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Modelling and Predicting Sound Level Around Selected Sections of Motorway A2

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Abstract

This article presents potential of modelling and predicting noise level around the section of motorway A2 Komorniki – Krzesiny. The models were worked out on the basis of sound levels registered in three stages of research connected with phases of utilization of this motorway (measurement of acoustic background without traffic, measurements after opening section Komorniki – Krzesiny and noise measurement after opening section Nowy Tomyśl – Konin). The models were verified on the basis of actual number of vehicles which passed by section Komorniki – Krzesiny on random day and at random hour.

Keywords: traffic noise, motorway, noise modelling, diffraction

1. Introduction

Intense development of cities, industry, transport networks and airports has not only undoubted industrial advantages but also many negative effects. Increased emission and extent of traffic and industrial noise in urban areas is an example of negative effects. Noise emission at housing estates and recreation areas reached so high level that they can hardly be used for the purposes they were created for. It is estimated that in Poland the number of people endangered by noise amounts between 13÷15 million, and during a day average equivalent sound level in the centers of big cities exceeds L_{Aeq} = 70 dB [17].

This article presents two models: mathematical-physical model and statistical model of predicting sound level around the section of motorway A2 Komorni-

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ki – Krzesiny. The models were worked out for specific location of the motorway: the carriageway is located in excavation and passes through urban agglomerations: Komorniki, Luboń and Poznań.

2. Modelling of Traffic Noise

Traffic noise has become a common and prevailing danger, which significantly influences the acoustic climate in many urban agglomerations. It is connected with dynamically developing road, railway and airway networks as well as with large number of vehicles moving in those networks. This situation caused intense development of research over identification of sources of those effects and over identification of effects which have significant influence on sound propagation in the environment.

First tests about road noise consisted mainly in defining dependences between the value of the index of noise assessment at observation point and parameters describing the source of sound without taking into account the influence of surrounding conditions. Quasi-maximum level L_{A10} or average level L_{A50} [6] were assumed as indexes of nuisance assessment. Further tests were characterized by fast development in urban acoustics. They comprised primary tests in the range of applied sciences and empirical research [13, 22]. Complex problems connected with sound emission and its propagation in urban built-up area were directed into determining characteristics and formulating analytical models of noise emission for various types of road [3, 20], railway or airway transport.

In some countries intense development of transport and infrastructure connected with transport triggered working out calculation standards, which helped to predict in the environment sound levels connected with passing vehicles. Those standards were created on the basis of results of empirical research carried out in a certain country and are mostly applied in the country in which they were worked out.

The most common worldwide calculation standards connected with assessing in the environment sound levels from vehicles moving in road traffic include: German method (RLS 90), French method (NMPB), Scandinavian method (Nord2000), British method (CoRTN), two Swiss methods (StL–86 and SonRoad), two American methods (FHWA and TNM) and Japanese method (ASJ). All calculation standards, which have been so far created in the world, can be divided into two groups. The first group includes those standards which had been created before standard ISO 9613 was introduced (Acoustics - Attenuation of sound during propagation outdoors. General method of calculation). The second group includes those standards which were created on the basis of ISO 9613. The first group of models includes American standard FHWA, British standard CoRTN, Swiss standard StL-86, German standard RLS 90 and Japanese standard ASJ. The second group (the newest calculation standards) includes American method TNM, French method NMPB, Scandinavian method Nord2000 and Swiss method SonRoad.

Calculation standards which had been created before ISO 9613 was introduced are characterized by the fact that they most often enable modelling the source of sound for typical conditions assuming that vehicles, which are linear sources of sound, are moving on straight sections of the road (most often one lane) at a constant speed. Such models are very often limited to two categories of vehicles: passenger cars and trucks.

The effects of sound propagation in those standards are presented in a very general way, and the presentation limits to specifying the influence of only few effects affecting sound propagation (e.g. reverberating form an obstacle placed on the route between the source and reception point) and they are added to initial dependence in a form of graphs, monographs or separated formulas, on the basis of which the propagation is specified.

In none of earlier calculation standards, during modelling of propagation, the influence of meteorological conditions on sound propagation in the environment was taken into consideration. The fact that earlier models enable prediction of sound levels whereas modern standards base on spectrum analysis is another element that differentiates earlier standards from standards which were created on the basis of ISO 9613. The most of the newest calculation methods take into consideration, although in slightly different ways, the same factors, which have influence on generation and propagation of sound in the environment.
Those factors include:

- number of vehicles moving in time unit,
- participation in the traffic different types of vehicle,
- pavement type of carriageway,
- run of the road,
- topography of the ground,
- meteorological conditions,
- elements attenuating sound (acoustic screens and baffles).

