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NEW RANKING METHOD OF TRAFFIC NOISE REDUCTION MEASURES

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Abstract. *The paper presents new ranking method of traffic noise reduction measures. Mathematical model for simultaneous estimation of different noise reduction methods for multiple locations was developed. For realization of the proposed model empirical dependencies for effective time for vehicles of different categories were obtained on the base of series of experimental studies.*

Keywords: traffic flows; noise reduction methods; ranking.

1. Introduction

There are various methods of noise reduction on the way of its propagation from a source to a receiver. However, the use of each of these methods has its limitations and is efficient only under certain conditions. The main criterion for the potential use of the noise reduction method is the ratio efficiency/cost. Therefore, the relevant issue is the selection of the most efficient noise reduction methods from the list of available and possible to use for the given conditions.

2. Literature analysis

Today assessment of noise reduction methods is based on series of criteria that involve ecological, economical and social elements according to the concept of green development. All of these method are well described and analyzed both in national [Maier 1975; Samoiliuk 1975; Didkovskii et al. 2001] and international literature [Kang 2006].

But all of them are assessed separately. Nevertheless it is necessary to take into account that each method has different both ecological and economic efficiencies and it is useful to asses them simultaneously for selection of the best combination of available noise reduction measures. That is why the present work is devoted to creation of mathematical model of joint estimation for such methods.

3. Mathematical formulation of the problem

In the present study the complex task of traffic noise reduction methods of both indoors and outdoors on the territory of residential development is studied.

Indoor traffic noise reduction can be achieved by noise decrease in the source of its generation (e.g., engine noise, rolling noise, traffic speed control and other methods).

Let P_j is a relative contribution of the *j*-th noise reduction method [Zaporozhets et al. 2011].

Since the traffic noise is time dependent, thus, equivalent noise levels are used for its evaluation. Equivalent noise level for the *m*-th vehicle is written as:

$$L_{Aeq} = 10\lg\left(\frac{1}{T_0}\sum_j \tau_{efm} 10^{0,1L_{A\max m}}\right), \qquad (1)$$

where T_0 – the observation time;

τ_{efm} – the effective time for the *m*-th vehicle, defined as the time of the top ten decibels sound;

$L_{A\max m}$ – the maximum sound level of the *m*-th vehicle.

The effective time for the *m*-th vehicle is defined as the ratio:

$$\tau_{efm} = k\frac{l_m}{v_m}, \qquad (2)$$

where k – empirical coefficient;

l_m – the shortest distance from the *m*-th vehicle to the receiver;

v_m – the sound speed of the *m*-th vehicle.

Observation time interval is divided into N segments. In this case, equation (1) can be rewritten as follows:

$$1-\sum_{i=1}^{N}\tau_{efm}T_0^{-1}P_j 10^{-0,1\Delta L_j} = 0, \qquad (3)$$

where $\Delta L_j = L_{Aeq} - L_{A\max}$, L_{Aeq} is set sound level.

In real cases the residential territory consists of multiple multistory buildings. That is why simultaneous assessment of noise reduction methods has to be done for multiple receiver locations.

Suppose that *i* receiver locations are considered and the *j*-th noise reduction method is used. Then, equation (3) has to be rewritten as a system of equations:

$$\begin{cases} 1-\sum_{i=1}^{N}\tau_{efm}T_0^{-1}P_j 10^{-0,1\Delta L_j^1} = 0\,; \\ 1-\sum_{i=1}^{N}\tau_{efm}T_0^{-1}P_j 10^{-0,1\Delta L_j^2} = 0\,; \\ \vdots \\ 1-\sum_{i=1}^{N}\tau_{efm}T_0^{-1}P_j 10^{-0,1\Delta L_j^i} = 0\,, \end{cases} \quad (4)$$

where $\Delta L_j^1, \Delta L_j^2 \ldots \Delta L_j^i$ are noise reduction values outdoors using j-th method for i-th receiver location.

