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INTERDEPENDENCE OF NOISE AND TRAFFIC FLOW

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Abstract. Traffic flows in cities, especially in city centres, are intensive and uneven, moreover, registered noise levels exceed allowable limits. Noise levels have been measured at K. Mindaugo ave. and Birštono street crossing in Kaunas and data of automated traffic flow registration equipment have been used. A constant reduction of noise level from the beginning till the end of the green light has been identified – "hot starts" generated noise dominates. To make estimates of noise and traffic flow interdependency, mathematical statistical models have been applied. Parameter distribution patterns have been analysed, prediction models have been composed.

Keywords: traffic flow, noise, statistics, regression, distribution.

1. Introduction

Modern Lithuanian big cities are constantly affected by transport generated noise due to increasing traffic flow intensity as a result of social, economic and political changes. Analysis of transport generated noise indicators and possible ways of reducing the noise are urgent issues in nowadays Lithuanian cities and the whole transport system.

Number of vehicles in Lithuania constantly grows, especially this process is evident in big cities. According to data of the Department of Statistics at the Government of the Republic of Lithuania the number of cars in Lithuania has grown since 1991 by 2.7 times. Traffic flows in cities, especially in their downtown parts, are intensive and uneven. Registered noise levels exceed allowable limits. Legal acts and initiated law projects of European Union and Lithuania emphasize importance of noise reduction, environmental effect issues, necessity to collect and store information related to traffic flows as well as introduction of traffic flow mathematical models, their implementation, integration, noise evaluation, as it is presented in the White Paper... (2001) and investigated by Ilgakojis *et al.* (2005).

Three types of vehicle generated noise are distinguished as follows:

1. Noise generated by the vehicle system – the engine, the gear box, the exhaust system, the drive shaft, the chassis, the wheels, etc.
2. Rolling noise, evolving as a result of tyres and road surface contact. It depends on the type of tyres and road surface as well as ambient conditions. The noise increases as speed of a vehicle increases and also during hard braking of a vehicle.
3. Noise generated due to the driver's attitude: abrupt increase of the engine's rpm at the start or awaiting, undisciplined driving, use of sound signal, which significantly increases traffic generated noise level, see Kliučininkas and Šaliūnas (2006).

Fig. 1. Kaunas city centre noise map

Negative effect of transport generated noise is especially evident in big cities, where traffic density is comparatively high, it is characterized by low speeds, frequent acceleration and deceleration. In Vilnius as much as 76.6% of inhabitants complain about noise day and night, and up to 68.1% of inhabitants consider noise the biggest problem in the city. Kaunas city centre map is shown in Fig. 1. Highest registered noise level in Kaunas city centre is in Jurbarko street / Vilijampolės bridge ave, Birštono street, St. Gertrūdos street and others, i.e. where traffic is evidently the most intensive.

2. Methods

2.1. Traffic noise and traffic flow measurements

In previous papers on analysis of traffic flows in Kaunas city centre transport network, the highest traffic intensity has been registered at Birštono street and St. Gertrūdos street crossing, however due to location of automated noise registration devices a nearby crossing of K. Mindaugo ave and Birštono street has been chosen for noise measurements. Measurements of urban traffic noise levels were performed only at the green traffic signal cycles.

Measurements of noise were performed according to the approved methods (LST ISO 1996–1:1993 and HN 33-1:2003) in Kaunas centre at crossing of Karaliaus Mindaugo ave and Birštono street (Fig. 2). Measured parameters are equivalent sound (noise) levels in dB(A) and maximal sound (noise) levels in dB(C). Noise levels were measured with two noise integrating measuring and analysing devices: "Brüel&Kjær" Type 2209, Type 4426 and "CEL – 440". Measurements were performed when speed of the wind was less than 5 m/s. Noise was measured in 1.5 m distance from the base and less than 7.5 m from the walls of the buildings according to the recommendations of Lithuanian standard LST ISO 1996-3-1993 "Acoustics-Description and measurement of environmental noise" to minimize the reflection of noise on the buildings.

