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VERIFICATION OF THE METHOD FOR PREDICTION OF THE EQUIVALENT LEVEL OF FREELY FLOWING TRAFFIC NOISE

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The evaluation of the "acoustic climate" near transport routes, using the numerical method is possible only when we know the values of the parameters describing single noise sources and those of the parameters connected with the attenuating properties of the area adjacent to the route. The paper presents a method for determining these parameters. Direct measurements of the equivalent level were also made. Good agreement between measurement results with values calculated according to the present analytical and theoretical method shows its correctness and thus its usefulness for the problem of shaping the acoustic environment near roads with freely flowing traffic.

1. Introduction

Noise is the cause of degradation of the environment. The measure of the degradation are the values of the noise indexes. One of these that is most often used, is the equivalent level — L_{eq}. The results from investigations, including those of LANGDON [12], SADOWSKI and SZUDROWICZ [23], show that means of transport are the most essential cause of noise pollution. They are the most annoying noise sources. The value of the equivalent level, L_{eq}, near transport routes depends, among other things, on:

— the parameters characterizing single vehicles as sources of acoustic field,

— numbers and velocities of vehicles passing the observation point in a time unit,

— the parameters determining the location of the transport route (e.g. distance from the observation point),

— the parameters characterizing the attenuating properties of the ground and of the air.

On the basis of the results from measurements of L_{eq} taken at different distances from a transport route, for various intensities and velocities of the traffic, using the regression method (see e.g. [4] or [6]), the relation

$L_{\mathrm{eq}} = f(m_i)$, where m_i is a set of the above-mentioned parameters determining the value of the equivalent level L_{eq}, is obtained. It is rather labourious, since it requires a great many measurements of the value of L_{eq} for time intervals of several minutes duration.

The investigations performed aimed at developing a new method for determination of the relation $L_{\mathrm{eq}} = f(m_i)$ (sections 2 and 3) and, subsequently, at its experimental verification (section 4).

Knowledge of the function $f(m_i)$ permits the quantity L_{eq} to be determined for different values of m_i, i.e. to evaluate the "acoustic climate" near a road with known traffic intensities and velocities of light and heavy vehicles, etc. (A full set of parameters m_i will be given later in the paper). This problem is particularly important for planners working on the transport network, i.e. when direct measurements of the equivalent level, L_{eq}, and a correct location of objects requiring particular noise protection, are impossible.

2. Theory

If the source is omnidirectional, then in open space filled with the ideal medium, the intensity I of the wave is a function of a distance r of the form

$$I = \frac{P}{4\pi r^2},$$

where P is the source power.

If the source moves near the plane, a direct wave and a reflected wave reach the observation point. In paper [16] an expression defining the intensity of the resultant wave was derived. It is a monotonically decreasing function of the distance r. The form of the function is very complicated, therefore it is convenient (similarly to FILOTAS [5] and LJUNGGREN [13], for example) to assume that

$$I = \frac{W}{4\pi r^{\varrho}}, \tag{1}$$

where W and ϱ are quantities depending on the acoustic parameters of the source and the reflecting plane, the attenuating properties of the medium (air) and the area separating the source from the observation point (e.g. tall trees or shrubs). Let us now consider the problem of the intensity of the field generated by a system of moving sources.

If the incoherent sources move on the plane (x, y) along linear paths, which are parallel to each other (Fig. 1), then the mean intensity of the resultant field [14, 15] at the observation point O is

$$\langle I\rangle = \frac{\sqrt{\pi}}{4\pi}\sum_{jk}\frac{\Gamma(\frac{1}{2}\varrho_{jk}-\frac{1}{2})}{\Gamma(\frac{1}{2}\varrho_{jk})}n_{jk}\frac{W_{jk}}{V_{jk}}\frac{1}{r_k\varrho_{jk}-1}+I^{(0)}, \tag{2}$$