Noise reduction can be achieved by urban planning techniques (e.g., by increasing the distance between the source and the receiver, acoustic screens installation, greenery plantings, use of terrain, increasing the insulation of windows, installation indoors sound-absorbing coating).

The value of sound level reduction inside the room is δL_j.

It is necessary to achieve the total reduction of noise in the room from traffic flows on the value:

$$\delta L = \sum_j P_j \delta L_j\,. \quad (5)$$

For considered i receiver locations equation (5) is rewritten as a system of equations:

$$\begin{cases} \delta L_1 - \sum_j P_j \delta L_j^1 = 0\,; \\ \delta L_2 - \sum_j P_j \delta L_j^2 = 0\,; \\ \vdots \\ \delta L_i - \sum_j P_j \delta L_j^i = 0\,, \end{cases} \quad (6)$$

where $\delta L_1, \delta L_{2\ldots} \delta L_i$ – total required noise reduction values inside room for i-th receiver location;

$\delta L_j^1, \delta L_{j\ldots}^2\, \delta L_j^i$ – values of sound level reductions inside the room using j-th method in i-th receiver location.

Consider the problem from the point of considering the analysis of complex systems [Viliams 1978]. In this system, we introduce the concept of entropy [Imelbaiev, Shmulian 1978; Zaporozhets et al. 2011]:

$$S = \sum_j P_j \left(1 + \ln\frac{v_j}{P_j}\right), \quad (7)$$

where v_j is a priori evaluation of the significance of j-th traffic noise reduction method inside the room.

Value P_j (the relative contribution of the j-th traffic noise reduction method) is defined as the maximum of the entropy (7) with constraints (4), (6) [Viliams 1978; Imelbaiev, Shmulian 1978].

According to the method of Lagrange multipliers let the auxiliary function is written in the form:

$$\Phi = S + \sum_i \lambda_i \left(1 - \sum_j \tau_{efj} T_0^{-1} P_j 10^{-0,1\Delta L_j{}^i}\right) + \\ + \sum_i \beta_i \left(\delta L_i - \sum_j P_j \delta L_j{}^i\right), \quad (8)$$

where λ_i, β_i are Lagrange multipliers.

The equations which maximize function (8) are:

$$\frac{\partial\Phi}{\partial P_j} = \ln\frac{v_j}{P_j} - \sum_i \lambda_i \tau_{efj} T_0^{-1} 10^{-0,1\Delta L_j^i} - \sum_i \beta_i \delta L_j^i = 0 \quad (9)$$

From equation (9) we obtain the value P_j:

$$P_j = v_j \exp(-\tau_{efj} T_0^{-1} \sum_i \lambda_i 10^{-0,1\Delta L_i^j} - \sum_i \beta_i \delta L_j{}^i)\,. \quad (10)$$

The Lagrange multipliers are determined from systems of equations (4) and (6).

In the proposed method of the selection of a priori estimates v_j (significance of the j-th noise reduction method inside the room) normalization condition is used:

$$\sum_j v_j = 1\,.$$

4. Studying effective time of vehicles of different categories

Effective time τ_{efi} for i-th vehicle in the investigation was determined on the basis of experimental studies of acoustic characteristics of vehicles of various categories. The measurement results have allowed determining empirical relationships for the effective time for vehicles of different categories.

Effective time mathematical model was investigated using a database of individual vehicles pass-by. Characteristics of traffic noise measurements were performed for the pass-by length 40 m.

For the known speed and segment length individual vehicle pass-by time was defined as:

$$T_0 = \frac{s}{v},$$

where s is the length of the pass-by distance, m;

v is vehicle speed, m/s.

To determine the coefficient k of equation (2) a Genetic Algorithm of Matlab Optimization Tool was applied [Gundogdu et al. 2005; Rahmani et al. 2011]. During modeling of the effective time genetic algorithm is used to minimize the deviation of the measured values from the calculated equivalent sound pressure level. Thus, by using genetic algorithm coefficients k for vehicles of I-III categories were obtained [GOST 31330.1-2006]. Second and third categories were combined, as studies have shown the identity of the calculated ratios.

