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APPLICATION OF THE ROAD TRAFFIC NOISE MODEL TO URBAN SYSTEMS

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In this paper, the computer simulation program PROP4, that allows prediction of the time-average sound level within an urban system, is presented together with the analysis of its accuracy. The simulation is based on an environmental noise model which contains the propagation model and the equivalent roadway model. The roadway as a noise source is represented by a sum of sound exposures due to the individual vehicle drive-by. The PROP4 allows for multi-lane roadways and different representations of sources for various classes of vehicles. Interactions of waves with obstacles are limited to multi-reflections from walls as well as single and double diffractions on wedges. The empirical data [14] have been compared with those obtained by using the PROP4 program. The comparison, especially for the relative decay of the time-average sound level with distance, shows a very good agreement with empirical data.

Notations

E^g_{Aj}	sound exposure (Eq. (4)),
G	number of vehicle classes (Eq. (5)),
$H(\mathbf{R}(u\Delta x_E), f)$	urban transfer function of a source at the $\mathbf{R}(u\Delta x_E)$ position in relation to the observation point (Eq. (14)),
J	number of lanes (Eq. (5)),
K	upper order of interaction (Eqs. (17), (18)),
$L_{A\mathrm{eq}}$	time-average sound level in $dB(A)$ (Eq. (2)),
L^g_{WA}	g-class vehicles equivalent source power level in $dB(A)$ (Eq. (9)),
N	number of panels in an urban system (Eqs. (17), (18)),
N^g_j	g-class vehicles rate flow on a j-lane in [vehicles/h] (Eq. (6)),
$p(S,P)$	acoustical pressure at the observation point P due to the unit simple-harmonic point source $Q(S)$ at the point S (Eqs. (15), (16))
$p_A(t)$	A-weighted sound pressure registered at the observation point (Eq. (2)),
$Q(...)$	source model (Eq. (1)),
$q^g_A(f_w)$	A-weighted relative power spectrum of a g-class vehicles (Eq. (11)),
$\mathbf{R}^g(x_j)$	vector describing a g-class vehicle position on a j-lane in relation to the observation point (Eq. (5)),
R_{jo}	smallest distance between the observation point and the moving source (Fig. 1),
$\{\mathbf{R}(n)\}$	set of vectors describing geometry of panels in an urban system (Eq. (19)),
$\{\mathcal{R}(n)\}$	set of reflection coefficients of panels in an urban system (Eq. (19)),
$\{\mathcal{T}(n)\}$	set of transmission coefficients of panels in an urban system (Eq. (19)),
U_j	number of the equivalent source discrete positions during its drive-by (Eq. (5)),

v_j^g	average speeds of g-class vehicles along a j-lane in [m/h] (Eq. (6)),
$W_A^g(f_w)$	experimentally obtained source power spectrum in octave bands for g-class vehicles (Eqs. (11), (12)),
Δx_j^g	g-class vehicles average spacing along j-lanes (Eq. (6))
Δx_E	summation step (Eq. (5)),
$\widehat{\Pi}(...)$	operator describing wave propagation (Eq. (1)),
$\widehat{\Pi}_0(...)$	operator describing human perception (Eq. (1)).

1. Introduction

A road traffic noise model in a built-up area has been proposed previously by the authors [1–4]. It comprises the source model which can be made up of unit simple harmonic point sources, and the propagation model, which can be simply identified with the urban system transfer function. The special model for the roadway, as the predominant noise source in an urban area, has been introduced. It is constructed of equivalent point sources representing the individual vehicles moving along a roadway [5]. Multiple reflections and multiple diffractions have been included in the propagation model as interactions with obstacles. Those interactions have been described as a high frequency approximation of the exact solution. The latter is appropriate for the far field conditions [6–8]. Generally, the noise model presented here can be used for any other systems for that the conditions are fulfilled.

A vast literature is devoted to the sound propagation in a system of a complex building arrangement where the results of field measurements, scale modeling and analytical models are used to predict the time-average sound level, e.g. [9–14]. Nevertheless, the applications of analytical models for the outdoor noise propagation in an urban area are the most favorable ones as, apart from their flexibility; they may be applied at various stages of a project design process.

In the analytical description, the first element disturbing the free propagation is the ground. To approach the real conditions, the ground is considered to be an impedance plane. As the next step, the layer structure of the atmosphere may be included [15]. Nevertheless, the analytical description of the large distance propagation in this simplest case is still not easy, mainly because of the varying weather conditions [16].

When neglecting the medium inhomogeneity and weather conditions (see Sec. 3), the acoustical field description can be simplified to the interactions with the obstacles. For the simplest example of a single screen on the impedance ground, the solution has been found as the well-known canonical solution of diffraction at the edge and the reflection from an impedance plane [17–19]. Obstacles of more complex shapes can be made up of plane screens of limited length (panels).