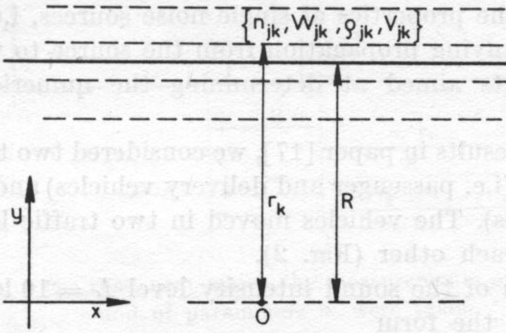

Fig. 1. Location of the observation point O with respect to the road (r_k – distance from traffic lanes, R – distance from the middle of the road)

where n_{jk} is the mean intensity of the traffic of the sources of the jth type along the kth path, V_{jk} is the mean velocity of the traffic of the sources of the jth type along the kth path, W_{jk}, ϱ_{jk} – the parameters related to the source of the jth type moving along the kth path, $\Gamma(x)$ is the Gamma function r_k is the distance of the observation point O from the kth path, $I^{(0)}$ is the mean intensity of the background.

The problem of the determination of the mean intensity $\langle I\rangle$ of the field generated by a system of moving sources was also investigated by ANDERSON [1], BLUMENFELD and WEISS [3], GORDON [7], JOHNSON and SAUNDERS [8], KUNO and IKEGAYA [9], KURZE [10], KUTTRUFF [11], LJUNGGREN [13], MARCUS [18], OHTA et al. [19], RATHE [22], SCHREIBER [24], TAKOGI et al. [25], ULLRICH [26], YEOW et al. [27], WEISS [28].

Relation (2) can be used for determining the equivalent level near roads with freely flowing traffic. According to PEARSON and BENNETT [20] we have

$$L_{\mathrm{eq}} = 10\log\frac{\langle I\rangle}{I_0}, \tag{3}$$

where I_0 is the reference intensity, and

$$\langle I\rangle = \frac{1}{T}\int_0^T I(t)\,dt,$$

with T being the averaging time of arbitrary duration related to day, night or the whole 24 hours.

3. Experimental investigations of noise from single sources

To determine the value of L_{eq} according to formulae (2) and (3) it is necessary to know distances of the observation point from the paths, i.e. the lanes of traffic, r_k, the parameters of the traffic, n_{jk}, V_{jk}, and also the quantities

W_{jk} and ϱ_{jk} describing the properties of single noise sources, i.e. vehicles, and the phenomena accompanying propagation from the source to the observation point. Our measurements aimed at determining the numerical values W_{jk} and ϱ_{jk}.

On the basis of the results in paper [17], we considered two types of vehicles ($j=1, 2$): light vehicles (i.e. passenger and delivery vehicles) and heavy vehicles (trucks, lorries and buses). The vehicles moved in two traffic lanes ($k = 1, 2$), distant by 14 m from each other (Fig. 2).

Using the definition of the sound intensity level $L = 10 \log I/I_0$, relation (1) can be rewritten in the form

$$L_{jk} = a_{jk} - 10 \varrho_{jk} x_k, \tag{4}$$

where

$$x_k = \log r_k, \quad a_{jk} = 10 \log \frac{W_{jk}}{4\pi I_0} \tag{5}$$

are the parameters related to the vehicle of the jth type, which moves along the kth path, with L_{jk} dB(A) being the acoustic pressure level (in this case the intensity level equals the pressure level [2]). In order to find the values of W_{jk} and ϱ_{jk} on the basis of relation (4), the measurements of L_{jk} were taken at distances r_k($k = 1, 2$; Fig. 2) from the two traffic lanes, for light and heavy vehicles ($j = 1, 2$).

The values of L_{jk} were read when single vehicles "passed" the measurement point. The measurements were taken when the traffic intensity was low, so that the values of L_{jk} were the levels of intensity of signal actually emitted from the single vehicles.

The measurements of the levels L_{jk} corresponding to single light and heavy vehicles which moved on the nearest lane, L_{11} and L_{12}, were taken at distances $r_1 = 10, 20, \ldots, 60$ m. The readings were $N_{11} = 65$ and $N_{12} = 35$, respectively.