Thus, equation (2) can be written as:

– for automobiles of category I:

$$\tau_{ef,1} = 2{,}19 \frac{l}{v_1},$$

– for automobiles of category II and III:

$$\tau_{ef,2,3} = 2{,}27 \frac{l}{v_{2,3}},$$

where l is the distance from the source to the receiver of sound oscillations.

Simulation results of the effective time were compared with experimental data for different speeds, which are the most characteristic for modern cities. Provided results are given in Table 1 for passenger cars and for heavy vehicles with absolute modeling error E.

Table 1. Comparison of experimentally $\tau_{ef,\exp}$ and theoretically $\tau_{ef,\mathrm{mod}}$ calculated effective time

v		$\tau_{ef,\exp}$, s	$\tau_{ef,\mathrm{mod}}$, s	E, s
km/h	m/s			
I category				
30	8,3	1,78	1,97	0,19
35	9,7	1,60	1,69	0,09
40	11,1	1,55	1,48	0,07
50	13,9	1,25	1,18	0,07
60	16,7	1,03	0,98	0,04
II and III categories				
30	8	2,05	1,99	0,06
46	12,9	1,47	1,28	0,19
63	17,4	0,84	0,95	0,11
69	19,0	0,91	0,87	0,04
72	20,0	0,75	0,83	0,08

Analysis of the results showed that an increase in pass-by speed of the vehicle the simulation accuracy increases. Thus, for a speed of cars and trucks above 60 km/h the absolute error of simulation is 0.04 s as opposed to 0.19 s for speeds of 30-40 km/h. It is necessary to note that for large traffic flows (more than 4,000 cars/h) in modern cities the speed of 50-80 km/h is the most typical, which is confirmed by experimental studies. Lower speeds are observed only for small traffic flows that do not provide excess noise levels.

The dependence of the effective time on vehicle speed is shown in Fig. 1.

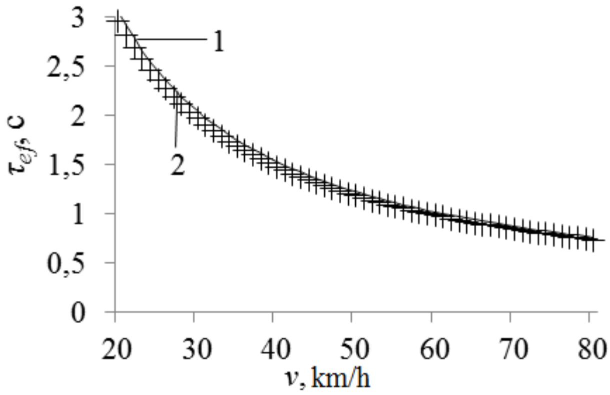

Fig. 1. Comparison of effective time of the top 10 dB for cars of various categories:
1 – for vehicles of the category I;
2 – for vehicles of categories II and III

As shown in Fig. 1, the curve of noise effective is determined by the monotonous dependence.

Obtained empirical dependences of the effective time were used for the further simulation of equivalent noise levels by approximate method [GOST 22283-88].

5. Case study of the relative contribution of the *j*-th noise reduction method in the overall acoustic field

The initial step in evaluating the contribution of noise reduction method is to determine the input data. For the selected list of noise reduction methods the values of noise reduction both on the territory of residential buildings and indoors are calculated. It is assumed that on the territory of residential development the receiver is located 2 m from the façade of the building, and its height is 1.2 m. Inside the room the height is similar to the receiver located outdoors, and the distance from the wall is assumed as 1 m. When using such methods to reduce noise as soundproofing or the use of active windows, it is supposed that these methods do not contribute to the reduction of noise on the territory of residential buildings.

Noise reduction is calculated by mathematical models described in [Didkovskii et al. 2001; Shevchenko 2010; Shevchenko 2011; Shevchenko et al. 2012].

Priori estimates of noise reduction methods are supposed to be the cost of method use to get necessary reduction values. Values of the priori estimates are defined based on expert evaluation. The economic aspect of noise reduction methods was defined on the basis of published data.