To analyze noise propagation within obstacles, the image sources method for enclosures and semi-enclosures can be used [20, 21]. To get the general field description, the phenomenon of diffraction has to be included. For an urban system the description including multiple reflections and the single diffraction at screens' edges has been most frequently applied [22]. The special case of a plane screen in front of a building, which fulfills the above assumptions, has been investigated and verified by scale modeling experiments [23, 24]. The description, other than that presented here, which contains multiple reflections and multiple diffractions, has also been elaborated [14]. In this case, the Keller geometrical theory of diffraction has been used in the form developed for building wedges [25]. The two methods [14, 22], as well as the environmental noise model presented here, result in computer simulation programs which can be used in forecasting noise.

In the PROP4 simulation program which is based on the road traffic noise model, the propagation model is adjusted to obstacles (buildings) whose shapes are approximated by a shoe-box. The plane acoustical screens are included. The double diffraction at the parallel building wedges and at the edges of two parallel screens are taken into account. The PROP4 program can be used for a multiple-lane roadway with different sources for different classes of vehicles.

The simulation program ENVIRA [26] founded on the description of propagation in a built-up area [14], is similar to the program presented here in its physical foundations and complexity. Contrary to this, commercially spread software, e.g. MICRO-BRUIT (CETUR France) [27], MITHRA (CSTB France), CADNA (DATAUSTIK Germany), can be judged mostly on the trusting to distributors since those programs are not accompanied by relevant information concerning the construction of the simulation model. In the case of the free distribution of DEMO, it is possible to perform a mutual comparison for the same input parameters. This is what the authors plan for the near future.

The aim of this paper is to show how the road traffic noise model works when the PROP4 program is applied to the urban system for which there are field measurements [14]. The exact analysis of the simulation program accuracy is almost impossible since it depends on the input data, models adequacy, and on the accuracy of the description of an individual wave interaction: the latter depends on the position of the observation point. In spite of that, a rough estimation performed here allows to say that the accuracy of the applied simulation program is comparable with that of the scale models [28, 29].

2. The road traffic noise model

In order to solve the noise abatement problem in an urban area, the model of environmental noise is needed. Taking the time-average sound level for the annoyance rating, the model can be presented in the following form:

$$L_{Aeq} = \widehat{\Pi}_0(...)\,\widehat{\Pi}(...)\,Q(...), \tag{1}$$

where the source is represented by $Q(...)$, the operator $\widehat{\Pi}(...)$ describes wave propagation, and the operator $\widehat{\Pi}_0(...)$ describes the human perception.

It is widely discussed how to measure and calculate the noise annoyance. Despite all doubts, the International Standards Organization recommends the time-average sound level. Thus, the operator $\widehat{\Pi}_0(...)$, acting on the acoustical pressure at the receiver, has to perform the A-weighting, time averaging and the level calculation.

In the time domain, the time-average sound level is defined by

$$L_{Aeq}(T) = 10\log\left\{\frac{1}{T}\int_{-T/2}^{T/2}\left[p_A^2(t)/p_0^2\right]dt\right\}, \tag{2}$$

$$p_0 = 2\cdot 10^{-5}\,\mathrm{N/m^2}, \tag{3}$$

where $p_A(t)$ is the A-weighted sound pressure registered during the time interval T. Its relation to the sound exposure level and its representation in the frequency domain, using the environmental noise model (Eq. (1)) will be given in the next two sections.

2.1. The roadway as a noise source

The roadway is a complex noise source composed of individual vehicles belonging to G classes and moving along J lanes. The equivalent source of a g-class vehicle is assumed to be an omnidirectional point source which radiates sound into a homogeneous and loss-free atmosphere at rest. It is characterized by the power spectrum $W_A^g(f_w)$ in the octave-frequency bands and the position above the road surface z_0^g [30].

The roadway model as noise source is assumed by adopting the concept of the sound exposure E_{Aj}^g [11, 12, 31–34] to a g-class vehicle on the j-lane:

$$E_{Aj}^g = \frac{1}{t_0}\int_{-\infty}^{\infty}\left(p_{Aj}^g(t)\right)^2 dt \simeq \frac{1}{t_0}\int_{-\tau/2}^{\tau/2}\left(p_{Aj}^g[\mathbf{R}(t)]\right)^2 dt, \tag{4}$$

where $t_0 = 1\,\mathrm{s}$.

