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Possible Improvement of Acoustical Climate Part I: Measurements and Theoretical Description

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In the paper, the simulation PROP5 program is used to predict the sound level in proximity of a road with defined surroundings. The simulation involves road geometry (number of lanes and their positions) and traffic structure (vehicle flow rates and their average speeds), with equivalent omnidirectional point sources representing vehicles. In Part I of the paper, the agreement between measurement and simulation results is tested to verify the accuracy degree of the applied models of a road, as a noise source and propagation throughout surrounding space. In Part II, using the pre-tested simulation program, the possibility of acoustic climate improvement has been analyzed.

Keywords: acoustical climate, simulation program, road traffic noise.

1. Introduction

The noise problems in urban areas exert pressure for rational means of noise abatement (Steele, 2001). It has been found that, in extend since 1966 to 1999, despite the lowering of the allowed sound level emitted by a vehicle from 84 to 74 dB(A), the sound level in built-up area of dominating traffic noise has not been lowered in accordance with this (Grossman, Ehinger, 1997). It is mostly due to growing vehicle number but also due to other reasons. They include the propagation process during which noise amplification could appear. Prediction of effectiveness of noise abatement means is the relevant problem, since the applied means act differently in different parts of space, for someone they can be a protector for others an amplifier. Moreover, their predicted effectiveness, evaluated without consideration of interaction with the whole surroundings, could be misleading. That is the case of a screen application, when the road surroundings are not taken into account (Walerian *et al.*, 1999a).

Generally, the effectiveness of feasible noise abatement means could be of a few decibels order. Thus, only a complex solution consisting of several means can provide a noticeable improvement of the subjectively assessed acoustical climate. The complex solution, which provides a noticeable improvement, should be built upon the detailed description of noise emission and propagation. The requirements are fulfilled by the here-presented software as well as by the HARMONOISE method (Jonasson *et al.*, 2004a), prepared to replace the currently used in Europe prediction methods: Nord2000. ISO 9613-2, SRM2, NMPB.

The simulation programs, as appropriate tools of the sound level prediction, allow noise control by variation of sources and surrounding space parameters. The general environmental noise model, developed by the authors, contains a source model and propagation model as independent parts (Walerian, 1995; Walerian, Janczur, 1998; Walerian *et al.*, 1999b). Traffic over a road of arbitrary number of lanes can be divided into arbitrary number of vehicle classes. A virtual vehicle representing the class can be replaced by a set of arbitrary number of equivalent point sources, each being characterized by its position and emitted power. All the parameters can be functions of frequency and vehicle speed. A vehicle movement is represented by the sequence of discrete positions along its route, what results in the sound exposure calculation as a sum with an adjustable summation step. For directional noise emission, the equivalent sources can be equipped with appropriate directivity characteristics. A road lane can be divided into straight segments of constant flow rate and average speed. This allows the consideration of interrupted traffic (Walerian *et al.*, 2005) and a road curvature for a level road as well as for depressed or elevated ones, with up-slope and down-slope segments. The objects in road surroundings can be modeled by sets of panels with defined acoustical features of their surfaces, joined at appropriate angles. As a road is modeled by a set of defined point sources, the propagation model is based on a point source emission. A wave traveling throughout an ideal gas at rest can undergo a chain of interactions: transmissions, reflections, and diffractions. The pressures of the waves reaching the observation point by different paths are summed, not the energy. The propagation model, where diffraction is described with acceptable accuracy for distances of a wavelength order (Walerian *et al.*, 2002), has been validated in the scale model experiment (Janczur, 1990; Sakurai *et al.*, 1990).

The sound level observed in built-up area due to complexity of an urban system with traffic as a noise source, depends on large set of parameters present in the simulation program. By rating the sensitivity of the simulation results to the input parameters, their number can be limited, what makes the simulation an efficient tool in acoustical climate investigation. The accuracy in estimation of input parameters of an urban system require the relevant accuracy of the source and surroundings modeling. The comparison of the simulation results with the field measurements allows assessment whether the assumed urban system model is the proper one for the assumed accuracy.

