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THE CALCULATION MODEL OF LEVELS OF NOISE PRODUCED BY TRAMS

Summary. The paper presents the new calculation model of levels of noise produced by tram traffic. The model is based on the experimental measurements of noise levels and factors which influence them. The model has been derived using principles of multiparameter linear regression analysis. Numerical formulae for the calculation of identified factors and the measure of their contribution into the resulting noise level produced by tram traffic are also reported in the paper.

MODEL OBLICZENIOWY POZIOMÓW HAŁASU EMITOWANEGO PRZEZ TRAMWAJE

Streszczenie. Artykuł prezentuje nowy model obliczeniowy poziomów hałasu emitowanego przez ruch tramwajowy. Model oparty jest na eksperymentalnych wartościach poziomów hałasu i wpływających na nie czynnikach. Model wykorzystuje wieloparametryczną liniową analizę regresji. Przedstawiono też wzory opisujące ustalone czynniki i wartość ich wpływu na poziom hałasu powstającego w ruchu tramwajowym.

1. INTRODUCTION

The level of noise from tram traffic is the result of the effects of many mutually-influencing characteristics. As a consequence, it is very difficult to identify the measure of influence of a specific characteristic. This, however, has to be done since this procedure is essential for building up the calculation models. The research project we worked on [1] focused on this problem. Our experimental results and their processing confirm that the presently-used model in Slovakia [2] could be enriched by other factors, as was already reported [1, 3], which could make the calculation of noise levels produced by tram traffic more accurate.

The result of our research is the prediction model for noise from tram traffic which is based on the model used so far in this country [1] :

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Given the breadth of this issue, in this paper attention will be paid only to the determination of equivalent noise levels $({}^{r}L_{Aeq,1h})$ at a reference distance from the axis of the tramline and the factors which have been proved to influence this level will be identified.

2. PREDICTION OF LEVELS OF NOISE FROM TRAM TRAFFIC

The following formula has been derived for the determination of the equivalent noise level ${}^{r}L_{Aeq.1h}$ up to a reference distance from the axis of an adjacent tramline:

$$ {}^{r}L_{Aeq.1h} = 10 \cdot \log m^{1.24} \cdot \prod_{i=1}^{n} F_i \qquad (1)$$

where

F_i are factors influencing noise levels,
m - number of tram trains which pass a given tramline profile per hour,
n - number of factors influencing acoustic noise levels, and
r - reference distance of 7.5 m from the axis of a tramline.

The analysis of obtained results did not enable us to determine directly the measure of influence of specific factors on the resulting measured noise levels. Therefore the measure of their contributions was determined by multiparameter linear regression analysis. In this way the following factors were identified and included into the prediction model of noise levels:

- m - number of tram trains,
- F_1 - tram velocity related to tramline type,
- F_2 - slope of tramline,
- F_3 - rail wavelets, $\cancel{F_3}$ - rail grinding,
- F_4 - age of tram,
- F_5 - age of tramline, and
- F_6 - composition of tram flow.

3. MATHEMATICAL – STATISTICAL ANALYSIS

The relationship between a dependent variable y - the equivalent noise level and independent variables x_i was approximated by a multiparameter regression model:

$$ y = b_1 x_1 + b_2 x_2 + \dots + b_k x_k \qquad (2)$$

where b_i (i = 1,2,..., k) are regression coefficients which were estimated by the least square method. Independent variables x_i were related to the factors F_i (i = 1,2, ... k) by the logarithmic or linear functions.

The variables x_i can be independent in pairs but there can be also a certain relationship. The following hypotheses were tested for the regression model (2):

1. Hypothesis (H) on the model significance
   $H_0 : b_1 = b_2 = \dots = b_k = 0$ against alternative hypothesis
   H_1 : at least one of the coefficients $b_1, b_2, \dots, b_k$ is non-zero.