For freely flowing traffic of flow rates N_j^g moving along the lines $(y = y_{j0},\ z = z_0^g)$ (Fig. 1) with the average speeds v_j^g [m/h], the time-average sound level is:

$$\begin{aligned} L_{Aeq}(T) &= 10\log\left(\sum_{g=1}^{G}\sum_{j=1}^{J} N_j^g E_{Aj}^g/p_0^2\right) \\ &= 10\log\left(\sum_{g=1}^{G}\sum_{j=1}^{J}\frac{1}{\Delta x_j^g}\int_{x_{j1}}^{x_{j2}} p_A^2\left[\mathbf{R}^g(x_j)\right]dx_j/p_0^2\right) \\ &\simeq 10\log\left(\sum_{g=1}^{G}\sum_{j=1}^{J}\frac{\Delta x_E}{\Delta x_j^g}\sum_{u=1}^{U_j} p_A^2\left[\mathbf{R}_j^g(u\Delta x_E)\right]/p_0^2\right), \end{aligned} \tag{5}$$

where

$$\Delta x_j^g\ \ [\mathrm{m/vehicle}] = \frac{v_j^g\ [\mathrm{m/h}]}{N_j^g\ [\mathrm{vehicle/h}]}, \tag{6}$$

is the average spacing between successive vehicles on the lane segments. In Eqs. (4) and (5), it is assumed that the sound level due to the source at the ends of the lane segment

(x_{j1}, x_{j2}) is by 10 dB lower than that due to the source at the smallest distance R_{j0} (Fig. 1); this means that

$$(x_{j2} - x_{j1}) \geq 6R_{j0}. \tag{7}$$

Since the analytical integration in Eq. (5) can be performed only for free space, i.e. when there are no buildings, for the propagation through an urban system it has to be replaced by discrete summation with a step Δx_E.

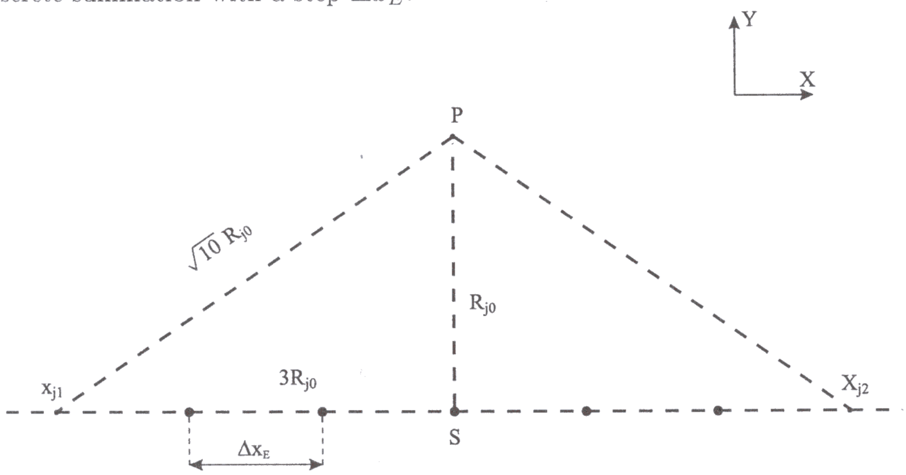


Fig. 1. The locations of an equivalent point source along the highway lane segment.

Thus, the time-average sound level is expressed by:

$$L_{A\mathrm{eq}}(T) = 10 \log 10 \left(\sum_{g=1}^{G} \sum_{j=1}^{J} \frac{\Delta x_E}{\Delta x_j^g} 10^{0.1 SL^g(U_j)} \right), \tag{8}$$

where

$$SL^g(U_j) = L_{WA}^g + L_{U_j}^g(P), \tag{9}$$

$$L_{U_j}^g(P) = 10 \log \left(\frac{1}{4\pi} \sum_{w=1}^{10} q_A^g(f_w) w^g(U_j, f_w) \right). \tag{10}$$

The quantity $SL^g(U_j)$ represents the sound level due to the set of U_j g-class equivalent sources spread along the j-lane with a Δx_E step. Their A-weighted relative power spectrum

$$q_A^g(f_w) = \frac{W_A^g(f_w)}{\sum_{w=1}^{10} W_A^g(f_w)}, \tag{11}$$

is defined by the obtained experimentally source power level spectra $L_{WA}^g(f_w)$ in ten octave bands:

$$\sum_{w=1}^{10} W_A^g(f_w) = W_0 10^{0.1 L_{WA}^g}, \tag{12}$$

$$W_0 = 10^{-12} \text{ Watts}. \tag{13}$$

In the w-octave-band of the center frequency f_w, the factor

$$w^g(U_j, f_w) = \frac{1}{D_w} \sum_{d=1}^{D_w} \sum_{u=1}^{U_j} \left| H(\mathbf{R}_j^g(u\Delta x_E), f_{wd}) \right|^2, \tag{14}$$

represents the average acoustical energy of the set of U_j point sources of unit strength that emit simple harmonics of frequencies $f_{wd} \in \langle F_w^{(1)}, F_w^{(2)} \rangle$. In Eq. (14) $H(\mathbf{R}, f)$ is the urban system transfer function of a source at $S_{uj}^g(x = x_{j1} + u\Delta x_E, y = y_{j0}, z = z_0^g)$ in relation to the observation point at $P(x_p, y_p, z_p)$. The number D_w of the simple harmonics f_{wd} within the octave-band $\langle F_w^{(1)}, F_w^{(2)} \rangle$ can be adjusted according to the required accuracy of calculation of the transfer function $H(\mathbf{R}, f)$ for the w-octave-band. (In the roughest approximation, the center frequencies f_w can be taken for the calculation of the transfer function in the w-octave-band.)