Sound pressure level equivalent of inconstant (changeable) noise at different time-spans can be calculated also according to given statistical distribution of sound pressure levels. The following simplified formula is used to calculate equivalent constant A-weighted sound pressure level:

$$L_{A,eq} = 10 \cdot \lg\left[\frac{1}{T}\sum_{i=1}^{n}(t_i \cdot 10^{0.1 \cdot L_{A,i}})\right], dBA, \quad (1)$$

where $L_{A},_i$ is received by direct measurements equivalent A-weighted sound pressure level at i- time-span of t_i or average A-weighted sound level at i- time-span when the noise can be described as continuous (constant) at time-span of t_i; n is the number of such time-spans t_i over duration T.

The traffic noise is estimated by $L_{A,egT}$ (equivalent of continuous A-weighted sound pressure level over duration T) and L_{AN} (percentile level), which are estimated from the time duration percentile of the required duration of measurement and taken as the radiated noise parameters L_5 or L_{10}, L_{50}, L_{90} or L_{99}, L_N, and $L_{A,eq}$ are the levels that exceed accordingly 5 %, 10 %, 50 %, 90 % or N % than time duration of measurement analysis by Lithuanian Standard LST ISO 1996-1:1993 (1996).

2.2. Mathematical models

As a result of recent researches by Reppin and Ebbing (1995), and Morillas *et al.* (2002) broad discussions have been addressed to the issues of comprehensive models of ambient noise, analysis of its component parts, possibilities and conditions of their integration and differentiation, as well as possibilities to apply the models, which do not require measurements of sound source noise lev-

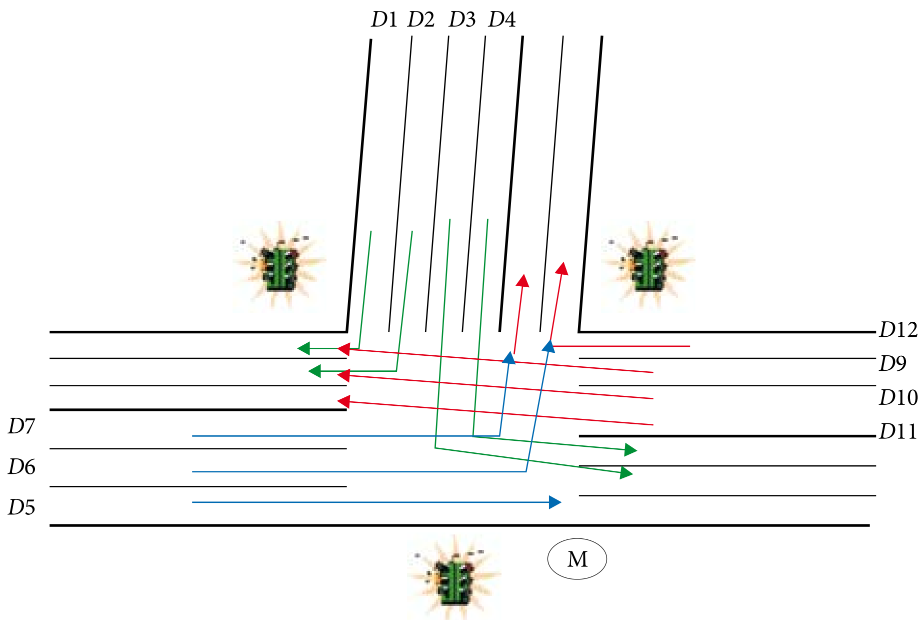

Fig. 2. Scheme of crossing at Karaliaus Mindaugo ave and Birštono street (M – place of performed measurements)

els, cover the sources on the move, in acceleration or deceleration. Importance of universally applied criteria is emphasized.

In order to define identification criteria for traffic flows and their generated noise, statistical mathematics methods have been chosen. Pearson x^2 agreement criterion is universal, its application possibilities do not depend on a theoretical distribution conclusion. Statistics D_n are described as difference of relative frequencies – falling into certain intervals of theoretical probabilities and their statistical estimates, whereas the criterion is based on low reliability of big deviation from these characteristics.

(X_1, X_2 ... X_n) are random samples of a variable X with an unknown distribution function $F(X)$. A simple hypothesis H_0 is being verified: $F(X) = F_0(X)$. The whole set of possible values of X variable is split into m intervals with a condition that k_i values of a concrete sample (x_1, x_2, ..., x_n) fall into i interval and H_0 is true, thus p_i theoretical probabilities are calculated:

$$p_i = P\left(a_{i-1} \le X < a_i\right) = F_0\left(a_i\right) - F_0\left(a_{i-1}\right) = \overline{1,m}, \quad (2)$$

where p_i probability is a theoretical distribution function $F_0(X)$ change in i interval (a_{i-1}; a_i), and relative frequency k_i/n – an empiric distribution function $\hat{F}_n(x)$ change in this interval.