The measurements of levels L_{jk}, for light and heavy vehicles moving on the second lane, L_{21} and L_{22}, were taken at distances $r_2 = 24, 34, \ldots, 74$ m, with the numbers of vehicles being $N_{21} = 58$ and $N_{22} = 22$, respectively.

Having four sets at disposal $\{L_{jk}, r_k\}$ for $\{jk\} = \{11, 21, 12, 22\}$ and using the least squares analysis, the following numerical values a_{jk} and ϱ_{jk} (Table 1) were obtained from relation (4).

Table 1 also shows the mean traffic velocities V_{jk} and the correlation coefficients r. Then, using the same method for two sets $\{L_j, R\}$ with $\{j\} = \{1, 2\}$, the values of a_j and ϱ_j for light and heavy vehicles moving along the first or the second lane were determined (where the numbers of vehicles passing were respectively $N_1 = N_{11} + N_{12} = 123$, $N_2 = N_{21} + N_{22} = 57$, and $R = 17, 27, \ldots$ $\ldots, 67$ m (Fig. 2) were distances of the observation point O from the middle of the road). The results of the calculations of a_j and ϱ_j, the correlation coeffi-

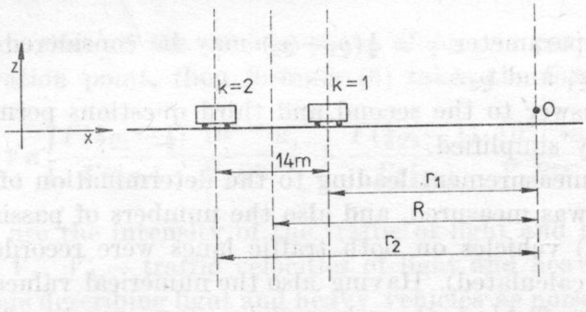

Fig. 2. Cross-section of the road near which the measurements of the equivalent level $L_{\mathrm{eq}}^{(z}$ and of parameters a, were taken

cients and traffic velocities V_j for individual types of vehicles are shown in Table 2.

On the basis of the relations given above, and using Tables 1 and 2 the value of the equivalent level can be determined.

4. Measurements of the equivalent level of freely flowing traffic noise

When $\bar{L}_{\mathrm{eq}}$ is the equivalent level of the background, from relations (2), (3), and (5) we obtain an expression which permits to determine the value of the equivalent level, L_{eq}, near a road with m lanes, on which vehicles move with a constant velocity:

$$L_{\mathrm{eq}} = 10 \log \left\{ \sum_{j=1}^{2} \sum_{k=1}^{m} \pi \frac{\Gamma(\frac{1}{2}\varrho_{jk} - \frac{1}{2})}{\Gamma(\frac{1}{2}\varrho_{ik})} \frac{10^{0.1 a_{jk}}}{V_{jk}} \frac{n_{jk}}{r_k \varrho_{jk}} + 10^{0.1 L_{\mathrm{eq}}} \right\}. \quad (6)$$

All the quantities on the right-hand side of the equation are measurable (the method for the measurement of parameters a_{jk} and ϱ_{jk} was discussed in section 3).

Taking into consideration the fact that a more precise division of vehicles (into types) than the one we spoke about before (light and heavy vehicles) is unnecessary [17], we assume that $j = 1, 2$. In the case considered here the road had two traffic lanes, i.e. $m = 2$.

The aim of direct measurements of L_{eq} near the same road (section 3) (for time intervals of five minutes for different distances r_k) was to answer the following three questions:

whether the method of prediction of L_{eq}, based on relation (6) is correct, i.e. whether the error committed in the calculation of L_{eq} is not too great,

whether for distance of the observation point from the road, that is much greater than the width of the road, it is necessary to account for single lanes of traffic, whether one parameter $\varrho = \frac{1}{2}(\varrho_1 + \varrho_2)$ may be considered in the calculations in place of ϱ_1 and ϱ_2.

A positive answer to the second and third questions permits the method to be considerably simplified.