2.2. *Noise propagation through an urban area*

To have an explicit expression for the time-average sound level (Eqs. (8)–(14)), the transfer function of an urban system $H(\mathbf{R}, f)$ is needed. It stems from the propagation model (Eq. (1))

$$|H(\mathbf{R}, f)|^2 = \left| \widehat{\Pi}(...) Q(S) \right|^2 = |p(S, P)|^2. \tag{15}$$

It represents the acoustical pressure at the point P, due to the unit strength simple harmonic point source $Q(S)$, after the propagation through a built-up area.

The operator $\widehat{\Pi}(...)$, describing the propagation through an urban area, in an ideal loss-free medium at rest, to the observation point in front of a building facade, results in the operator describing interactions with obstacles.

The urban system under consideration is represented by the half-space limited by the ground on which the obstacles are placed. The obstacles are modeled by a set of panels. In the case of buildings, this yields shoeboxes (four side walls and a roof), in the case of plane acoustical screens — single panels.

When the dimensions of the obstacles and their mutual distances are large in comparison to the wavelength predominant in the A-weighted noise spectrum, the large-distance approximation ($kR \gg 1$) is justified. Then the interaction of the sound with an obstacle made up of panels can be divided into reflection and transmission through a panel, treated as an unlimited one, and the diffraction at the wedges (edges) [6, 8]. Thus, the operator $\widehat{\Pi}(...)$ (Eq. (15)) contains the sum of parallel chains of elementary interactions of the transmission, reflection and diffraction at wedges (edges). Each chain describes a different wave path to the observation point. The total field, in the system of N panels with M wedges (edges), for the upper order of interactions K, is a sum of the geometrical and diffraction parts [4]:

$$p(S, P) = p^g(S, P) + p^d(S, P), \tag{16}$$

where

$$p^g(S, P) = \sum_{k=1}^{K} \sum_{i=1}^{I(N,k)} p_i(S, P; k), \tag{17}$$

and

$$p^d(S,P) = \sum_{k=1}^{K} \sum_{i=1}^{I(N,M,k)} p_i(S,P;k), \tag{18}$$

The geometrical part of the field $p^g(S,P)$ (Eq. (17)) is composed of chains of interactions containing only transmissions and reflections, where $I(N,k)$ is the number of the wave possible paths for this kind of interactions. The diffraction part of the field $p^d(S,P)$ (Eq. (18)) contains the chains in which, apart from transmissions and reflections, a diffraction appears at least once, and $I(N,M,k)$ is the number of the wave possible paths of this kind.

3. Simulation model

The roadway model (Sec. 2.1) and the propagation model (Sec. 2.2), describing the wave interaction with buildings for the noise environmental model in an urban area (Eq. (1)), enable the construction of a simulation program. In the PROP4 simulation program, allowing calculation of the time-average sound level, the propagation model

$$\widehat{\Pi}(...) = \widehat{\Pi}\left(N, \{\mathbf{R}(n)\}, \{\mathcal{R}(n)\}, \{\mathcal{T}(n)\}, \mathbf{R}(P), K\right) \tag{19}$$

contains the following parameters: N – number of the panels, $\{\mathbf{R}(n)\}$ – set of the vectors describing the geometry of the panels, $\{\mathcal{R}(n)\}$ – set of the reflection coefficients of the panels, $\{\mathcal{T}(n)\}$ – set of the transmission coefficients of the panels, $\mathbf{R}(P)$ – observation point position, K – upper order of the interaction.

The roadway model of several lanes and different equivalent sources for different classes of vehicles:

$$Q(...) = Q\left(J, G, \{N_j^g\}, \{v_j^g\}, \{\mathbf{R}^g(x_j)\}, \{q_A^g(f_w)\}, \{L_{WA}^g\}, \Delta x_E\right), \tag{20}$$

has the following source parameters: J – number of the lanes, G – number of the vehicle classes, $\{N_j^g\}$ – set of the vehicle rate flow on the lanes [vehicles/h], $\{v_j^g\}$ – set of the average vehicle speeds [m/h], $\{\mathbf{R}^g(x_j)\}$ – set of vectors describing the vehicle positions on the lanes, $\{q_A^g(f_w)\}$ – set of the A-weighted relative power spectrum of the vehicles, $\{L_{WA}^g\}$ – set of the vehicle equivalent source power levels, Δx_E – the summation step.