The algorithm of determining distribution of sound levels from vehicles moving in the traffic in the environment consists in: first modelling the source of sound and then modelling the propagation. The differences between various methods consists in the way of defining the level of initial noise and the way of assuming location of the reference point for calculating sound propagation around the road.

In calculations connected with sound propagation in the environment from the reference point to the reception point, a slightly different approach to the way about taking into consideration particular factors influencing the result of calculating sound level at reception point can be noticed. All the elements differentiating certain calculation algorithms used in various countries caused that comparing those methods is not possible in all aspects in an unequivocal and direct way, but only through comparing results of calculations carried out in long distances from the road. Equivalent sound level L_{Aeq} and basing during calculations on spectrum analysis of the sound are the basic elements that unite all calculation methods created in the past [1, 4, 7, 12, 14, 19, 21].

Despite satisfactory recognition of effects, which have influence on the emission and propagation of the sound connected with vehicles moving in the traffic in the environment and undertaking many actions to limit the negative influence of traffic noise, they are still a main and unsolved problem in all countries in the world. That is way a necessity to work out common and uniform for all countries methods, which will help to predict sound levels connected with vehicles moving in the environment, appeared. The first step was creating by the European Parliament Directive 2002/49/EC of 25 June 2002 about assessment and management of environmental noise. This directive pointed temporary computation standards, according to which noise in the environment should be predicted. For road noise the directive recommends the French national computation method NMPB-Routes-96 (SETRA-CERTU-LCPC-CSTB), for railway noise it recommends the Netherlands national computation method Reken-en Meetvoorschrift Railverkeerslawaai 96 and for aircraft noise Report on standard methods of computing noise contours around civil airports 1997 section 7,5 of ECAC.CEAC Doc 29. Standards recommended by the European Union are not obligatory, they were recommended as temporary until prediction methods common for all EU countries are determined.

Polish experience in predicting traffic noise is not that rich as in other countries. In Poland no uniform computation standard enabling prediction of sound levels from roads, railways and aircrafts in the environment has been worked out yet. Works about specifying influence of traffic noise on the environment are carried out by science centers in Gdańsk, Kraków, Poznań, Warszawa and Wrocław. Recently the main directions of the research refer to full-scale and empirically verified methods of prediction taking into consideration in their algorithms a big number of factors characterizing both the source of sound and propagation conditions, which enable to predict distribution of sound levels in urban areas connected with phases of traffic [15], distribution of acoustic field of a certain area [2, 18] and carrying out current monitoring of acoustic climate of the areas [9, 11]. Methodologies worked out and issued by Ministry of the Environment, according to which measurements of sound in the environment should be made and regulation about acceptable sound levels in the environment are obligatory for monitoring measurements of noise.

In predicting noise from expressways Polish experience is also not as rich as in other countries. Lack of possibility to verify computation algorithm in Polish conditions stems mostly from few expressways in Poland. This caused, that Polish computation models lagged behind western models. Lack of broader practice of carrying out research over noise on expressways is the reason why so far no methods or rather procedures, which can be applied in case of necessity to assess danger of the condition of acoustic climate before realizing a road investment such as a motorway or expressway and after opening it and using, have been worked out [10]. Research over noise on this type of roads is carried out according to methodologies of Ministry of the Environment, which are uniform for all types of roads. It is characteristic for all methods of predicting road noise, which have been worked out so far, that in their algorithms they take into account a large number of parameters, on which the level of predicted noise depends. Research carried out in the world leaded to developing many computation standards, which include in their algorithms descriptions of vehicle movement, which are often characteristic for traffic streams of countries where the standards were worked out.

Differences between various methods refer to the way the noise initial level if defined and a different assumption of location of the reference point to compute sound propagation around the road.

At present a lack of universal basic models, which enable the administrator of a certain road assessment of sound levels locally (only for this road) on the basis of traffic volume on a certain road and the distance from the source of sound, can be indicated. That is why the main purpose was to work out a method of assessing sound levels in the environment of motorway on the basis of distance from the carriageway and the number of cars, which were registered by motorway meters of traffic volume.

3. Research Methodology

During realization of works, three stages of research stemming from condition of the motorway were assumed. The first stage was connected with measuring noise before opening the motorway – without traffic (measurement of acoustic background). The second stage referred to measuring noise after opening the motorway and after opening for traffic section Września – Krzesiny. The third stage was connected with measuring noise after opening next section of motorway A2 Nowy Tomyśl – Konin.