For the simulation program PROP5 applied here, the object of interest is the sound level spread over the building façade due to the noise emitting road. Under these conditions, the local traffic is mostly composed of passenger cars with some participation of public transportation buses, which are smaller in number but more noisy. Thus, in the applied road model MAK2, the representative sets of the equivalent sources for these two classes of vehicles are assumed. The vehicles belonging to the class of light vehicles or the heavy ones, are represented by the single omnidirectional equivalent point source of appropriate parameters (Makarewicz, 1996; Glegg, Yoon, 1990). The simulation tests with the road model have been successively performed for different urban systems (Walerian *et al.*, 2001a; 2001b; Janczur *et al.*, 2001a; 2001b).

In the paper, the simulation program PROP5 with the MAK2 road model as a noise source has been applied for the existing urban system. The investigation procedure of the measured and simulation field is directed to verify the prediction accuracy of the sound level spread over the building façade (Subsec. 3.1, Subsec. 3.2). Applying the simulation procedure described in Sec. 2, the adequate road surroundings model, the proper one for the analyzed situation, has been searched for. By establishing the number of objects of important influence on the acoustical field, the basic urban system model has been found (Subsec. 3.3). The comparison of the simulation results with the field measurements, has been performed for finding whether the observed dependence on the source and surroundings parameters is properly described in the basic urban system model (Subsec. 3.4). Looking for possible improvement of the agreement with the measurements in the range of the lower floors, the more complex model of noise emission by a vehicle has been tested (Sec. 3.5). Among others, the HARMONOISE model with a vehicle represented by a set of four point sources has been included.

The final goal of the current investigation is preparation of the urban system model, suitable in further application, for evaluation of efficiency of noise abatement means. The obtained model will be used in Part II of the paper (Walerian *et al.*, in press in Archives of Acoustics) for analysis of application of such noise abatement means as plane screens.

2. Simulation procedure

The fundamental element of the road as a noise source is a moving vehicle. When vehicles belonging to the g-class move over the j-lane with the flow rate $\mathcal{N}_j^g$, then the time-average sound level observed at the point P is given by

$$L^g_{Aeq\,j}(v^g_j, \mathcal{N}^g_j) = L^g_{WA}(v^g_j) + 10\log\frac{\Delta x_E}{\Delta x^g_j(v^g_j, \mathcal{N}^g_j)} + L^g_j(v^g_j, U_j, P). \tag{1}$$

In the above expression, for the simplest case, the single equivalent point source at the height above the ground z_0^g is assumed to represent a vehicle. As a noise source, a vehicle is characterized by the power level $L_{WA}^g(v_j^g)$ and its spectral distribution:

$$q_A^g(v_j^g, f_w) = \frac{W_A^g(v_j^g, f_w)}{\sum\limits_{w=1}^{10} W_A^g(v_j^g, f_w)}. \tag{2}$$

The source power level and its spectral distribution are functions of vehicle's average speed v_j^g. The average speed v_j^g and flow rate $\mathcal{N}_j^g$ together characterize the traffic over the j-lane by spacing:

$$\Delta x_j^g(v_j^g, \mathcal{N}_j^g) = v_j^g / \mathcal{N}_j^g. \tag{3}$$

Thus, the first two terms in Eq. (1) depend only on the source parameters. In the third term, the propagation process is reflected. The term depends on the source power spectrum [Eq. (2)] and the urban system transfer function, describing interactions with the road surroundings. The resulting sound level