During each measurement leading to the determination of $L_{eq}^{(z)}$, the background level, L_0, was measured, and also the numbers of passing light ($j = 1$) and heavy ($j = 2$) vehicles on both traffic lanes were recorded. (The traffic intensity n_{jk} was calculated). Having also the numerical values of parameters a_{jk}, ϱ_{jk} and V_{jk} from Table 1, the values of L_{eq}, corresponding to the measured values of $L_{eq}^{(z)}$, were calculated from formula (6). The results are shown in Fig. 3.

Table 1. Coefficients a_{jk}, ϱ_{jk} ($j = 1, 2$; $k = 1, 2$) calculated by the linear regression analysis (formula (4))

Vehicle type (j)	Traffic lane (k)	Mean velocity V_{jk} [km/h]	a_{jk}	ϱ_{jk}	Correlation coefficient
light $j = 1$	$k = 1$	65	95.33	2.10	0.941
heavy $j = 2$	$k = 1$	55	103.04	2.12	0.925
light $j = 1$	$k = 2$	65	107.91	2.68	0.885
heavy $j = 2$	$k = 2$	55	117.57	2.89	0.908

Table 2. Coefficients a_j, ϱ_j ($j = 1, 2$) calculated by the linear regression analysis formula 4

Vehicle type (j)	Mean velocity V_j [km/h]	a_j	ϱ_j	Correlation coefficient
light $j = 1$	65	103.09	2.48	0.910
heavy $j = 2$	55	112.48	2.63	0.907

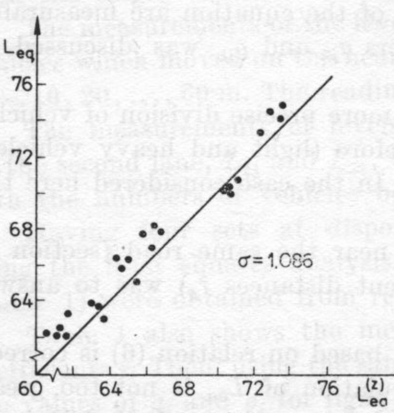

Fig. 3. Measured ($L_{eq}^{(z)}$) and calculated (L_{eq}) values of the equivalent level for the same traffic intensities (calculated according to formula (6))

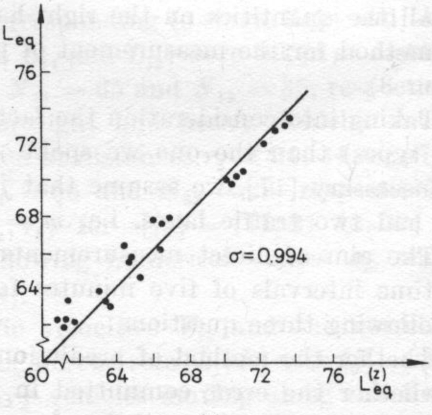

Fig. 4. Measured $L_{eq}^{(z)}$ and calculated (L_{eq}) values of the equivalent level for the same traffic intensities (calculated according to formula (7))

If we assume that all the vehicles move along one path at a distance R from the observation point, then formula (6) takes the form

$$L_{\mathrm{eq}} = 10\log\sqrt{\pi}\left\{\frac{\Gamma(\frac{1}{2}\varrho_1-\frac{1}{2})}{\Gamma(\frac{1}{2}\varrho_1)}\,\frac{10^{0.1a_1}n_1}{V_1R^{\varrho_1-1}}+\frac{\Gamma(\frac{1}{2}\varrho_2-\frac{1}{2})}{\Gamma(\frac{1}{2}\varrho_2)}\,\frac{10^{0.1a_2}n_2}{V_2R^{\varrho_2-1}}+10^{0.1\bar{L}_{\mathrm{eq}}}\right\}, \quad (7)$$

where n_1 and n_2 are the intensity of the traffic of light and heavy vehicles on all traffic lanes, V_1, V_2 – traffic velocities of light and heavy vehicles, a_1 a_2, ϱ_1, ϱ_2 – parameters describing light and heavy vehicles as noise sources and the process of the propagation of acoustic wave (section 3), R – a distance from the observation point to the middle of the road (Fig. 2), $\bar{L}_{\mathrm{eq}}$ – the equivalent level of the background $\Gamma(x)$ – the Гamma function, respectively.