Deviation index of theoretical and empirical distribution function is:

$$X_n^2 = \sum_{i=1}^{m} \frac{n}{p_i}\left(\frac{k_i}{n} - p_i\right)^2 = \sum_{i=1}^{m} \frac{k_i^2}{np_i} - n. \quad (3)$$

If hypothesis H_0 is true, statistics X_n^2 is asymptotically ($n \to \infty$) distributed along χ^2 pattern with m–1 degree of freedom. At big samples, X_n^2 statistics distribution is approximated to χ^2 distribution, where the approximation is considered good, when $np_i \ge 5$, with all $i = \overline{1,m}$. Undeniable statistics X_n^2 is composed so that the closer to zero is the value the bigger is probability that H_0 is true. That is why hypothesis verification criterion is based on the right critical area, which is composed of high X_n^2 values. Critical area K of X_n^2 statistics distribution and p quantile x_p^2 is described by equation:

$$P(X_n^2 \ge x_p^2) = \alpha. \quad (4)$$

Not knowing X_n^2 statistics distribution, only approximated χ^2 distribution with m–1 degrees of freedom and p quantiles is given: $x_p^2 \cong x_p^2(m-1)$. Critical area K is roughly characterized by interval $K = \left(X_p^2(m-1), \infty\right)$, $\quad p = 1 - \alpha$ with criteria:

- if X_n^2 statistics specific value is $x_p^2 \ge x_p^2\left(m-1\right)$ – H_0 hypothesis is rejected;
- if $x_p^2 < x_p^2\left(m-1\right)$ – H_0 is accepted.

If $F_0(x) = F_0(x, \theta_1, \ldots, \theta_s)$, and $\hat{\theta}(i = \overline{1,s})$ parameters are unknown, basing on grouped sample data, coordinated estimates $\hat{\theta}(i = \overline{1,s})$ of the unknown parameters are found and probabilities are calculated as follows:

$$\hat{p}_i = F_0(\alpha_i, \hat{\theta}_1, \ldots, \hat{\theta}_s) - F_0(\alpha_{i-1}, \hat{\theta}_1, \ldots, \hat{\theta}_s), \quad (5)$$

where, $i = \overline{1,m}$.

When sample volume n is big, the real analogue of X_n^2 statistics is:

$$\hat{X}_n^2 = \sum_{i=1}^{m} \frac{\left(k_i - n\hat{p}_i\right)^2}{n\hat{p}_i}. \quad (6)$$

X_n^2 statistics distribution, when sample volume is big, is also approximated by χ^2 distribution, however with m–s–1 degree of freedom, and with significance level α, critical area is approximately described by the interval, see Aksomaitis (2000):

$$K = \left[X_p^2\left(m - s - 1\right), +\infty\right], \quad p = 1 - \alpha. \quad (7)$$

Traffic flows and their generated noise intensity dependencies are estimated by using *SAS* statistical software.

3. Results

Traffic flow generated noise registered at the chosen crossing is presented in Fig. 3. Evolution of L_{Aeq} levels is recorded during the green traffic signal cycle (t = 20 s) at the analysed crossing. It can be noted that L_{Aeq} levels almost continuously decrease till the end of the green traffic signal cycle. At the beginning of the green traffic signal cycle the recorded maximal noise level is 101.2 dB(A) and at the end of the cycle it is less than 50 dB(A). Interrupted traffic flows give higher noise levels at urban environment due to acceleration (hot-starts) of the vehicles during the traffic signals cycle.