Priori estimates initially defined as the cost parameters in local currency, but for ease of calculation have been reduced to standard units.

Calculations of the relative contribution of the j-th noise reduction method were performed for two cases of required noise reduction inside the room: for $\delta L = 8$ dB and $\delta L = 17$ dB.

Different noise reduction values were studied in the article as the model is sensitive to the value δL and calculates the relative contribution of the j-th method of noise reduction based for the defined δL value. This dependence is shown on Fig. 2.

To find the relative contribution of the j-th noise reduction method with the help of equation (10) it was solved the problem of the unknown Lagrange multipliers by using Optimization Toolbox software of MatLab with solver of nonlinear equations.

For the purpose of testing the developed mathematical model it was conducted simulation test case for which a priori estimate was taken as 1 for all methods of noise reduction. The simulation results are given in Fig. 2.

In Fig. 2 it can be traced the difference in the distribution of the relative contribution of each noise reduction method based on the set necessary reduction δL.

At $\delta L = 17$ dB major contributions correspond to methods such as installation of acoustic screens and sound insulation of windows, as most of these methods produce the most noise reduction. Unlike the first case, when $\delta L = 8$ dB major contributions correspond to decreasing intensity of traffic flows (from the 4,000 cars/h to 1,000 cars/h) and reducing traffic speed (on 10 km/h), since the use of such methods would achieve the required cumulative noise reduction.

Therefore, when using the proposed model an important step is specifying the total noise reduction value required by the set task. This characteristic feature was taken into account in the further simulation test case.

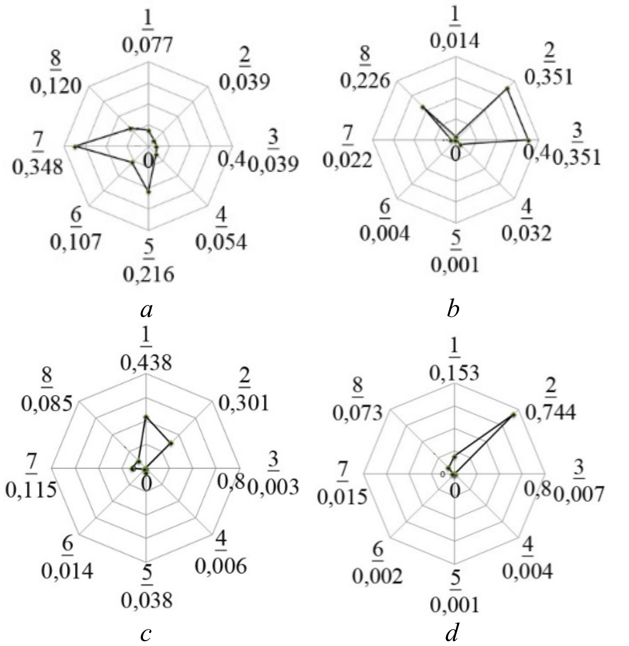

Fig. 2. The relative contribution of the j-th noise reduction method for the investigated case, where the numerator is given a serial number of noise reduction method:

a, c – $\delta L = 17$ dB;

b, d – $\delta L = 8$ dB;

1 – traffic flow intensity decrease;
2 – traffic flow speed decrease;
3 – the use of porous pavements;
4 – green areas;
5 – thin acoustic screen installation;
6 – acoustic screen of finite thickness installation;
7 – soundproofing windows;
8 – using the active windows, and the denominator of its relative contribution

As in the case of equal priory estimates simulations were conducted for noise reduction on 8 and 17 dB. The initial data is provided in Table 2. In both cases, most contributions are characteristic for such methods as reducing the intensity of traffic flow, reducing traffic speed and the use of active windows. This is explained by set priori estimate that define these methods as more economically efficient.

Different results were obtained for study of multiple Receiver Location (RL) of interest. Two sets of RLs were analyzed: the number of RLs was changed from 1 to 5 with the same values of δL and ΔL for each RL; the second case study was for 3, 4 and 5 RLs with different values of noise reduction. The initial data for the second case study are presented in Table 3. It was supposed that receivers are located different stories of the multistory building.