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

is the level due to the set of U_j point sources representing the g-class vehicle movement along the j-lane (the sound exposure level). The average acoustical energy in the w-octave-band

$$\begin{aligned} &w^g(f_w, U_j(\Delta x_E), P) \\ &\quad = w^g\left(N, \{\mathbf{R}(n)\}, \{R(n)\}, \{T(n)\}, \mathbf{R}(P), \{\mathbf{R}(S_{ju}^g)\}, K, \Delta x_E, f_w\right) \end{aligned} \tag{5}$$

results from an urban system transfer function, defined for the vehicle position in the lane $\mathbf{R}\left(S_{ju}^g\right)$. It allows the road surroundings description with use of the following parameters (Walerian, 1995; Walerian, Janczur, 1998; Walerian *et al.*, 1999b):

- K – upper order of interaction,
- N – number of panels,
- $\{\mathbf{R}(n)\}$ – set of vectors describing geometry of panels,
- $\{R(n)\}$ – set of reflection coefficients of panels,
- $\{T(n)\}$ – set of transmission coefficients of panels,
- $\mathbf{R}(x_p, y_p, z_p)$ – observation point position,
- $\{\mathbf{R}(S_{ju}^g)\}$ – set of vectors describing vehicle positions in lanes.

For a road of J lanes, as a noise source, on which move the vehicles ascribed to G different classes, the time-average sound level of an interval T is obtained as a result of summation over all the vehicle classes and road lanes:

$$L_{Aeq}(T) = 10 \log \left\{ \sum_{g=1}^{G} \sum_{j=1}^{J} 10^{0.1 L_{Aeq}{}_j^g (v_j^g)} \right\}. \tag{6}$$

The simulation program PROP5 used here contains the MAK2 ($G = 2$) model of a road, where the vehicles are divided into two classes: light ($g = l$) and heavy ($g = h$) ones (Makarewicz, 1996; Glegg, Yoon, 1990). The single omnidirectional equivalent point source representing the class has been characterized by (Appendix A):

- $L_{WA}^{l(h)}\left(v_j^{l(h)}\right)$ – power level,
- $q_A^{l(h)}(f_w)$ – power spectrum,
- $z_0^{l(h)}$ – position above ground.

The road geometry, which stems from the analyzed urban system geometry, completes the description of the positions of the equivalent sources by giving:

- J – number of lanes,
- $\{y_{0j}\}$ – lane positions for the assumed x-axis parallel to a road segment.

A share in the total sound level due to an individual vehicle pass-by is calculated as the sound exposure level for the limited road segment and parametrizes the vehicle position along its route (Walerian *et al.*, 2001b). Thus, as the source parameter appears,

- Δx_E – step parametrizing vehicles' position along the lane (Fig. 1), then the x-coordinate along a vehicle route is $x_0(u) = u\Delta x_E$, with $1 \le u \le U_j\ (\Delta x_E)$, where

$$U_j(\Delta x_E) = 1 + 2\frac{(x_{j2} - x_{j1})/2 + \varepsilon}{\Delta x_E}, \qquad \varepsilon < \Delta x_E, \tag{7}$$

$$x_{j2} - x_{j1} \ge 6R_{j0}, \tag{8}$$

$$R_{0j} = \sqrt{(y_{0j} - y_p)^2 + (z_0^g - z_p)^2}. \tag{9}$$

The last road parameter as a noise source stems from the traffic organization:

- $\Delta x_j^{l(h)}$ – a set of vehicles' spacing along the lanes [Eq. (3)].

The database needed to perform simulation consists of surroundings and source parameters. For the applied MAK2 road model of light and heavy vehicles moving over the j-lane, the source power levels $L_{WA}^{l(h)}(v_j^{l(h)})$, their spectral distributions $q_A^{l(h)}(v_j^{l(h)}, f_w)$, and positions above the ground $z_0^{l(h)}$, are perma-