In all assumed stages of research, measurements were carried out at the same measurement points three times a day. Measurements of sound levels were made for four depths of excavation: 2.50 m, 2.85 m, 4.30 m and 7.15 m. Measurement points were located according to the following algorithm: the first measurement in the distance of 1 m from the edge of the carriageway, the second measurement 1 m from the edge of the slope, next measurement points were located from 10 m to 100 m from the center of the motorway (line separating carriageways). Measuring microphones were located 1.5 m above the ground level.

4. Mathematical-Physical Model

4.1. Assumptions of the model

Initiating the process of creating methematical-physical model of predicting noise in the environment of motorway, two aspects were considered. At first, the type of model describing the source of sound was defined and then the influence of diffraction, which because of locating the carriageway in excavation has influence on sound propagation in the environment, was considered.

Next stage of works about working out the model referred to defining description of road situation and basic dimensions of road's elements stemming from construction of motorway A2 section Komorniki – Krzesiny. Figure 1 presents a scheme of cross-section of motorway A2 section Komorniki – Krzesiny with marked basic dimensions of road's elements, which were used to determine methematical-physical model of predicting sound levels in the environment of motorway A2.

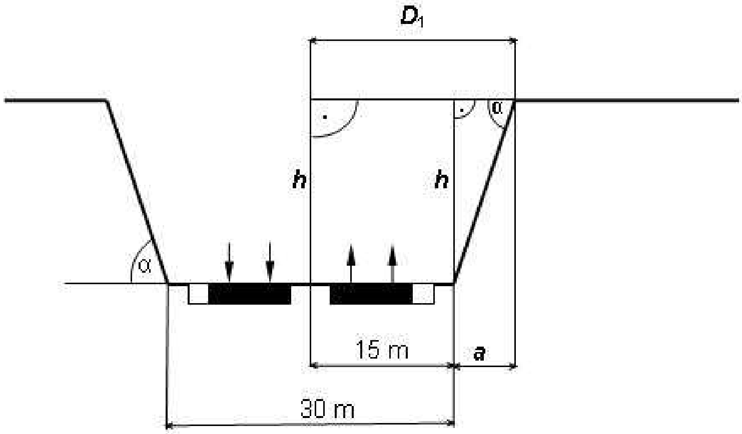

Fig. 1. Scheme of cross-section of motorway A2 section Komorniki - Krzesiny
α – angle of inclination of the slope for section Komorniki – Krzesiny of motorway A2 α = 60°,
h – depth of excavation [m], a – distance from the edge of excavation to road crown [m],
D_1 – distance from the edge of slope to geometric center of the motorway [m]

For the physical model the following assumptions were taken:
- vehicles are moving along a straight section of the road with uniform motion,
- the model does not take into account the type of vehicle (passenger cars, trucks) and their speed,
- in the model a set of real point sources is replaced with a stationary linear source,
- all distances of measurement points are calculated from the center of the motorway located on the line separating carriageways,
- considerations are limited to the case of diffraction of acoustic wave, which encounters an obstacle in a form of the wall of excavation,
- the following parameters are the initial parameters of the model: traffic volume of all vehicles, which passed by the section of motorway in both directions in time unit Q [veh/s], distance of measurement point from the center of the motorway located on the line separating carriageways r_{odl} [m] and equivalent sound level measured at the edge of the slope $L_{Aeq,skarpy}$ [dB].

4.2. Construction of the model

The most important matter about formulating the model of sound emission is seeking for certain relations between the values characterizing the object (the source of sound) and parameters of acoustic filed in its surrounding which enable to assess nuisance of its interaction. For a case where the carriageway of the motorway is located in excavation, the following general model of predicting equivalent sound level was assumed with consideration of diffraction:

$$L_{Aeq,T} = L_{Aeq} - \Delta L \tag{1}$$

where:

$L_{Aeq,T}$ – equivalent sound level with diffraction [dB],

L_{Aeq} – equivalent sound level without diffraction [dB],

ΔL – difference of sound level caused by diffraction [dB].

Predicted value of equivalent sound level $L_{Aeq,T}$ in reception point depends on the following factors: traffic volume on the motorway Q, distance of the source of sound from the receiver r_{odl} and difference of sound levels stemming from diffraction of acoustic wave at the edge of the slope ΔL, that is why the general model obtained the following form:

$$L_{Aeq,T} = [10\log(Q) - 10\log(r_{odl}) + C] - \Delta L \tag{2}$$

where:

Q – traffic volume on the motorway [veh/h],

r_{odl} – distance of measurement point from the source of sound [m],

C – constant,

ΔL – difference of sound level caused by diffraction [dB].