The simulation program PROP4 gives a quantitative answer to the question how the time-average sound level depends on the source parameters (Eq. (20)) and on the urban system parameters (Eq. (19)). Though a change of the reflection coefficients of the panels (walls, ground surface) is possible, the decisive factors are the mutual arrangement of the buildings, their dimensions, and the source locations (a roadway) [35, 36].

The accuracy of the sound level calculation is affected by:

- the adequacy in the modeling of the real conditions,
- the simulation model accuracy.

The adequacy is related to the general assumptions made in modeling the source and the propagation phenomenon. Here, both the source model and the propagation model are constructed for the far field conditions. It is justified for the A-weighted spectra of urban noise since the distances from a source to the place of the first interaction, and between the subsequent ones, are of the order of a few wavelengths of the dominating component.

In the source model assumed, a vehicle is represented by the equivalent point source of a given power spectrum with a directivity characteristic (when needed). The energy (sound exposure), emitted during a drive-by of a single vehicle, is calculated as the sum of energies at the sequence of discrete positions along the route instead of an integral. The acoustical pressure at the observation point, due to the equivalent point source representing a vehicle at a discrete position, is the sum over all the possible wave paths with their phases included. Summing up the squared pressures over all discrete positions gives the sound exposure of a vehicle drive-by.

In the propagation model, describing transmissions, reflections and diffractions at obstacles, all the effects related to the air inhomogeneity and variations in the meteorological conditions are omitted. Thus, the propagation model is adequate only for neutral meteorological condition [37]. The question whether these conditions are representative for the annoyance judgment is still an open one [12, 38]. Other simplifications are related to the urban system geometry, where the real obstacles are replaced by shoeboxes or plane panels.

In the case when the general assumptions are fulfilled, the accuracy of the simulation model depends on the modeling adequacy (assumed simplifications in the system geometry) and the accuracy of estimation of the input parameters. Some of them are not easily to obtain. However, the absolute value of the time-average sound level $L_{A\mathrm{eq}}$ is not always required. Sometimes the change of $L_{A\mathrm{eq}}$ caused by the variations in the source and/or propagation parameters (Eqs. (19), (20)) is sought, as e.g. in the case of shielding efficiency of screens and other obstacles where the equivalent source power level L_{WA}^{g} is not needed. Then, the information provided by the simulation model of the relative change in the $L_{A\mathrm{eq}}$ value could be regarded as more reliable one than that of the absolute value. In this situation some parameters can be eliminated and, at least, some effects of simplifications can be removed.

Generally, the noise rating in the real environmental conditions, expressed as annoyance, depends on nonacoustical factors. It still remains unclear to what extent an annoyance-based approach is protective for human health and well-being. Although, keeping up with the noise limits, time-average sound level can be treated as a guideline in the acoustical designing. Since the simple noise abatement is limited because of technical and economic reasons, a new tendency appears which is called soundscape designing [39–41]. According to it, the simulation program comprising the sound field description has to be completed by an appropriate procedure of real annoyance estimation.

However, there are still problems with transferring the acoustical field description of better accuracy offered and the new techniques of metrology into the formulation of standards [42]. Moreover, although the science and technology provide tools and measures for noise abatement, the scope of policy is decided by the authorities. They issue laws, that are legal tools for the standard execution and can influence the process by determining economic preferences [43]. Simulation models, which can provide alternative solutions, are the best grounds for making decision.

3.1. Sound level calculation

For the simplest road model in the simulation model PROP4 $J = 1$ and $G = 1$. This means that the vehicle stream is treated as if it were concentrated at the road axis and one equivalent point source is assumed for all the vehicles. The reason for those assumption is the fact that, most frequently, a full set of data required for the simulation model is lacking. Moreover, representing a vehicle by a single equivalent point source, the fact that there are several noise sources in a vehicle is neglected. One can find expressions for equivalent source power as a function of the vehicle speed. The dependence of the energy spread within the spectrum on vehicle speed and the equivalent source height above the ground, which results from the varying participation of the vehicle elementary sources, are rarely available [30].

When vehicles are divided into two classes: light and heavy vehicles, and when the average speeds for these classes v^l and v^h are given, the single equivalent source can be applied with the percentage of heavy vehicle, p, as parameter of the simulation model. Then:

$$N = N^l + N^h, \tag{21}$$

$$v = \left[(1 - 0.01p)v^l + 0.01pv^h\right], \tag{22}$$

$$L_{WA} = 10\log\left((1 - 0.01p)10^{0.1L^l_{WA}} + 0.01p10^{0.1L^h_{WA}}\right). \tag{23}$$

The equivalent point source can be assumed to be a point emitting noise of a spectrum typical of traffic [44].