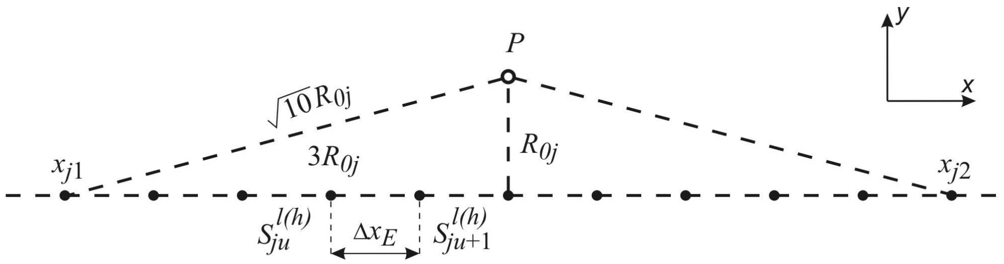


Fig. 1. Discrete vehicle positions along a road during its pass-by.

nently loaded. Thus, the set of source input parameters is reduced to the analyzed road geometry and traffic composition: vehicle flow rates $\mathcal{N}_j^{l(h)}$ and their average speeds $v_j^{l(h)}$, that give spacing [Eq. (3)]. In addition, the two adjustable parameters: the upper number of reflections K and the length of summation step Δx_E (Fig. 1) in calculation of the sound exposure (energy emitted due to vehicle pass-by) have to be chosen. They are decisive for the simulation efficiency in terms of the calculating time. The upper number of interactions limits the number of wave paths considered in the sound level calculation. The length of summation step determines the number of considered sources over lanes [Eq. (7)]. The values of parameters Δx_E, K have to be adjusted to the assumed accuracy in the urban system modeling.

3. Evaluation of acoustical climate

According to legislation, the acoustical climate is evaluated by the average sound level for the defined time intervals e.g. L_{den} (Directive, 2002). Possessing the field verified simulation program, it is possible to suggest modification of the involved parameters to obtain better acoustical climate conditions. To this end, the simulation program PROP5 is applied. For simulation, the analyzed urban system could be described with different accuracy. The required modeling accuracy, adequate for the analyzed urban system, is found by comparison of the simulation results with the measurements. When the road model and the appropriate model of the road surroundings are obtained, the PROP5 program could be used for simulation of efficiency of noise abatement solutions allowed due to the source and its surroundings parameters variation.

3.1. Investigation procedure

The real building 25 m high, located at Klonowicza Street 2 in Warsaw, is taken as the object of investigation. The measurements have been carried out over the façade facing the busy Kasprzaka street. The observation points have

Fig. 2. Observation point positions.

been placed in the middle part of the façade without balconies (Fig. 2). The whole surrounding urban system and the observation point positions above the ground are presented in Fig. 3 and Fig. 4, respectively. The positions of observation point are taken, in accordance with the ISO recommendation, 1 m from the building façade and 1.5 m above each floor of interest (ISO 1996). Having at disposition the four-channel equipment, the measurements have been carried out for the observation points divided into two groups ($f = 1, 2$), formed by the observation point positions at the four neighboring floors. The absolute sound level values have been investigated and the relative variation within the group of the observation points with the lowest point position as reference:

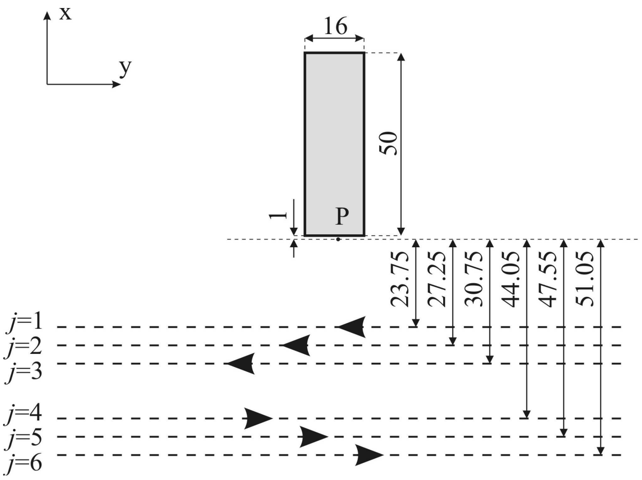


Fig. 3. A sketch of an urban situation (dimensions in meters).