It is assumed that noise generated by vehicles passing by the motorway can be treated as resultant signal consisting of elementary signals from passenger cars and trucks passing by the motorway. The values of measured sound levels depend in such case on the number and the level of exposition of different types of vehicles (passenger cars, trucks) passing by on a section of the motorway. For this reason dependence (2) is formulated in the following way:

$$L_{Aeq,T} = [10\log(Q_1 \cdot \alpha_1 + Q_2 \cdot \alpha_2 + \alpha_0) - 10\log(r_{odl}) + 10\log(C)] - \Delta L \tag{3}$$

where:

Q_1, Q_2 – traffic volume of passenger cars and trucks [veh/h],

α_1 α_2 – sound exposure level of a singular passenger car or truck [dB],

α_0 – level of acoustic background [dB],

r_{odl} – distance of measurement point from the source of sound [m],

C – constant,

ΔL – difference of sound level caused by diffraction [dB].

Because of big traffic volume on the motorway approx. 1000 vehicles per hour, complicated road situation (four lanes), it was assumed that the model will not take into consideration division of vehicles into particular types. That is why dependence (3) gained the following form:

$$L_{Aeq,T} = \left\{\left[10\log\left(Q\cdot\alpha + 10^{0,1\cdot L_{Aeq,TLA}}\right) - \log\left(\frac{r_{odl}}{C}\right)\right]\right\} - \Delta L \qquad (4)$$

Replacing $\alpha = \dfrac{C}{r_{odl}}$ a resulting form of the model was received, according to which sound levels in the environment of the motorway can be predicted without taking diffraction into consideration:

$$L_{Aeq,T} = \left[10\log\left(C\cdot\frac{Q}{r_{odl}} + 10^{0,1\cdot L_{Aeq,TLA}}\right)\right] \qquad (5)$$

Constant C in dependence (5) is determined separately for each depth of excavation on the basis of earlier measurement of sound level and traffic volume at the edge of the slope. Constant C is determined by transforming dependence (5) into the following form:

$$C = \frac{r_{sk}}{Q_{sk}}\left(10^{0,1\cdot L_{Aeq,SKARPY}} - 10^{0,1\cdot L_{Aeq,TLA}}\right) \qquad (6)$$

where:

r_{sk} – distance of measurement point located at the edge of the slope to the geometric center of the motorway [m],

Q_{sk} – traffic volume of vehicles on the motorway during measuring sound level at the edge of the slope [veh/h],

$L_{Aeq,SKARPY}$ – equivalent sound level measured at the edge of the slope [dB],

$L_{Aeq,TLA}$ – level of acoustic background [dB] $L_{Aeq,TLA}$ = 51 dB.

In next step of construction of the model, influence of diffraction on sound propagation in the environment was taken into consideration. Because of the location of the carriageway of motorway A2 section Komorniki – Krzesiny in excavation, the wall of the slope was treated as an acoustic screen, assuming that acoustic wave is subject to diffraction on the edge of the slope. Figure 2 presents general schemes of diffraction of acoustic wave on the edge of the acoustic screen and for described kind of location of the motorway.

For further calculations connected with determination of influence of diffraction on sound propagation in the environment Maekawa's approximation was used, which assumes that the efficiency of acoustic screens is connected with the angle of diffraction of acoustic wave on its edges and depends on Fresnel number. The value of Fresnel number is determined in the following way:

$$N = \frac{2\cdot f\cdot \Delta r}{c} \qquad (7)$$

where:

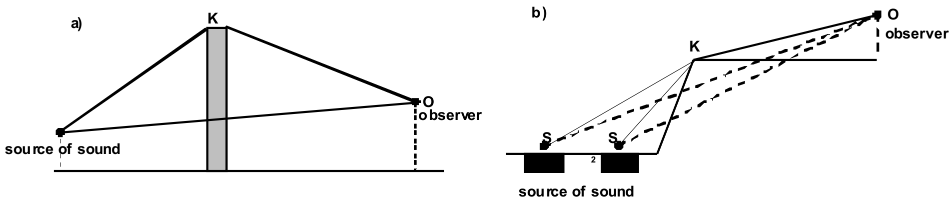

Fig. 2. Scheme of diffraction of acoustic wave encountering an obstacle
a) in reference to acoustic screen, b) in reference to excavation

f – band frequency, for which sound level corrected with characteristics A takes maximum value $f = 1000$ Hz,

Δr – difference of propagation tracks of wave diffracted on edge SK + KO and direct wave SO Figure 2, Δr = SK + KO – SO [m],

c – velocity of sound propagation in the air $c = 340$ [m/s].

Efficiency of the surface of the acoustic screen (in this case the wall of the excavation is treated as an acoustic screen) is described with the following dependence:

$$\Delta L = 10 \log (3 + 20N) \tag{8}$$

where:

N – Fresnel number

At the same time scheme from Figure 3 (stemming from the construction of motorway A2 section Komorniki-Krzesiny) was assumed to estimate individual distances Δr.