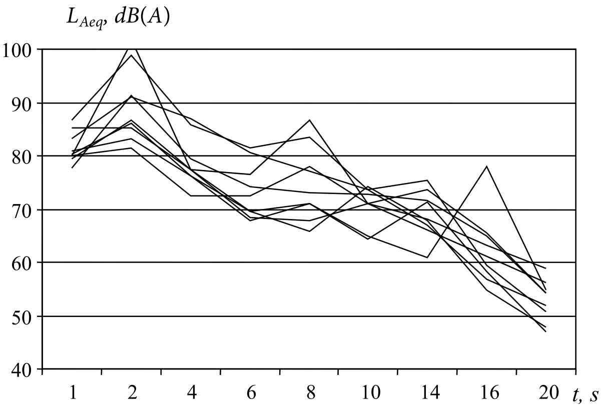

Fig. 3. Measuared L_{Aeq} levels during the green traffic signal cycle

Registered traffic flows and their generated noise have been analysed using statistical mathematics methods, firstly, checking distribution patterns and defining dependencies between them. To define traffic flow distribution all traffic lanes at the analysed crossing have been checked. Fig. 4 presents defined Poisson distribution of *D*3 traffic lane, proposing a hypothesis H_0: $X \sim P(\lambda)$,that the traffic flow is Poissonic and thus the hypothesis is verified by Pearson χ^2 criterion. Traffic flows in the remaining lanes are analysed similarly, the results are presented in Table 1.

Table 1. Traffic flow hypotheses and Poisson distributions in the analysed crossing lanes

	Hypothesis	Poisson distribution
*D*1	$\overline{X}^2_{0.95}(8) = 7.182639 < 15.50731 = X^2_{0.95}(8)$	$P_i(t) = \frac{(4.066667t)^i \cdot e^{-4.066667t}}{i!}$
*D*3	$\overline{X}^2_{0.95}(8) = 7.182639 < 15.50731 = X^2_{0.95}(8)$	$P_i(t) = \frac{(1.066667t)^i \cdot e^{-1.066667t}}{i!}$
*D*4	$\overline{X}^2_{0.95}(14) = 15.602 < 23.685 = X^2_{0.95}(14)$	$P_i(t) = \frac{(0.933333t)^i \cdot e^{-0.933333t}}{i!}$
*D*5	$\overline{X}^2_{0.95}(16) = 18.751 < 26.296 = X^2_{0.95}(16)$	$P_i(t) = \frac{(1.525t)^i \cdot e^{-1.525t}}{i!}$
*D*6	$\overline{X}^2_{0.95}(33) = 36.943 < 47.400 = X^2_{0.95}(33)$	$P_i(t) = \frac{(3.725t)^i \cdot e^{-3,725t}}{i!}$
*D*7	$\overline{X}^2_{0.95}(20) = 30.785 < 31.411 = X^2_{0.95}(20)$	$P_i(t) = \frac{(2.075t)^i \cdot e^{-2,075t}}{i!}$
*D*9	$\overline{X}^2_{0.95}(14) = 15.86649 < 23.68478 = X^2_{0.95}(14)$	$P_i(t) = \frac{(1.5833t)^i \cdot e^{-1.58337t}}{i!}$
*D*10	$\overline{X}^2_{0.95}(15) = 22.603 < 24.996 = X^2_{0.95}(15)$	$P_i(t) = \frac{(1.03333t)^i \cdot e^{-1.03333t}}{i!}$
*D*12	$\overline{X}^2_{0.95}(24) = 30.194 < 36.415 = X^2_{0.95}(24)$	$P_i(t) = \frac{(2.29167t)^i \cdot e^{-2.29167t}}{i!}$

Table 2. Noise distrubution pattern statistical estimates

Average		72.05068
Standard deviation		18.34118
Test	Statistics	*p*-value
Kolmogorov-Smirnov	*D* 0.0901247	*Pr* > *D* >0.1500
Cramer-von Mises	*W-Sq* 0.0772124	*Pr* > *W-Sq* 0.228
Anderson-Darling	*A-Sq* 0.5537917	*Pr* > *W-Sq* 0.152
Chi-Square	*Chi-Sq* 30.7951623	*Pr* > *Chi-Sq* 0.001