Then, the time-average sound level in an urban system due to the roadway segment of total flow rate N [vehicles/h] moving along the x-axis ($y = y_0$, $z = z_0$) with a steady speed v [m/h] is expressed by

$$L_{A\mathrm{eq}}(J = 1, G = 1) = L_{WA} + 10\log\frac{\Delta x_E}{\Delta x} + L_U(P), \tag{24}$$

$$L_U(P) = 10\log\left(\frac{1}{4\pi}\sum_{w=1}^{10} q_A(f_w)w(U, f_w)\right). \tag{25}$$

As can be seen, the time-average sound level is straight affected by the equivalent source power level, L_{WA}, and the average vehicle spacing (Eq. (6)). The sound level $L_U(P)$ depends on the equivalent point source relative power spectrum, $q_A(f_w)$, and the urban system transfer function for the sequence of U sources:

$$w(U, f_w) = \left|H\left(N, \{\mathbf{R}(n)\}, \{\mathcal{R}(n)\}, \{\mathcal{T}(n)\}, \mathbf{R}(P), \{\mathbf{R}(S_u)\}, K, U(\Delta x_E), f_w\right)\right|^2. \tag{26}$$

Its value depends on the upper order of interactions K, and the summation step Δx_E which can be arbitrary chosen by the user of the simulation program.

From the physical point of view, the number of interactions is unlimited. When the source is placed within two parallel surfaces (canyon structure), the specifying of an appropriate K value can be substantial. In other cases $K = 3$ seems to be sufficient [1–4, 35, 36]. The summation step Δx_E appears explicitly in the expression for the sound level (Eq. (24)) and affects the value of $w(U, f_w)$ by the number of point sources $U(\Delta x_E) = (x_{j1} - x_{j2})/\Delta x_E$ representing a moving vehicle, and by their positions, $\mathbf{R}(S_u)$, in the urban system. The number of sources and their exact positions are decisive factors in the calculation of the $w(U, f_w)$ value as they determine the possible paths of reaching the observation point (Eqs. (16)–(18)). The influence of the Δx_E value is not easy to predict but for enough small values of Δx_E, the $w(U, f_w)$ value is expected to be independent of it [35]. For both parameters: the length of the summation step Δx_E and the upper order of interactions K, the appropriate values can be chosen with a step-by-step procedure taking 1 dB as the limit of the final change in the sound equivalent level.

4. Example

Now, the results of measurements carried out in Wrocław at the site of the Zachodnia St. (Fig. 3) [14] will be discussed. Next, the results obtained by the two simulation models $R(1)$ and $R(2)$ given in [14] and the PROP4 model will be compared.

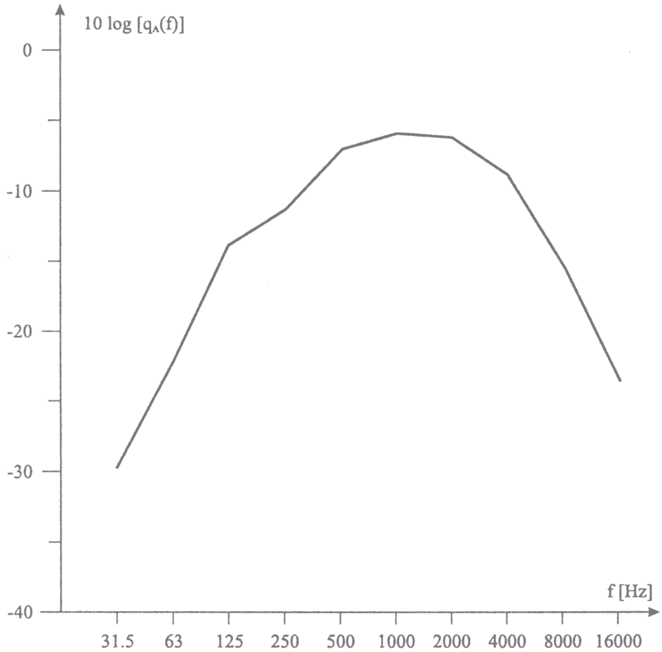


Fig. 2. The A-weighted relative power spectrum $q_A(f)$ (Eq. (11)) of the average traffic noise [14].

The sound levels are measured for $T = 900$ s and the sampling time $t = 1$ s at the observation points $P(z_p = 2\,\mathrm{m})$. The values of flow rates and speeds have been estimated for light and heavy vehicles.