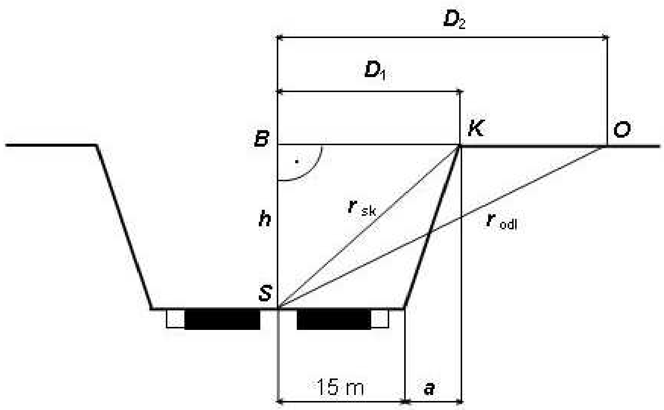

Fig. 3. Scheme of cross-section of motorway A2 section Komorniki - Krzesiny, according to which distance Δr should be estimated

h – depth of excavation [m], SK, KO, SO – geometric parameter connected with defining propagation tracks of acoustic wave [m], D_1 – distance of the edge of the slope from the geometric center of the motorway [m], D_2 – distance of measurement point from the geometric center of the motorway [m]

The final form of the model enabling predicting sound level in the environment where the carriageway runs in excavation worked out on the basis of parameters of motorway A2 section Komorniki – Krzesiny is presented with the following dependence:

$$L_{Aeq,T} = \left[10\log\left(C \cdot \frac{Q}{r_{odl}} + 10^{0,1 \cdot L_{Aeq,TLA}}\right)\right] - 10\log(3 + 20N) \tag{9}$$

The algorithm of using the model has the following form: for a certain distance r_{odl} and traffic volume on motorway Q first, equivalent sound level without diffraction is determined and then depending on ΔL calculated from dependence (7) difference of sound levels caused by diffraction is received.

4.3. Verification of the model

For worked out mathematical-physical model of predicting sound levels taking diffraction into consideration, verification of the presented model was carried out with results obtained from noise measurements in two stages of the research in 2004 and 2005. Table 1 presents exemplary comparison of day-long results of equivalent sound levels obtained in three measurement periods with results obtained from worked out mathematical-physical model for depth of excavation: h = 2.85 m.

Analyzing sound levels calculated with usage of worked out model and sound levels obtained during research the following conclusion was worded: estimated relative approximation errors for mathematical-physical model referring to measurements carried out on section Komorniki – Krzesiny of motorway A2 in particular measurement periods in 2004 and 2005 at the average do not exceed 10%.

5. Statistical Model

5.1. Assumptions of the model

The process of constructing statistical model of predicting noise around discussed section of the motorway for carriageway in excavation consisted of the following stages:

- checking correctness and adequacy of data used to build the model,
- determining regression equation and calculating individual coefficients with variables connected with traffic volume an distance from the motorway,
- verification of hypotheses connected with defining the influence on variables on dependence variable and determination of the degree of matching of the worked out model to empirical data,
- verification of the assumed model.

Table 1

Comparison of results of measurements with results obtained from the model for depth h = 2,85 [m]

Measurement period	Distance [m]	1st stage of research			2nd stage of research		
		Measurements [dB]	Model [dB]	Relative approximation error [%]	Measurements [dB]	Model [dB]	Relative approximation error [%]
1st period	17	75	70	7	78	73	6
	40	54	58	7	57	61	7
	45	53	58	9	54	61	13
	69	50	55	10	56	58	4
	100	49	52	6	55	55	0
2nd period	17	73	68	7	76	71	7
	40	59	56	5	58	59	2
	45	58	56	3	56	59	5
	69	57	53	7	54	56	4
	100	53	50	6	55	53	4
3rd period	17	69	64	7	76	71	7
	40	55	52	5	60	59	2
	45	53	52	2	57	59	4
	69	54	49	9	55	56	2
	100	47	47	0	52	53	2

Scheme of cross-section of motorway A2 section Komorniki – Krzesiny, on the basis of which, statistical model of predicting noise was worked out. The scheme is presented in Figure 4.