Hypotheses were tested by the inequality resulting from Fisher's distribution, which for the final number of regression coefficients used in the model (2) has the form:

$$F = 1044.104 > F_{0.05} = 2.016$$

This inequality indicates that the hypothesis $H_0 : b_1 = b_2 = b_3 = b_4 = b_5 = b_6 = b_7 = 0$ can be rejected and at least some of the regression coefficients are considered to be non-zero at the significance level $\alpha = 0.05$ of this test.

2. Hypothesis (*H*) on the contribution of a variable x_i into the model which already comprises all variables:
   $H_0 : b_i = 0$ against alternative hypothesis $H_1 : b_i \neq 0$.
   The characteristic *t* which obeys Student t-distribution was used for the testing:

$$t_i = \frac{|b_i|}{s_{b_i}} > t_{0.05}(1462 - 7 - 1) = 1.962$$

where s_{b_i} is the standard deviation of regression coefficient b_i.

The results of this testing are listed in Table 1 and they indicate that the contributions of the factors listed there into the model (2) is significant. Constant b_0 has been excluded from the model due to the requirement of zero equivalent noise level at the zero tram intensity.

Table 1

Test of regression coefficients of model (2)

INDEPEN-DENT variable	Related physical quantity	Regression coefficients b_i	t_i		$t_{0.05}$
x_1	m [tr/h]	12.3988	55.047	>	1.962
x_2	V [km/h]	10.0022	48.536	>	1.962
x_3	s [‰]	0.0103	4.416	>	1.962
x_4	l [cm]	-0,1017	4.915	>	1.962
x_5	T_{tr} [year]	0.8106	5.617	>	1.962
x_6	T_{trl} [year]	6.1985	13.855	>	1.962
x_7	${}_T m_1, {}_T m_2, {}_T m_3$ [tr/h]	17.0318	15.362	>	1.962

The presence of correlation relation between variables was tested by Pearson's coefficients of pair correlation. The coefficients form a correlation matrix. The determinants of correlation matrix $|\boldsymbol{R}|$, and expanded matrix $|\boldsymbol{R}^*|$ can be written in the following form:

$$\boldsymbol{R} = \begin{bmatrix} 1 & R_{x_1x_2} & \cdots & R_{x_1x_7} \\ R_{x_1x_2} & 1 & \cdots & R_{x_2x_7} \\ \vdots & & & \\ R_{x_1x_7} & R_{x_2x_7} & \cdots & 1 \end{bmatrix} \qquad \boldsymbol{R}^* = \begin{bmatrix} R_{y\,x_1} & R_{y\,x_2} & \cdots & R_{y\,x_7} & 0 \\ 1 & R_{x_1x_2} & \cdots & r_{x_1x_7} & R_{y\,x_1} \\ R_{x_1x_2} & 1 & \cdots & R_{x_2x_7} & R_{y\,x_2} \\ \vdots & & & & \\ R_{x_1x_7} & R_{x_2x_7} & \cdots & 1 & R_{y\,x_7} \end{bmatrix} \tag{3}$$

The coefficient of multiple correlation which results from mutual interaction of variables x_i (i = 1, 2,..., 7) with a dependent variable y can be calculated using the following equation:

$$R_{y\cdot x_1 x_2 x_3 x_4 x_5 x_6 x_7} = \sqrt{\frac{|\boldsymbol{R}^*|}{|\boldsymbol{R}|}} = 0.9137 \tag{4}$$

The value obtained for the coefficient of multiple regression proves that the model (2) is satisfactory. Variables x_i were successively incorporated into the model (2) by the method of successive regression analysis. The correlation coefficients calculated are listed in Table 2. The difference between coefficients δR (Table 2 the third column) reflects the increase of the explained variability of the variable y achieved by adding another independent variable x_i to the model (2).

The influence of the changes of i-th independent variable on the variability of dependent variable y (noise level) was assessed by the calculation of partial correlation coefficients (Table 2). The tests of partial correlation coefficients were carried out using standard procedures.

