<td>E</td>
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<td>0.12</td>
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<td>0.05</td>
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<tr>
<td>F</td>
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<td>0.45</td>
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<tr>
<td>H</td>
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<td>2.80</td>
<td>2.82</td>
<td>2.91</td>
<td>2.84</td>
<td>2.93</td>
</tr>
</tbody>
</table>

Figure 10: Relation between the normalized annual hourly traffic flow and time at business days in 2012 for a) passenger vehicles, b) medium heavy vehicles c) heavy vehicles

The first phase from 0.00 to 5.00 for both vehicle groups is similar to Figure 9. Traffic flow is less than 0.2 of the $FLOW_{max}$. In the case of passenger vehicles, the remaining phases can be described by the following equations: the second phase from 5.00 to 8.00 – $FLOW_{norm} = 0.30x + B$, third phase from 8.00 to 16.00 – $FLOW_{norm} = 0.016x^2 - 0.39x + F$, the fourth phase from 16.00 to 23.00 – $FLOW_{norm} = -0.13x + H$. The values of the B, F and H coefficients are presented in Table 3. In the case of medium heavy vehicles, the second phase can be described by an equation $FLOW_{norm} = 0.25x + B$ and the fourth phase $FLOW_{norm} = -0.12x + H$. For the third phase of this group of vehicles (in 2011-2015) the $R^2$ coefficient for the second-order polynomial is from 0.30 to 0.64, which is not satisfactory. Additionally for some coefficients probability value $Pv$ is less than 0.05. Moreover, the maximum values of the traffic flow of these vehicles, depending on the year under study, occur at 9.00 or 10.00 and from 13.00 to 15.00. Whereas in 2016 for the second phase polynomial $FLOW_{norm} = 0.009x^2 - 0.22x + F$ is satisfactory because the fit factor $R^2=0.90$ and for all coefficients the $Pv$ is less than 0.05. For heavy vehicles, the traffic flow is always greater than 0.4 of the $FLOW_{max}$. The maximum values of traffic flow occur between 9.00 and 15.00, depending on the invest-
tigated year. Both the increase and decrease in the value of traffic flow is much slower than in the case of passenger or medium heavy vehicles. The $V_q$ parameter ranges from 10% to 27% and the uncertainty $u_a$ is lower than 4 vehicles per hour. It follows that the proposed procedure should be modified to describe the normalized traffic flow of heavy vehicle.

The reconstruction of the analyzed section of road No. 73 was also aimed at reducing the acoustic nuisance of vehicle traffic. This aspect was analyzed later in the paper. Figure 11 compiles the measurement results for the equivalent sound level for sub-intervals day (from 6.00 to 18.00), recorded in 2012 and 2016. Figure 11b shows Q-Q quantile plots for the standardized values of the data under analysis. The graphical representation of the spread of variables is shown on the box plots in Figure 11c.

The graphs in Figure 11a and Figure 11c indicate that despite the reconstruction of the road, the values of $L_{Aeq,T}$ underwent only slight changes. The quantile plots in Figure 11b confirm that the data do not follow a normal distribution. The calculations of the $L_{Aeq,T}$ values in 2012 showed that the median of $L_{Aeq,T}$ values on working days range from 71.9 dB(A) to 72.3 dB(A) and decreases up to 69.4 dB(A) on Sundays. But percentile C95 of $L_{Aeq,T}$ used in Nordic country’s as the maximum sound pressure level \[38\] range from 70.5 dB(A) to 73 dB(A). The lowest value of $L_{Aeq,T}$ equal to 69.36 dB(A) was obtained on Sundays. Identical calculations of the $L_{Aeq,T}$ in 2016 showed that median of $L_{Aeq,T}$ values on working days range from 71.4 dB(A) to 71.5 dB(A) and decreases up to 68.3 dB(A) on Sundays. But percentile C95 of $L_{Aeq,T}$ range from 68.8 dB(A) to 72.6 dB(A). Figure 12 shows the box plots of the $L_{Aeq,T}$ value in 2012 and 2016.
The outliers visible in the graphs should be accounted for in the analysis because, in the authors’ view, they do not represent measurement errors. Analysis of the measurement results database revealed the outliers on the days of public holidays. The data confirmed a regularity between the box plots in Figure 12a and in Figure 12b, showing that the highest \(L_{Aeq,T}\) values occurred on Fridays.

The analysis of the calculation results of \(L_{Aeq,T}\) in 2012 and 2016 indicates that the reconstruction of Popiełuszki Av. reduced the maximum values of \(L_{Aeq,T}\) on working days from 72.3 dB(A) to 71.5 dB(A). By contrast, on Sundays the \(L_{Aeq,T}\) value decreased from 69.4 dB(A) to 68.3 dB(A). Noise studies in 2013 and 2014, when intensive construction works related to the road reconstruction were carried out, showed that on working days the minimum value of the median \(L_{Aeq,T}\) was about 60.6 dB(A), but the percentile 95 was 74.2 dB(A). During this period, the maximum value of \(L_{Aeq,T}\) for the median was 68.6 dB(A) and the 95 percentile increased to 78 dB(A). The obtained measurement results of traffic flow over the period of six years made it possible to validate the Cnossos noise model currently in force in the EU countries. Very good agreement of the experimental results with the model was obtained, especially the medians \(L_{Aeq,T}\). For example, in 2011 the median determined experimentally was 71.70 dB(A) (77 mPa) and according to the model 71.38 dB(A) (74 mPa). In 2016, the median determined experimentally was 70.77 dB(A) (70 mPa) and according to the model 71.36 dB(A) (74 mPa). Type A measurement uncertainty was less than 0.7 km/h. The positional coefficient of variation of annual hourly traffic speed did not exceed 4% and the uncertainty was less than 0.7 km/h.

The mathematical model of the normalized annual hourly traffic flow for all vehicle groups can be divided into four phases. The \(R^2\) coefficients of fitting the proposed model curves to the experimental data are in the range from 0.93 to 0.99. The share of passenger vehicles in the total number of all vehicles ranges from 40% in the morning to 71% during peak hours and 63% in the night at 23:00. This confirms that passenger vehicle traffic is changing faster than other groups. For heavy vehicles, the traffic flow is always greater than 0.4 of their maximum value and the increase and decrease of traffic flow is much slower than in the case of passenger or medium heavy vehicles.

The median of equivalent sound level as well as maximum sound pressure level before the road reconstruction in 2011 and after the reconstruction in 2016 decreased slightly despite the fact that in 2016, there was an increase in traffic (compared to 2011) for all vehicles by 13.1%, passenger vehicles by 19.3%, medium heavy vehicles by 12%, and heavy vehicles by 20%. The analysis of the share of individual groups of vehicles in the traffic structure showed that the dominant group are passenger vehicles, for which the share in the traffic flow for 2011 was 67% and 80% on Sundays. This share in 2016 increased to 71% and on Sundays to 84%.

Values of the positional coefficient of variation of annual hourly traffic flow at business day in 2011–2016 for all vehicle groups from around 8.00 to 17.00 range from 3% to 7%. In the remaining periods of the day, the width of this interval is much greater up to around 18%.

Median of annual hourly traffic speed in 2011–2016 has slightly changed even in the traffic rush hours and ranges from 65 km/h to 74 km/h. The positional coefficient of variation of annual hourly traffic speed did not exceed 4% and the uncertainty was less than 0.7 km/h.

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A bottom-up methodology for both nationally-aggregated and spatially-disaggregated results. Journal of Transport Geography, 58, 186-195.