Inserting into relation (7) the values from Table 2 of a_1, a_2, ϱ_1, ϱ_2 V_1 and V_2, as determined from the measurements of $L_{\mathrm{eq}}^{(z)}$, the traffic intensities $n_1 = n_{11}+n_{12}$ and $n_2 = n_{21}+n_{22}$, and distances of measurement points from the middle of the road $R(R = r_1+7$ m or $R = r_2-7$ m), the values of L_{eq}, shown in Fig. 4, were obtained.

From comparison of the results shown in Figs. 3 and 4, where the values of standard deviations were plotted,

$$\sigma = \left\{\frac{1}{n}\sum_{i=1}^{n}(L_{\mathrm{eq},i}-L_{\mathrm{eq},i}^{(z)})^2\right\}^{1/2},$$

it may be seen that using the method based on relation (7), where the traffic lanes are not considered, involves the error of about 1 dB.

The calculations of L_{eq} were performed (on the basis of relation (7)), under the assumption that the equivalent background level $\bar{L}_{\mathrm{eq}} = 0$.

For traffic intensities of the order of several hundred vehicles per hour, this assumption is permissible, since the error involved is smaller than 0.1 dB.

With a view to a maximum simplification of the method of prediction of L_{eq}, it was assumed for further calculations that

$$\varrho = \tfrac{1}{2}(\varrho_1+\varrho_2), \qquad V = \tfrac{1}{2}(V_1+V_2),$$

hence expression (7) can be rewritten in the following form:

$$L_{\mathrm{eq}} = 10\log\left\{\sqrt{\pi}\,\frac{\Gamma(\frac{1}{2}\varrho-\frac{1}{2})}{\Gamma(\frac{1}{2}\varrho)}\,\frac{(n_1 10^{0.1a_1}+n_2 10^{0.1a_2})}{VR^{\varrho-1}}\right\}. \quad (8)$$

The results of the calculations of L_{eq} according to this formula are shown in Fig. 5.

The standard deviation σ is in this case of the same order as in Fig. 4, which leads to the conclusion that simplified formula (8) permits L_{eq} to be determined with sufficient exactness. In the formula n_1 and n_2 is traffic intensity of light and heavy vehicles, [veh./hour], $V = \frac{1}{2}(V_1+V_2)$ – the mean

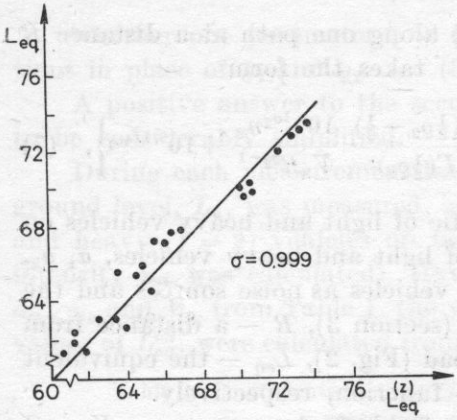

Fig. 5. Measured ($L_{\mathrm{eq}}^{(z)}$) and calculated (L_{eq}) values of the equivalent level for the same traffic intensities calculated according to formula (8)

traffic velocity of vehicles of both types [m/h], $\varrho = \frac{1}{2}(\varrho_1 + \varrho_2)$ — the mean value of parameters ϱ_1 and ϱ_2 determined for light and heavy vehicles by the method discussed in section 3, a_1, a_2 — the values of parameter a for light and heavy vehicles, R — a distance from the observation point to the middle of the road.

The investigations showed that a_1, a_2 and ϱ depend on the weather. For example, the investigations performed in winter, near the same road as in section 3, showed that $a_1 = 108.00$, $a_2 = 121.21$, and $\varrho = 2.73$. The measurements being performed at present aim at determination of the values of a_1, a_2, and ϱ for typical weather conditions.

At the same time, the experimental investigations performed near forest roads yielded still other values of these parameters. Plans foresee the broadening of the investigation of parameters a_1, a_2, and ϱ, for differently used areas (parking-lots, greens etc.)