Table 3. Statistical characteristics of traffic flow and noise interdependence

Pearson criterion (%)	R^2	*p*	*F-value*	*L*
93,27	0,8699	<0.0001	53.48	$L1_i = 24.390665 + 5.56782q_{1_i}$
96.45	0.9303	<0.0001	106.7	$L2_i = 28.86000 + 4.99882q_{2i}$
99.49	0.9898	<0.0001	778.41	$L3_i = 27.39528 + 5.15189q_{3i.}$
97.11	0.9431	<0.0001	132.51	$L4_i = 25.92687 + 5.35821q_{4i}$
98.92	0.9583	<0.0001	184.06	$L5_i = 30.18737 + 4.79474q_{5i}$
98.83	0.9748	<0.0001	309.94	$L6_i = 32.60542 + 5.11098q_{6i}$
91.73	0.8414	<0.0001	42.44	$L7_i = 26.78488 + 4.887212q_{7i}$
98.94	0.9791	<0.0001	373.99	$L8_i = 23.70071 + 5.71453q_{8i}$
97.67	0.9539	<0.0001	165.63	$L9_i = 22.31459 + 5.71993q_{9i}$

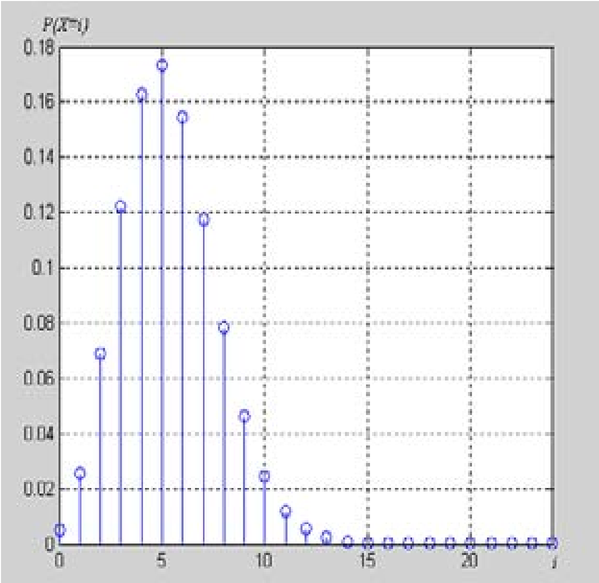

Fig. 4. Poisson distribution in *D*3 traffic lane

Upon evaluation of the proposed hypotheses and distributions in all the traffic lanes a conclusion is drawn that a microscopic traffic flow is Poissonic and ordinary. For further analysis of traffic flow and noise interdependence a condition of traffic distribution pattern identification is required. Statistics of noise measured at the crossing of K. Mindaugo Av. and Birštono street are presented in Table 2, and the pattern of distribution – in Fig. 5. Basing on Chi-Square criterion we have the result that traffic flow noise is distributed along Normal line distribution with an average of 73.05068, standard deviation 18.34118 and skewness factor –0.5774 (Normal line distribution diagram is stretched to the left).

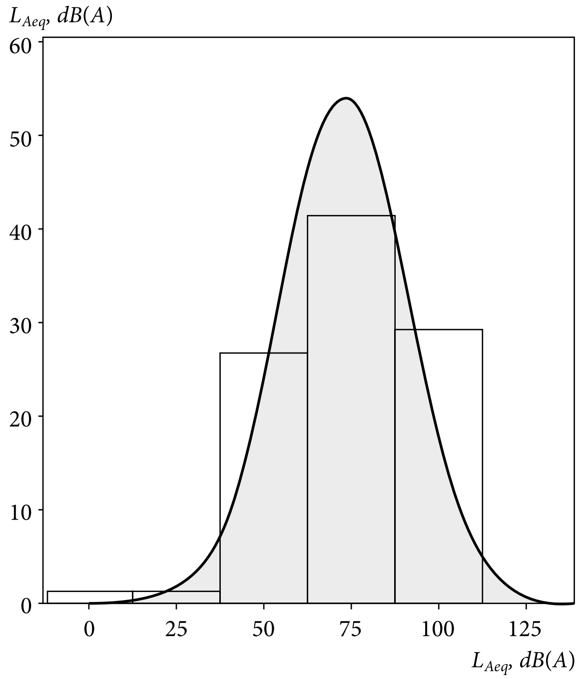

Fig. 5. Distribution law of noise level L_{Aeq} at the crossing of K. Mindaugo ave and Birštono street

Analysing independent variables – the intensity of traffic flow and dependent variables – the noise, a regressive model is composed. Its data are presented in Table 3.