Table 2

Multiple and partial correlation coefficients (CC)

INDEPENDENT variable	Multiple CC $R_{y,x_1\ldots x_7}$	$\delta R_{y,x_1\ldots x_7}$	Partial CC R_{y,x_1x_2}	$R_{y,x_1x_2x_6}$	$R_{y,x_1x_2x_6x_4}$	$R_{y,x_1x_2x_6x_4x_3}$	$R_{y,x_1x_2x_6x_4x_3x_7}$	$R_{y,x_1x_2x_6x_4x_3x_7x_5}$
x_1	0.7409							
		0.1268	0.7995					
x_2	0.8677			0.8305				
		0.0434			0.8309			
x_6	0.9111					0.8304		
		0.0003					0.8295	
x_4	0.9114							0.8216
		0.0017						
x_3	0.9131							
		0.0002						
x_7	0.9133							
		0.0004						
x_5	0.9137							

4. ANALYSIS OF IDENTIFIED FACTORS

4.1. Number of tram trains

The dependence of the equivalent level of acoustic pressure on the number of tram trains per hour is given by the following formula:

$$ {}_{m}^{r}L_{Aeq} = 10 \cdot \log m^{1.24} \tag{5}$$

where m is the number of tram trains per hour in a profile (tr/h) within the interval ⟨1,70⟩.

4.2. Velocity

The factor of velocity of a tram was related to the type of tram track. The contribution of this factor to the increase in the total equivalent level of acoustic pressure at the reference distance may be expressed by rearranging formula (4) and substituting the velocity factor:

$$ {}_{V}^{r}L_{Aeq} = 10 \cdot \log F_1 = 10 \cdot \log V^{x} \tag{6}$$

where
V is the tram velocity (km/h) within the interval ⟨1,80⟩,
x = 1.6 - for tramlines set in pavement, bitumenous or concrete panels,
x = 1.9 - for tramline made from large panels with block rails,
x = 1.8 - for open tram track.

4.3. Slope of tramline

A tram driving up a tramline with longitudinal slope has to have its electrical drives engaged and driving down this tramline the drives are released or the tram has to brake. These facts cause an increase in equivalent noise levels depending on the slope magnitude:

$$ {}_{s}^{r}L_{Aeq} = 10 \cdot \log F_2 = 10 \cdot \log 10^{0,001 \cdot s} = 0,01 \cdot s \tag{7}$$

where s is the longitudinal slope of the tramline (‰) within the interval ⟨0,60⟩.

4.4. Rail wavelets and rail grinding

Rail wavelets are defects on the rail surface visible as alternating light and dark stripes at a mean distance *l*. The formula for determining the influence of the rail wavelets was derived in the following form:

$$ {}_{l}^{r}L_{Aeq} = 10 \cdot \log F_3 = 10 \cdot \log 10^{-0,01 \cdot (3+l)} = -0,1 \cdot (3+l) \tag{8}$$

for l within the interval ⟨1,30⟩ cm. This interval resulted from experimental measurements of rail wavelets. For $l > 30$ cm only the constant l_{max} value is considered in formula (8).

The influence of rail grinding was derived by the correlation and regression analysis of the two sets of data obtained in measurements before and after rail grinding by a grinding tramcar. This means that the derived factor has only limited applicability since it is valid only for one passing of the grinding tramcar used by the Municipal Transportation Company. The resulting formula describing the dependence of noise increase on the velocity of a tram is given in the form:

$$ {}_{h}^{r}L_{Aeq} = 10 \cdot \log F_3 = 10 \cdot \log 10^{-0,0002 \cdot V} = -0,002 \cdot V \tag{9}$$

where v is tram velocity in km/h within the interval ⟨0,80⟩.