The two simulation models, $R(1)$ and $R(2)$, have taken into account, as an averaged effect, the attenuation in the propagation medium and the influence of the impedance ground. In both the models a single reflection from the buildings' walls has been assumed

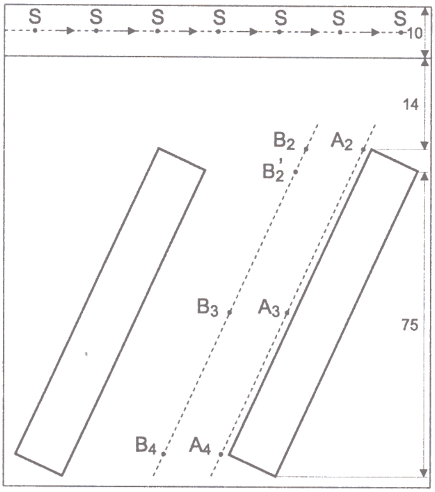


Fig. 3. The urban system under consideration [14].

for the distance $R_0 < 40$ m from the street axis and two reflections for $R_0 > 40$ m. The $R(1)$ model has omitted the diffraction phenomenon, while the $R(2)$ model has omitted the background noise which is 50 dB (A). In the $R(1)$, model the movement of the vehicles has been simulated as a statistical process. In the $R(2)$ model, the 10 m street segments have been replaced by the equivalent point source at the street axis and at a height $z_0 = 0.5$ m, with equivalent sources of the traffic noise spectrum $q_A(f)$ (Fig. 2).

The same equivalent source parameters z_0 and $q_A(f)$ as in the $R(2)$ model have been used in the PROP4 model. For the following measured vehicle stream parameters on the roadway segment: total flow rate $N = 1200$ vehicles/h, the speed of light vehicles $v^l = 60$ km/h and that of the heavy ones $v_h = 45$ km/h, with a percentage of heavy vehicles $p = 20\%$, the average speed of the vehicle flow (Eq. (22)) is

$$v = 57\,\text{km/h}, \tag{27}$$

that results in the average spacing (Eq. (6)):

$$\Delta x = v/N = 47.5\,\text{m/vehicle}. \tag{28}$$

Using the PROP4 simulation program the time-average sound level (Eq. (24)) for $\Delta x_E = 4$ m is given by

$$L_{A\text{eq}}(P) = L_{WA} + 10\log\frac{\Delta x_E}{\Delta x} + L_U(P) = L_{WA} - 10.7 + L_U(P), \tag{29}$$

where $L_U(P)$ (Eq. (25)) is calculated with a number of interactions up to $K = 3$.

To calculate the sound equivalent level (Eq. (29)), the value of the source power level L_{WA} is needed. To this end, using the expression relating the source power to the vehicle speed [12, 14, 45–47], the source power level L_{WA} (Eq. (23)) is calculated (Table 1).

For the point A_2 (Fig. 3), which is nearest to the source and at that the direct wave has to prevail the other terms, the time-average sound level $L_{A\text{eq}}(A_2)$ (Eq. (29))

Table 1. The calculated equivalent point source power level values L_{WA}.

source	L_{WA}
[12]	101.03
[14]	101.65
[45]	101.65
[46]	103.32
[47]	103.72

Table 2. The time-average sound level in an urban system (Fig. 3) at the observation point A_2 calculated using of the source power levels from Table 1.

source	$L_{Aeq}(A_2)$
[12]	69.8
[14]	70.4
[45]	70.4
[46]	72.1
[47]	72.5
measured [14]	68.0

is calculated for different values of L_{WA} (Table 1). The results obtained presented in Table 2 are used for choosing the appropriate value of the source power level. As the L_{WA} value estimated according to [12] results in the best fit to the value measured in the real urban system, it has been used for the calculation of $L_{Aeq}(P)$ at all the observation points in the urban system. The results are presented in Tables 3 and 4 and in Fig. 4.

Table 3. The time-average sound level at observation points lying along the A line in the urban system (Fig. 3).

point	L_{Aeq}				$\Delta L_{Aeq} = L_{Aeq}(A_i) - L_{Aeq}(A_2)$			
	M	$R(1)$	$R(2)$	PROP4	M	$R(1)$	$R(2)$	PROP4
A_2	68.0	66	69.4	69.8				
A_3	60.5	57	58.7	64.2	−7.5	−9	−10.7	−5.5
A_4	57.5	54	58.2	60.0	−10.5	−12	−11.2	−9.8

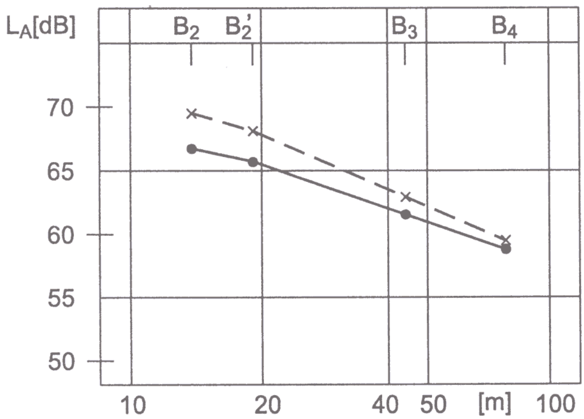
M – measured, $R(1)$ – calculated according to the $R(1)$ model [14], $R(2)$ – calculated according to the $R(2)$ model [14], PROP4 – calculated according to the PROP4 simulation program.