The following assumptions were considered for the worked out statistical model:

– vehicles are moving along a straight section of the road with uniform motion and in one direction,
– the model does not take into account the type of vehicle (passenger cars, trucks),
– distances of individual sections $r_1, r_2, \ldots, r_n$ were selected by counting from the edge of the slope, so that the length of the last section r_n equaled 100 m from the carriageway of the motorway,
– to each assumed distance calculated from the edge of the slope, distance from the edge of the slope to the carriageway should be added. This distance consists of two elements: distance of measurement point from the sideway assumed as constant for the whole motorway equaling 4 m, and section a, whose length depends on the depth of excavation h. The length of section a is calculated from the following dependence:

$$a = \frac{h}{tg\alpha} \tag{10}$$

where:

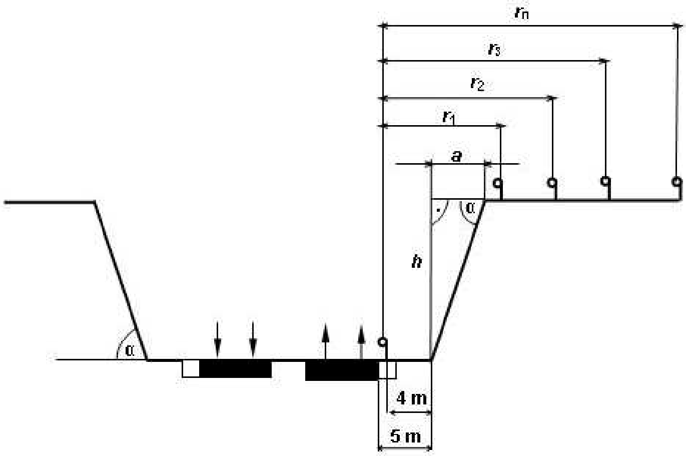

Fig. 4. Scheme of cross-section of section of motorway A2 where the carriageway is located in excavation
r_1, r_2, r_3, r_n – distance of measurement points from the carriageway of the motorway [m],
h – depth of excavation [m], a – distance of the edge of excavation to road crown [m],
α – angle of inclination of the slope $\alpha = 60°$

h – depth of excavation [m],
α – angle resulting from inclination of the slope, for motorway A2 section Komorniki – Krzesiny $\alpha = 60°$.

– the following parameters are initial elements of the model: traffic volume Q, which is the sum of all vehicles that passed by the motorway in certain hour in both directions expressed in [veh/h] and distance from the carriageway of the motorway r expressed in [m].

Preliminary conditions of correct construction of the equation of the model were assumptions that independent variables should be strongly correlated with dependent variable and weakly correlated between each other.

Relations between independent variables and between independent variables and dependent variable were determined by calculating correlation coefficient by using dependence below [5].

$$\rho = \frac{\operatorname{cov}(X, Y)}{D(X)\,D(Y)} \tag{11}$$

where:
$\operatorname{cov}(X, Y)$ – covariance of selected pair of variables,
$D(X)D(Y)$ – variance of variable X and variance of variable Y.

To determine correlation degree between independent variables X and dependent variable Y, all variables for which inequality $|r_i| \leqslant r_{kr}$ is fulfilled, were removed from set of potential independent variables X assuming that they are too weakly correlated with dependent variable Y.

In case of determining correlation degree between independent variables X between each another, all variables X_j which were correlated with variable X_i and which fulfilled inequality $|r_{ij}| > r_{kr}$ were removed from set of dependent variables.

Calculated critical value of correlation coefficient for assumed significance level $\alpha = 0{,}95$ equaled $r_{kr} = 0.184$. Calculated correlation coefficients for verification of condition about determining correlation degree between independent variables X and dependent variable Y equaled respectively:

- correlation coefficient between measured equivalent sound levels and traffic volume on the motorway $|r_1| = 0.2009$,
- correlation coefficient between measured equivalent sound levels and distance from the carriageway $|r_2| = 0.9067$.

That is why there were no grounds to remove variables connected with traffic volume and distance from the carriageway of the motorway. Calculated correlation coefficients for both cases were larger than assumed critical value of correlation coefficient r_{kr}.

To check the condition connected with determining correlation between independent variables X between each another, correlation coefficient was calculated and equaled $|r_{ij}| = 0.0787$.

Taking into consideration assumed inequality $|r_{ij}| > r_{kr}$ (that such variables should be removed), it was found out that variables connected with traffic volume and distance from the motorway are weakly correlated between each another $|r_{ij}| < r_{kr}$, that is why there were no grounds to remove this condition either.

Additionally to determine variability of variables used to build the model, coefficients of variability were calculated. They showed that the largest variability was obtained by data connected with distance $V_1 = 41\%$, and the smallest by data connected with traffic volume $V_2 = 4\%$.

On the basis of selected data and verified conditions referring to describing variables and described variable it was found out that on the basis of presented data it is possible to build a model which will enable predicting equivalent sound level in the environment of the motorway where the carriageway runs in excavation.