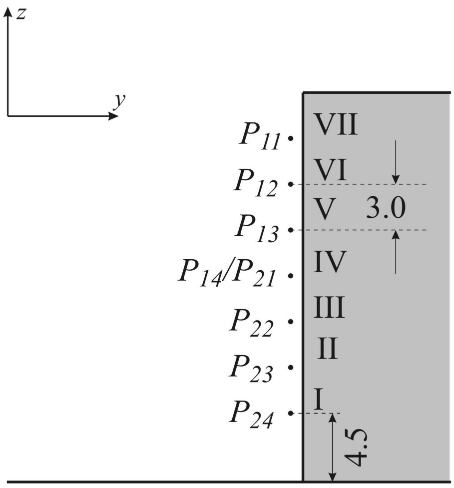


Fig. 4. Observation point positions above ground.

$$\Delta L_{fi} = L_{Aeq}(P_{fi}) - L_{Aeq}(P_{f4}), \qquad f = 1, 2, \qquad i = 1, 2, 3, 4. \tag{10}$$

The comparison of the sound level within the group of the observation points allows for investigation of the field features for the same noise emission. The obtained results are free from some systematic errors.

3.2. Measurements

To verify the simulation results, the measurements have been carried out with use of the SVAN 912 AE digital analyzer with the SV08A four-channel input module, allowing simultaneous four-channel measurements. The differences between four channels, after ten hours of operation, were 0.2–0.4 dB(A). The measurements have been carried out during the two measurement sessions: (25) and (09). All the time, the measurements have been carried out twice for each group of the four neighboring floors. The 10-minutes equivalent sound pressure levels have been measured, while the traffic has been recorded by the digital video camera SONY DCR-TRV355E. The 10-minutes equivalent sound levels due to the observed traffic, have been taken as the representative for one hour. The camera records have been used for establishing the traffic parameters in laboratory conditions (Table 1, Table 2).

Table 1. Traffic parameters during the (25) measurement session.

series	lane	flow rate [veh/h]		mean speed [km/h]	
	J	N_j^l	N_j^h	v_j^l	v_j^h
2A	1	402	36	57	50
	2	528	48	67	50
	3	552	0	75	
	4	456	0	70	
	5	738	0	64	
	6	300	36	55	45
2B	1	432	42	59	49
	2	582	24	50	
	3	474	0	70	
	4	522	0	65	
	5	756	36	66	50
	6	348	36	53	45
3A	1	396	30	59	49
	2	522	0	64	
	3	462	0	69	
	4	426	0	65	
	5	630	24	65	52
	6	354	24	51	42
3B	1	474	24	60	43
	2	630	24	55	50
	3	474	0	72	
	4	504	0	67	
	5	578	36	54	45
	6	228	36	52	41

Table 2. Traffic parameters during the (09) measurement session.

series	lane	flow rate [veh/h]		mean speed [km/h]	
	J	N_j^l	N_j^h	v_j^l	v_j^h
2A	1	354	42	60 ± 5	50 ± 5
	2	504	30		
	3	408	0		
	4	366	6		
	5	660	24		
	6	306	240		
2B	1	282	12	60 ± 5	50 ± 5
	2	522	24		
	3	420	0		
	4	432	6		
	5	642	42		
	6	342	36		
3A	1	420	12	60 ± 5	50 ± 5
	2	582	12		
	3	360	0		
	4	366	0		
	5	588	18		
	6	264	42		
3B	1	372	24	60 ± 5	50 ± 5
	2	636	30		
	3	402	0		
	4	402	0		
	5	528	48		
	6	234	18		

3.3. Simulation

To obtain the adequate model of the urban system, the simulation error resulting from the error in speed estimation is taken as the criterion for accuracy in the urban system modeling (Janczur *et al.*, 2009). When the influence of the involved parameter is below the simulation error due to vehicle speed estimation, its presence can be omitted in the urban system modeling.