Table 2. Initial data for calculation of the contribution of the *j*-th traffic noise reduction method for single receiver location

Number of method	Noise reduction method	δL, dB	ΔL, dB	ν, relative units	Normalized a priori estimate, ν_j
1	Traffic flow intensity decrease	3	5	100	0,463
2	Traffic flow speed decrease	1	2	100	0,463
3	Porous road surfaces	1	2	1	0,005
4	Green plantings	2	5	2	0,009
5	Acoustic screens installation: Thin acoustic screen	6	9	3,3	0,015
6	Acoustic screen of finite thickness	4	7	2,5	0,012
7	Soundproofing windows	7	0	2	0,009
8	Active windows exploitation	4	0	5	0,023

Table 3. Calculation of the contribution of the *j*-th traffic noise reduction method for multiple RLs

Noise reduction method	Number of investigated RLs 5									
	RL N 1		Number of investigated RLs 4							
			RL N 2		Number of investigated RLs 3					
					RL N 3		RL N 4		RL N 5	
	ΔL	δL	ΔL	δL	ΔL	δL	ΔL	δL	ΔL	δL
Traffic flow intensity decrease	5	3	5	3	5	3	5	3	5	3
Traffic flow speed decrease	2	1	2	1	2	1	2	1	2	1
Porous road surfaces	2	1	2	1	2	1	2	1	2	1
Green plantings	5	2	5	2	5	2	2	0	1	0
Thin acoustic screen	9	6	9	6	9	6	6	3	4	2
Acoustic screen of finite thickness	7	4	7	4	7	4	4	3	3	2
Soundproofing windows	0	7	0	7	0	7	0	7	0	7
Active windows exploitation	0	4	0	4	0	4	0	4	0	4

Fig. 3 *a*, *b* shows the modeling results for the first case study for different values of δL. It can be clearly distinguished that RLs more than 1, the largest contribution P_j belongs to 5th method that is installation of thin acoustic screen on the contrary to the single RL (Fig. 2), where the most efficient methods were reducing the intensity of traffic flow, reducing traffic speed and the use of active windows. Increasing the number of RLs increase the single contribution of just one noise reduction method and the value P_j approximates to 1.

The same results of single noise reduction method largest contribution are observed for multiple RLs with different reduction values (Table 3) are demonstrated on Fig. 3, *c*.

If for three RLs two methods of noise reduction were selected (1st and 5th methods accordingly), than for five RLs most of contribution goes to 5th method - installation of acoustic screens.

6. Conclusions

In this paper the problem of traffic noise reduction methods ranking on the territories of residential development and indoor considering both environmental and economic performance of the studied methods was formulated and solved.

For development of ranking method empirical dependencies for effective time for different vehicles categories were obtained on the base of the conducted series of experimental studies.

Based on the developed model of traffic noise reduction methods ranking study of the relative contribution of the *j*-th method of noise reduction for a given noise reduction value was conducted. This model allows us to choose the most efficient from an environmental and economic point of view noise reduction techniques by using a priori estimates of the effectiveness of each method, but the methods it chooses strongly depend on the boundaries of set value of required noise reduction.