4.5. Age of tramcar

The factor F_4 identified by multiparameter regression analysis takes into account the influence of worsening technical condition.
The contribution of the technical condition of trams, expressed by their age, to the total noise levels is given by formula:

$$ {}_{tr}^{r}L_{Aeq} = 10 \cdot \log F_4 = 10 \cdot \log T_{tr}^{0.08} \tag{10} $$

where T_{tr} is the age of a tramcar within the interval $\langle 1,15 \rangle$ (years)

4.6. Factor of age of tramline

In spite of the fact that the tram velocity factor F_1 was related to the type of tram permanent way, it does not take into account completely the influence of tramlines on the noise levels. Statistical analysis has shown the need to introduce another factor into the prediction model which would take into account the technical condition of tramlines. This factor was related to the age of tramlines counted from their construction or general reconstruction. The contribution of this factor to the noise level along the tramlines is given by the formula:

$$ {}_{trl}^{r}L_{Aeq} = 10 \cdot \log F_5 = 10 \cdot \log T_{trl}^{0.62} \tag{11} $$

where T_{trl} is the age of a tramline within interval $\langle 1,30 \rangle$ (years).

4.7. Factor of tram flow composition

The tram flow in Košice consists of tram trains with resistance driving control (trams of type T_3) and tram sets with thyristor driving control (trams of type T_6 and KT_8). Tram trains in traffic flow consist of one, two or three tramcars. Factor F_6 takes this into account by means of sub-factors derived for individual tram types [3]. The contribution of tram flow composition into the total noise level is expressed by the formula:

$$ {}_{p}^{r}L_{Aeq} = 10 \cdot \log F_6 = 10 \cdot \log\left({}_{T3}F_6 + {}_{T6}F_6 + {}_{KT8}F_6\right)^{1.7} \tag{12} $$

where

- ${}_{T3}F_6$ is the sub-factor of tram flow consisting of tramcars of type T_3,
- ${}_{T6}F_6$ is the sub-factor of tram flow consisting of tramscar of type T_6,
- ${}_{KT8}F_6$ is the sub-factor of tram flow consisting of tramcars of type KT_8.

5. CHARACTERIZATION OF CALCULATION MODEL

From the point of view of identified factors or independent physical quantities and their maximum contributions to the dependent quantity L_{Aeq} (Table 3), presented in this paper can be characterized as follows:

Table 3

Contributions of identified factors to equivalent noise level $'L_{Aeq}$

Factor	Independent quantity	$'L_{Aeq}$ (dB)	
		minimum	maximum
m	m	0	22.88
	V (covered permanent way)	0	30.45
F_1	V (BKV permanent way)	0	36.16
	V (open permanent way)	0	34.26
F_2	s	0	0.60
F_3	l	- 3.30	- 0.40
$\not F_3$	V (rail grinding)	- 0.16	0.00
F_4	T_{tr}	0	0.94
F_5	T_{trl}	0	9.20
F_6	$_{T3}m_1$, $_{T3}m_2$, $_{T3}m_3$, $_{T6}m_1$, $_{T6}m_2$, $_{KT8}m_1$	14.68	16.62

6. CONCLUSIONS

The model for the calculation of equivalent noise levels at the reference distance from the rail axis includes seven identified factors. They have been determined by multiparameter regression analysis and they also incorporate accumulated background noise along tram tracks. The background noise distribution to individual factors is not known but in any case it is not balanced. The model average error is of 1 % and maximum deviation is of 4 dB(A).

References

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Abstract

The level of noise from tram traffic is the result of the effects of many mutually-influencing characteristics. As a consequence, it is very difficult to identify the measure of influence of a specific characteristic. This, however, has to be done since this procedure is essential for building up the calculation models.

The new model for the calculation of equivalent noise levels at the reference distance from the rail axis – presented in this paper – included seven identified factors (m - number of tram trains, F_l - tram velocity related to tramline type, F_2 - slope of tramline, F_3 - rail wavelets, $\not F_3$ - rail grinding, F_4 - age of tram, F_5 - age of tramline and F_6 - composition of tram flow). They have been determined by multiparameter regression analysis. The model average error is of 1 % and maximum deviation is of 4 dB(A).