According to the results of Pearson criterion (93.27–99.49 %) the correlation between the flow intensity and the noise is strong and a null hypothesis *H*0 (the data are correlated) is accepted. Having defined the correlation a regressive model is composed, and the data distribution is explained by regression equation. Hypotheses that regression equation factor being equal to 0 are rejected. Coefficient of determination R^2 is used to evaluate the dispersion along the average, which can explain direct regression between the variables, and the remaining part is the dispersion part unexplained by the linear regression between the variables. Based on the received results dispersion analysis is also performed and the received significant independent variables are included in the direct regression equations. If conditions of direct regression and model adequacy are acceptable, predictions of traffic flows and noise are made.

To evaluate interdependence of noise level L_{Aeq} and traffic flow q intensity H_0 hypothesis about equality of the averages is verified, however due to nonconformity of the data to some minimum requirements, one of which is that the data must be distributed according to Gauss (normal) distribution, Student criterion is not applicable. Basing on the analysis data noise level is directly proportional to the intensity of traffic flow, that is why average, dispersion and reliable interval values have been evaluated. The received results are graphically presented in Fig. 6. According to the proven direct dependence of the noise level on traffic flows, dependencies to evaluate the average noise level are defined as follows:

$$L_{Aeq\ vid} = 4.6\ q + 33.1,$$

$$95\%\ PI = [(3.25\ q + 34) - (5.3\ q + 39.1)]$$

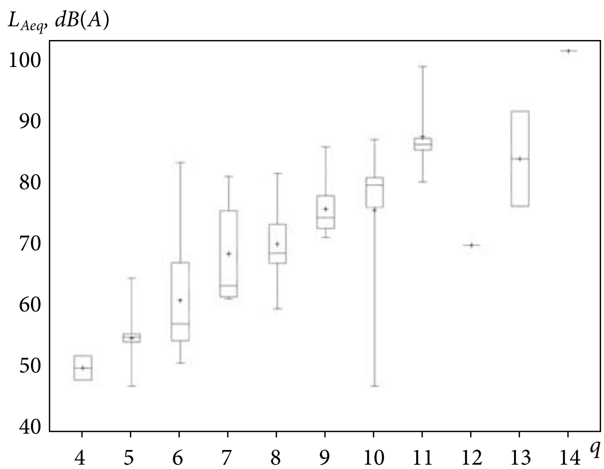

Fig. 6. Interdependence of noice level L_{Aeq} and traffic flow q

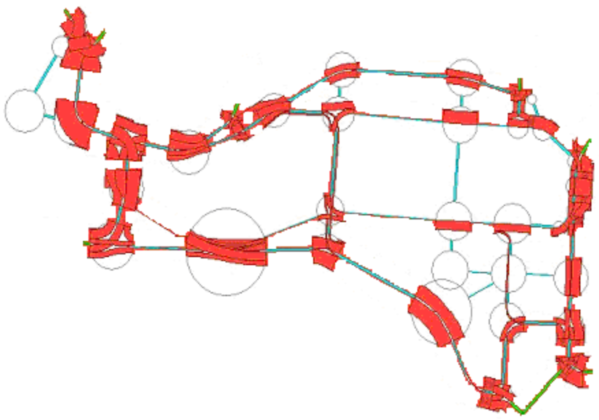

Fig. 7. Computed L_{Aeq} level at the intersections in the centre of Kaunas

This dependence as well as the methodology used to define it allows to estimate simultaneously noise levels in a city according to data provided by the automated traffic flow registration system and the result is obtained with EMME/2... (1999) software (Fig. 7). Coefficients of the dependence can be adjusted taking into consideration acoustic environment in the analysed territories, qualitative changes of the transport. This information is necessary for environmental transport management systems, creation of interactive noise maps of a city.

4. Conclusions

1. At the crossing of Birštono street and Karaliaus Mindaugo ave in Kaunas, analysed L_{Aeq} levels almost continuously decrease from 101.2 dB(A) to 50 dB(A) till the end of the green traffic signal cycle, i.e. noise generated by "hot starts" dominates. It must be aimed to minimize interrupted and maximize continuous intervals of traffic flows trying to reduce urban noise levels.
2. Statistical mathematics methods have been chosen to evaluate traffic flows and their generated noise. It has been defined that the traffic flow is distributed according to Poisson distribution, whereas noise is distributed according to the Normal distribution. Average, dispersion and reliable intervals values have been evaluated to define interdependence.
3. The formed prediction models allow to estimate simultaneously noise levels in a city according to data provided by the automated traffic flow registration system.

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