The results obtained from these investigations will permit the present method (formula (8)) to be used in planning on a broader scale.

5. Conclusions

The results from the experimental investigations (Figs. 3, 4, and 5) show that the present methods for determination of the equivalent level near roads with freely flowing traffic (formulae (6), (7) and (8)) are correct, since the standard deviations σ (errors committed when the methods are used) are about 1 dB. The simplest method is particularly correct (σ for this case, Fig. 5, is nearly the same as for more complicated methods, Figs. 3 and 4), which requires consideration of smallest number of parameters (formula (8)) is less complicated, compared to formulae (6) and (7).

The method suggested (section 4) was verified for time periods of several minutes. This, however, does not mean that this method cannot be used for time intervals of the order of hours, i.e. for arbitrary time of day or night. In this case the mean values of intensities (n_1, n_2) and traffic velocities (V) for these time intervals (e.g. the mean n_1, n_2, V for 8 hours) should be inserted into the relations given above. In this case, however, we must take into consideration the adequate equivalent level of the background, $\bar{L}_{eq}$, variable in 24 hours.

It follows from formula (8) that L_{eq} in the area near the road (Fig. 6) depends on the distance, R, on the parameters describing the traffic, n_1, n_2, V, and the parameters depending on the properties (type of area) of the adjacent area $\{a_1, a_2, \varrho\}$.

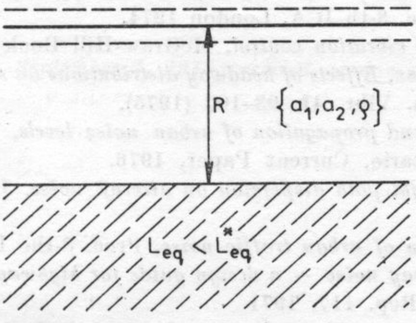

Fig. 6. Location of the area where the equivalent level must not exceed the value L^*_{eq}

The starting point for the establishing of the correctness criteria in planning is the establishment of the value L^*_{eq} which must not be exceeded in the area meant for specific purposes.

It is possible to obtain the inequality $L_{eq} < L^*_{eq}$ in the area considered (Fig. 6) by adequate location of the road with respect to the area (or the area with respect to the road), $R = ?$, if the parameters $\{n_1, n_2, V\}$ and $\{a_1, a_2, \varrho\}$ are known. It follows from equation (8) that $L_{eq} < L^*_{eq}$ if the border of the area is a streight line distant from the middle of the road by

$$R > \left\{ \frac{\sqrt{\pi}\,\Gamma(\frac{1}{2}\varrho - \frac{1}{2})}{\Gamma(\frac{1}{2}\varrho)} \, \frac{n_1 10^{0.1a_1} + n_2 10^{0.1a_2}}{V \cdot 10^{0.1L^*_{eq}}} \right\}^{1/(\varrho-1)}. \tag{9}$$

Example. Llet us assume that $L^*_{eq} = 60$ dB, $n_1 = 800$ veh./h, $n_2 = 100$ veh./h, and the values of parameters a_1, a_2, $V = \frac{1}{2}(V_1 + V_2)$, $\varrho = \frac{1}{2}(\varrho_1 + \varrho_2)$ are the same as in Table 2. After insertion into (9) we obtain $R > 95$ m, which is the minimum distance from the road of the area where $L_{eq} < 60$ dB.

From the inequality $L_{eq} < L^*_{eq}$ (where L_{eq} is determined by the right-hand side of equation (8)) information can be obtained on the values of parameters $\{n_1, n_2, V\}$, which define the class of the road planned (or the way in which the traffic on the already existent road must be controlled). On the basis of calculated values $\{a_1, a_2, \varrho\}$ it also gives information how to utilize the area adjacent to the road, to plant gross or trees etc.

In this case a "catalogue of parameters $\{a_1, a_2, \varrho\}$ (determined by the method presented in section 3) for differently covered areas, for different weather conditions, and for different traffic velocities, is necessary.

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