5.2. Construction of the model

After checking initial assumptions referring to using data to build the model, the construction of the model commenced. For worked out model, assumptions of classical linear regression model were accepted. The model is expressed by the following dependence [8]:

$$Y_i = \beta_1 x_{i1} + \beta_2 x_{i2} + \ldots + \beta_k x_{ik} + \beta_{k+1} + \varepsilon_i \quad (i = 1, \ldots, n) \tag{12}$$

$$E\varepsilon_1 = 0 \tag{13}$$

ε_i have normal distribution N(0,σ)

$$D^2(\varepsilon_i) = E\varepsilon_i^2 = \sigma^2 \tag{14}$$

$$\mathrm{cov}\left(\varepsilon_i \varepsilon_j\right) = E\varepsilon_i\varepsilon_j = 0 \qquad i \neq j \tag{15}$$

Because of the fact that sensitivity of the organ of hearing decreases logarithmically in approximation, which is in accordance with psychoacoustic Weber-Fechner's law, which says that generated aural impression is proportional to logarithm of sound volume, that is why for calculations a logarithmic function was accepted.

For accepted logarithmic function and considering assumptions (13)÷(15) to be appropriate for classical regression model, regression model described with dependency (12) gained the following form:

$$Y_i = \beta_1 \log(x_{i1} + 1) + \beta_2 \log(x_{i2} + 1) + \ldots + \beta_k \log(x_{ik} + 1) + \beta_{k+1} \log 10 + \varepsilon \tag{16}$$

Because of the fact that predicted value of equivalent sound level L_{Aeq} is connected with two values: traffic volume (Q) and distance from the carriageway of the motorway (r) finally the model in the following form was accepted:

$$L_{Aeq}(Q, r) = \beta_3 \log 10 + \beta_1 \log(r + 1) + \beta_2 \log(Q + 1) \tag{17}$$

where:

$L_{Aeq(Q,r)}$ – equivalent sound level dependant on traffic volume on the motorway and distance from the motorway [dB],

β_1 – coefficient connected with distance from the source of sound,

β_2 – coefficient connected with traffic volume,

β_3 – regression residual,

Q – traffic volume on the motorway [veh/h],

r – distance from the motorway [m],

ε – noncorrelated random variables.

Application Microsoft Excel was used to determine multiple regression coefficients and regression statistics connected with them, and to analyze variance. The model enabling predicting sound levels in the environment of motorway A2 section Komorniki –Komorniki gained the following final form:

$$L_{Aeq}(Q, r) = 10.13 \cdot \log(Q + 1) - 16.46 \cdot \log(r + 1) + 52.93 \tag{18}$$

where:

Q – traffic volume on the motorway [veh/h],

r – distance from the motorway [m].

The next stage after determining constants in regression model was to assess influence of independent variables on dependant variable. For this purpose an analysis of variance in regression was carried out. The following null hypothesis was assumed:

$H_0 : \beta_k = 0$ (k = 1, 2, …, n)

against alternative hypothesis,

$H_1 : \beta_k \neq 0$ (k = 1, 2, …, n)

which assumes that there is no linear dependence between equivalent sound level and traffic volume, and distance from the motorway. Hypothesis H_0 was verified with two tests: Student's t and Snedecor's F.

If null hypothesis in the form of $H_0 : \beta_k = 0$ against alternative hypothesis $H_1 : \beta_k \neq 0$ assuming veracity of H_0 statistics:

$$t = \frac{\hat{\beta} - \beta}{S_{\hat{\beta}}} \tag{19}$$

has Student's t-distribution of (n–2) degrees of freedom, where $\hat{\beta}$ is an estimator of parameter β and $S_{\hat{\beta}}$ is an estimator of standard errors of estimation of individual parameters, critical area for this statistics is specified in the following way:

$$P\left(|t| \geqslant t_{\alpha:(n-2)}\right) = \alpha \tag{20}$$

where:

α – significance level.

If from comparing calculated value of statistics t with critical value t_α inequality $|t| \geqslant t_\alpha$ is received, then hypothesis H_0 should be rejected in favor of its alternative H_1. However, when inequality $|t| < t_\alpha$ is fulfilled there is no ground to reject the hypothesis. Regression coefficient β_1 equals zero.

Verifying the above mentioned hypotheses for calculated regression coefficients the following values were received: for the first coefficient connected with traffic value $t_1 = 3.414$, and for the other coefficient connected with the distance from the motorway $t_2 = -23.47$. With significance level $\alpha = 0.05$ the value of statistics read from Student's t-distribution equals $t_{0,05(111)} = 1.980$, which gives a ground to reject verified hypotheses that $\beta_1 = \beta_2 = 0$, and there is a ground to claim that variables X_1 and X_2 have influence on expected value of variable Y.