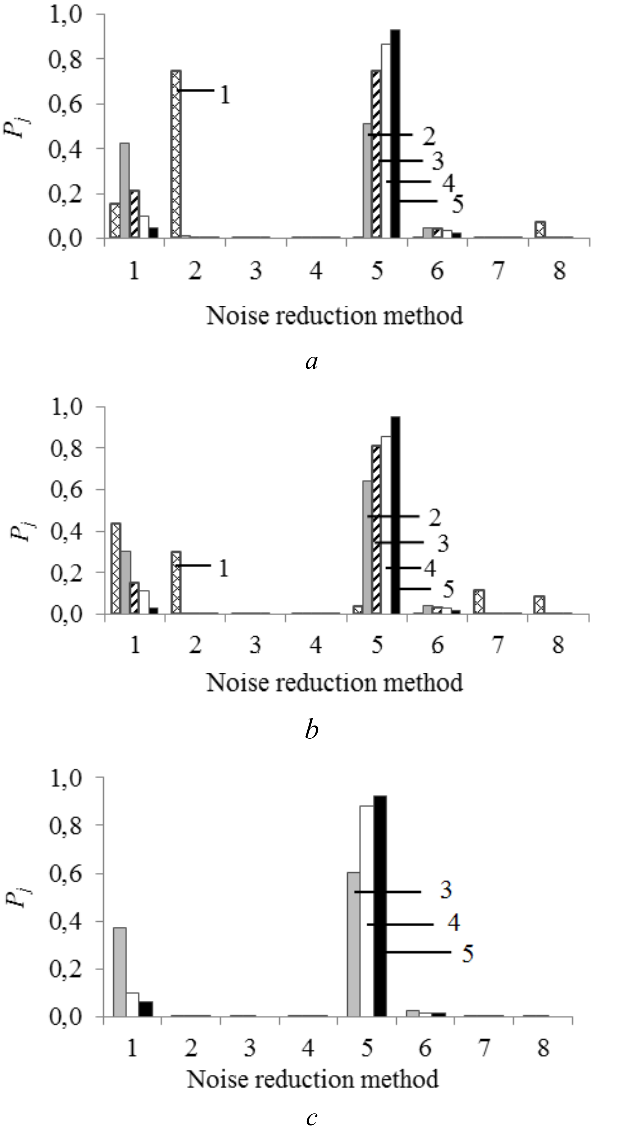

Fig. 3. The relative contribution of the *j*-th noise reduction method (as in Fig. 2) for number of investigated RLs:
a – required noise reduction was $\delta L = 17$ dB;
b, c– required noise reduction was $\delta L = 8$ dB;
1 – one location;
2 – two locations;
3 – three location;
4 – four locations;
5 – five location

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Ю.С. Шевченко. Новий метод ранжування заходів зниження шуму транспортних потоків

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Досліджено актуальну проблему оцінювання ефективності методів зниження шуму від автомобільного транспорту. На основі проведеного математичного моделювання отримано значення акустичної ефективності кожного з досліджуваних методів з урахуванням їх економічної ефективності. Запропоновано математичну модель ранжування заходів зниження шуму транспортних потоків із використанням ентропійного методу. На основі даних серії експериментальних досліджень розроблено емпіричні залежності ефективного часу звучання для автомобілів різних категорій. Отримані залежності використано в математичній моделі ранжування заходів зниження шуму. Оцінено внесок кожного з методів у загальне зниження шуму. Показано, що важливим параметром є задане зниження шуму, якого необхідно досягнути описаними методами. Значення зниження шуму враховано для ряду положень приймачів. Змодельовано зону житлової забудови, коли ефективність методів залежить від взаємного розташування лінії джерела шуму та приймача, наприклад, для вікон різних поверхів.

Ключові слова: методи зниження шуму; ранжування; транспортні потоки.

Ю.С. Шевченко. Новый метод ранжирования мероприятий снижения шума транспортных потоков

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Исследована актуальная проблема оценки эффективности методов снижения шума от автомобильного транспорта. На основе проведенного математического моделирования получены значения акустической эффективности каждого из исследуемых методов с учетом их экономической эффективности. Предложена математическая модель ранжирования мероприятий снижения шума транспортных потоков с использованием энтропийного метода. На основе данных серии экспериментальных исследований разработаны эмпирические зависимости эффективного времени звучания для автомобилей различных категорий. Полученные зависимости использованы в математической модели ранжирования мероприятий снижения шума. Оценен вклад каждого из методов в общее снижение шума. Показано, что важным параметром является заданное снижение шума, которого необходимо достичь описанными методами. Значение снижения шума учтено для ряда положений приемников. Смоделирована зона жилой застройки, когда эффективность методов зависит от взаимного расположения линии источника шума и приемника, например, для окон разных этажей.

Ключевые слова: методы снижения шума; ранжирование; транспортные потоки.

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