In Tables 3 and 4 there are also collected the time-average values of the sound levels measured in the urban system [14] and those calculated according to the two simulation models $R(1)$ and $R(2)$ given in [14]. The absolute values of the time-average sound levels, $L_{Aeq}(A_i)$ and $L_{Aeq}(B_i)$, are accompanied by the relative values $\Delta L_{Aeq} = L_{Aeq}(A_i) - L_{Aeq}(A_2)$ and $\Delta L_{Aeq} = L_{Aeq}(B_i) - L_{Aeq}(B_2)$. As it can be seen, the relative values calculated according to the PROP4 model match the best measured relative values. The better matching of the relative values results from the omission of the source power level of the moving equivalent point source which represents the vehicles. The source power estimation constitutes a separate problem. Its accuracy affects immediately

Table 4. The time-average sound level at observation points lying along the B line in the urban system (Fig. 3).

point	L_{Aeq}				$\Delta L_{Aeq} = L_{Aeq}(B_i) - L_{Aeq}(B_2)$			
	M	$R(1)$	$R(2)$	PROP4	M	$R(1)$	$R(2)$	PROP4
B_2	67.0	68	69.6	69.0				
B_2'	66.3	66	65.0	68.1	−0.7	−2	−4.6	−0.9
B_3	61.5	62	57.2	63.2	−5.5	−6	−12.4	−5.8
B_4	59.5	56	52.4	59.6	−7.5	−12	−17.2	−9.4

M - measured, $R(1)$ – calculated according to the $R(1)$ model [14], $R(2)$ – calculated according to the $R(2)$ model [14], PROP4 - calculated according to the PROP4 simulation program.



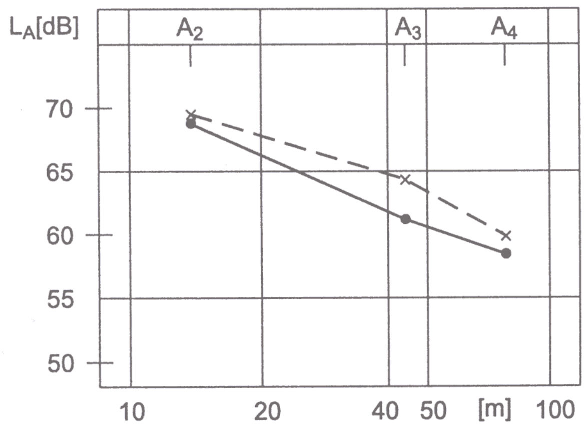


Fig. 4. The sound equivalent level in the analyzed urban system (Fig. 3): (•) – measured [14], (x) – calculated according to the PROP4 model.

the absolute value of the sound equivalent level L_{Aeq} at the observation point in an urban system (Eq. (29)). When a relative change in L_{Aeq} is awaited, L_{WA} is not needed. But the results depend still on the source model geometry with the assumed summation step $\Delta x_E = 4$ m. In the analyzed case, although a single lane vehicle stream is assumed instead of the two lanes in the real situation, the agreement with experiment is very good. This means that the application of the PROP4 model, with the assumed source model and $K = 3$ interactions, gives a satisfactory accuracy in relation to the empirical data.

5. Conclusions

The operating of the urban infrastructures yields noise as by-product. The noise level is one of the comfort parameters of habituation. Thus decisions concerning the infrastructure should take into account the resulting acoustic climate; the final decisions should be a compromise between economy and socio-psychologic aspects of acoustic climate in relation to the defined urban system. The ways to obtain time-average sound levels in an area of interest not exceeding an admissible value can be different and not all of them are socially accepted. Therefore, alternative solutions should be prepared. Simulation models are the most efficient tools for this purpose.

Any simulation program gives results being in agreement with real records only in limited range. Thus, its application has to be accompanied by an analysis of accuracy. As for a system like an urban one the calculation of accuracy is hardly possible, a qualitative assessment of the physical foundations has to be performed. Here the presented PROP4 program holds for most the important phenomena of propagation in a system with obstacles: transmission, reflection and diffraction described for far field conditions. This choice seems to be justified for distances of few hundreds meters from the road.

How the PROP4 works has been shown by its application to the real urban situation for which field measurements are available. The agreement between the calculation and measured results is pretty good. When this would not be the case, an improvement can be achieved by raising the upper limit of the interaction number K. This results in more terms in the summation over the wave possible paths which raises generally the total acoustic pressure despite the wave phase inclusion. Other option is the decrease of the summation step Δx_E which should give a more accurate value of the sound exposure related to the vehicle drive-by. If these two ways of improvement do not work, this means that the model is not adequate for the real situation because of the physical foundations or the values of input parameters.

With all the limitations borne in mind, the application of the simulation program PROP4 for the forecasting of the acoustic climate can provide the ability to assess quantitatively the influence of a pretty good bunch of parameters involved in modeling of a noise source and urban system itself in an area of interest, e.g. in apartment house facades, recreation grounds.

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