The applied simulation program PROP5, with the MAK2 ($G = 2$) model of a road as a noise source, delivers the sound level, which is a function of the set of parameters presented in Sec. 2. They belong to two groups: some describe road surroundings, others the road itself. Surroundings description concerns their geometry, the number of present objects, their shape model and surface reflection coefficient. The road is described by its geometry, lanes number, traffic composition and the model of noise emission by a vehicle. The one of two adjustable parameters, the upper number of reflections K involved in propagation description, is ascribed to the group of the surroundings parameters. The second parameter, the length of summation step Δx_E (Fig. 1) in calculation of the energy emitted due to vehicle movement, belongs to the road parameters. Previous investigations of urban systems typical for cities have shown a limited sensitivity of simulation results to the operational parameters values, (Walerian, Janczur, 1998; Walerian *et al.*, 2001a; 2001b; Janczur *et al.*, 2009). According to this, the length of summation step $\Delta x_E = 5$ m and the number of interactions $K = 3$, have been assumed in the current investigation.

To investigate the influence of surroundings parameters on the sound level spread, the standard traffic composition (Table 3) has been assumed in the PROP5 simulation program. The standard traffic composition is obtained by simplification of the observed real traffic composition. There is only light vehicle movement as it is dominant, and the higher flow rate and speed are assumed for inner lanes. For the loaded standard traffic composition, influence of the factors determining propagation in surroundings could be observed. In the expression of the sound level due to the j-lane [Eq. (1)], by keeping the traffic composition constant, the first two terms remain unchanged while the change in surroundings is reflected by variations of the third term. Since the total field results as a sum over all road lanes [Eq. (6)], thus the obtained relations are more complex and concern only the assumed traffic composition; in the analyzed case – the real and standard traffic composition due to their likeness.

Table 3. Standard traffic composition and vehicles' parameters.

lane	flow rate [veh/h]	mean speed [km/h]	source power level* [dB(A)]	position above ground** [m]
$j = 1$	$N_1^l = 400$	$v_1^l = 60$	$L_{WA}^l \; v_1^l \; = 101.70$	$z_0^l = 0.50$
$j = 2$	$N_2^l = 600$	$v_2^l = 70$	$L_{WA}^l \; v_2^l \; = 103.73$	
$j = 3$	$N_3^l = 600$	$v_3^l = 70$	$L_{WA}^l \; v_3^l \; = 103.73$	
$j = 4$	$N_4^l = 600$	$v_4^l = 70$	$L_{WA}^l \; v_4^l \; = 103.73$	
$j = 5$	$N_5^l = 600$	$v_5^l = 70$	$L_{WA}^l \; v_5^l \; = 103.73$	
$j = 6$	$N_6^l = 400$	$v_6^l = 60$	$L_{WA}^l \; v_5^l \; = 101.70$	

*(Makarewicz, 1996), **(Glegg, Yoon, 1990).

For controlled accuracy of the interaction description in propagation model (Walerian *et al.*, 2002), the number of surroundings objects, whose shapes could be modeled by a set of panels joined at proper angles, with known acoustical properties, has to be tested. In the analyzed case, as the present objects are distant from the measurement site, the model of the surroundings is assumed to be an open half-space with the analyzed building, where propagation is modified only by a fence at the road's opposite side. In the assumed model of the urban system without (S(1)) and with the fence (S(2)), all reflection coefficients are assumed as $R = 0.9$ (Table 4). In Fig. 5, for the standard traffic (Table 3), the effect of a fence presence in modeling of the urban system is presented. As the effect has approached 1 dB(A) only on the lowest floor and decreased with height, the fence presence could be omitted. Thus, the assumed basic urban system model (S(1)) is defined as it containing only the investigated building on the ground (Fig. 3).