Verification of hypothesis $H_0 : \beta_k = 0$ against $H_1 : \beta_k \neq 0$ was carried out also with Snedecor's F-test. Statistics F for verification of hypothesis $H_0 : \beta_k = 0$ has the following form [8]:

$$F = \frac{\left(\left[\sum_{i=1}^{n} \left(\hat{Y}_i - \bar{Y}\right)^2\right] \Big/ k\right)}{\left[\sum_{i=1}^{n} \left(Y_i - \hat{Y}_i\right)^2\right] \Big/ (n-k-1)} \tag{21}$$

where:

$\left[\sum_{i=1}^{n} \left(\hat{Y}_i - \bar{Y}\right)^2\right] \Big/ k$ – mean square of deviations explained by regression,

$\left[\sum_{i=1}^{n} \left(Y_i - \hat{Y}_i\right)^2\right] \Big/ (n-k-1)$ – mean square of deviations not explained by regression.

Carrying out analysis with Snedecor's F-test values of testing statistics were obtained on level $F = 289.27$, whereas the critical value read from Snedecor's F table equaled $F_{0,05(2;111)} = 3.07$, that is why for this test hypothesis H_0 should be rejected as well.

From the carried out tests it can be found out that equivalent sound level L_{Aeq} depends on traffic volume and distance from the carriageway. The parameter of this dependence is described by defined multiple correlation coefficient $R = 0.916$ and coefficient of determination $R^2 = 0.839$. At the same time assessed for this model standard error of estimate equaled 3.96, which confirms correct selection of the model and mainly its parameters [16].

5.3. Verification of the model

Verification was carried out after determination of regression coefficients $\beta_1, \beta_2, \beta_3$ on the basis of experimental data, and verification of hypothesis about influence of variables on dependent variable. On random days and at random hours measurements of noise in different distances from the motorway were carried out. For the analysis three depths of excavation $h_1 = 2.5$ m, $h_2 = 7.15$ m and $h_3 = 2.85$ m were selected. For a certain day and for a certain hour of noise measurements, information about the number of vehicles that passed by discussed section was taken from motorway meters. The information about traffic volume was substituted in the model and noise for certain conditions (depth of excavation and distance) was assessed. Table 2 presents exemplary comparison of results of noise measurement on the motorway for the depth of excavation $h = 2.85$ m with results obtained from the worked out model.

Table 2

Comparison of results of measurements with results obtained from statistical model for the depth of excavation h = 2.85 [m]

Traffic volume Q [veh/h]	Distance [m]	Measurements [dB]	Statistical model [dB]	Relative approximation error [%]
822	1	76	78	2
	8	73	67	8
	32	59	58	2
	37	58	57	3
	62	57	53	7
	100	53	49	7
1589	1	78	80	3
	8	76	70	8
	32	58	60	4
	37	56	59	6
	62	54	56	3
	100	55	52	5

Worked out statistical model of predicting sound levels in the environment of motorway A2 well associates acoustic climate near the motorway. Received relative approximation error did not exceed 10%.

6. Conclusion

This paper presents two models (statistical and mathematical-physical) which enable predicting noise in the environment of the motorway with condition that the carriageway runs in excavation. Working out both models, it was assumed that the vehicles are moving on a straight section of the road at a constant speed, and that the type of vehicle is not taken into consideration. In statistical model all distances are calculated from the edge of the slope, whereas in mathematical-physical model individual distances are defined from the center of the motorway. Mathematical-physical model and statistical model can be used up to about 100 m from the motorway. Additionally in mathematical-physical model influence of diffraction on sound propagation in the environment was taken into consideration. Traffic volume on the motorway and distance from the carriageway of the motorway are input parameters in both models.

Worked out statistical and mathematical-physical models and their verification allow drawing the following conclusions:

- Estimated relative approximation error after verification of mathematical-physical model did not exceed 20% for the first stage of research and 10% for the second stage, which stems from a bigger traffic volume.
- In statistical model relative approximation error did not exceed 10% in both first and second stages of research. The biggest relative approximation error occurred at the edge of the slope and equaled 8% and 12%.
- Worked out models of predicting noise around the motorway proved that increase of traffic volume (opened further sections of the motorway) had influence on decrease of relative approximation error.
- Worked out models can be used in practice for current assessment of sound levels in the environment of motorway or in a system of constant monitoring of noise on the basis of data from meters of traffic volume at the motorway.
- Application of mathematical-physical model can be more complex because of assessing the difference of propagation tracks of a diffracted wave and direct wave stemming from using Maekawa's approximation. In statistical model certain distances used to assess sound level are calculated from the edge of the slope.

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