Table 4. Parameters of the urban system model.

model	objects on the ground	reflection coefficient R		reflection number	road lanes number	summation step Δx_E [m]	point P distance from façade [m]
		ground	walls, fence				
S(1)	building	0.9	0.9	$K = 3$	$j = 1, 2, 3, 4, 5, 6$ ($J = 6$)	5.0	1.0
S(2)	building and fence						

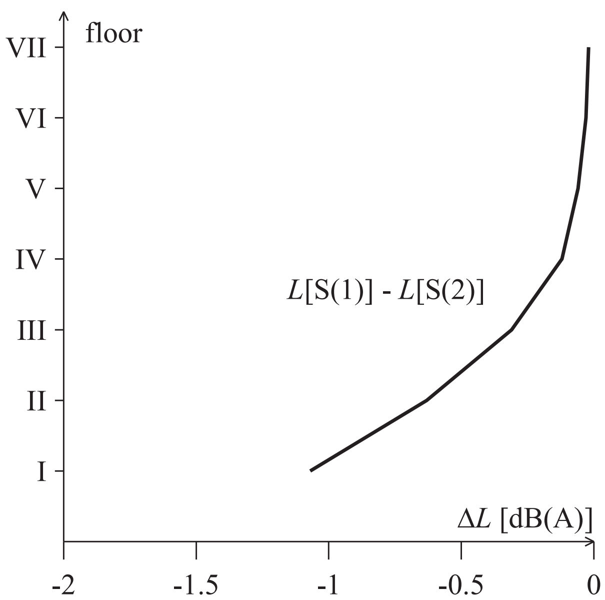


Fig. 5. The effect of the fence presence in modeling the urban system (Table 1) for the standard traffic (Table 3).

The accuracy in prediction of the sound level spread over a building façade is the result of the assumed road model and accuracy in estimation of the involved parameters. To find whether the replacement of a real traffic by the standard one is justified, the results for the standard traffic composition have been compared with the ones of the composition observed during the (25) measurement session. The observed differences for the basic urban model are in the range of 1 dB(A) and concern the sound level magnitude, while the shape of the sound level spread remains unchanged (Fig. 6). This allows the use of the standard traffic composition in place of the real traffic composition for the field investigation. The underestimation of the sound level for the standard traffic composition is the result of omission of heavy vehicles. The heavy vehicle flow rates are low in comparison with light vehicle flow rates; thus, they affect only the magnitude of the sound level but the shape of the sound level spread over a building façade is determined by light vehicle flow rates over lines.

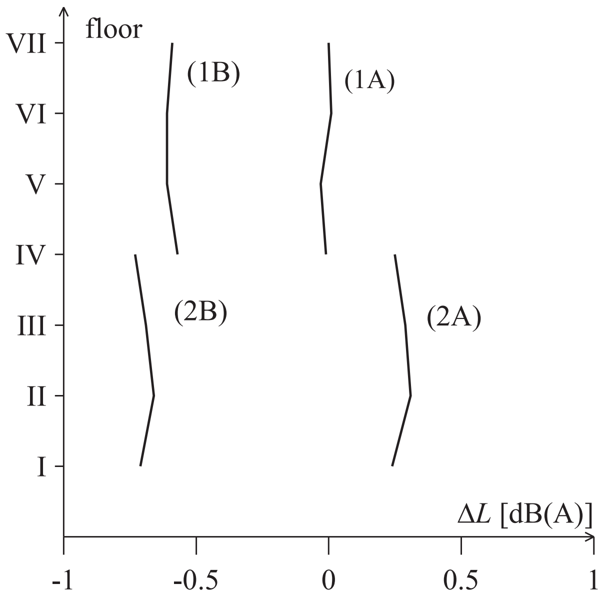


Fig. 6. Comparison of simulation results for real traffic composition of the (25)-session and standard traffic composition.

3.4. Comparison with measurements

To make a comparison of the sound levels measured and calculated for the basic urban system model (Table 4, S(1)), the PROP5 simulation program has been applied with the real traffic composition observed during the two measurement sessions (Table 1, Table 2). The results obtained for the (25)-session are in Fig. 7 and Table 9. In the measurement, the sound level grows with height by about 1.5 dB(A) while in the simulation it decreases by about 0.5 dB(A). In this way they meet at the height of the seventh floor. The same effect has been observed previously for the comparable distance from the road (Janczur *et al.*, 2009). The difference in absolute values between the measured and predicted sound levels is 2.45 dB(A) for the lowest floor, and diminishes on the highest floor to less than 0.5 dB(A) (Table 9). The relative spread of sound level [Eq. (10)], free of some systematic errors, gives more reliable information about the sound field over the building façade. In the measurement, for the first four floors range, the increase of about 1 dB(A) has been observed, while for the higher four floors it is about 0.5 dB(A). In the simulation, for both ranges the same decrease of about 0.3 dB(A) has appeared. Thus, the difference in the relative sound level spread between the simulation and the measurements is a little above 1 dB(A).

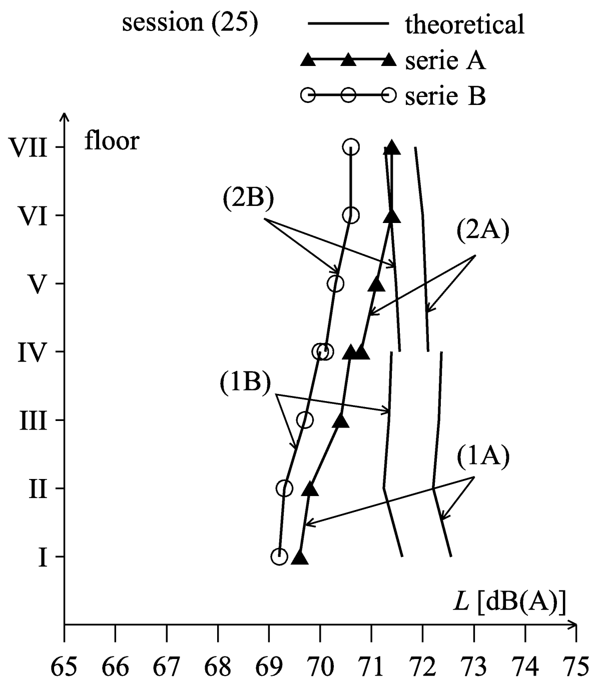
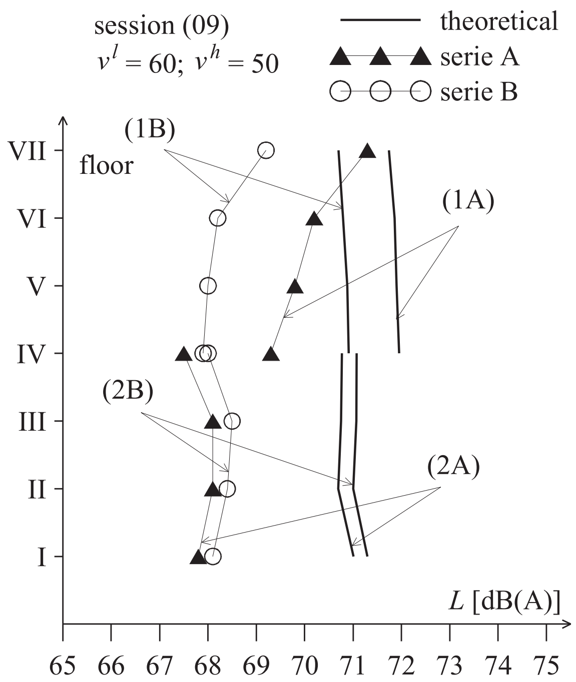


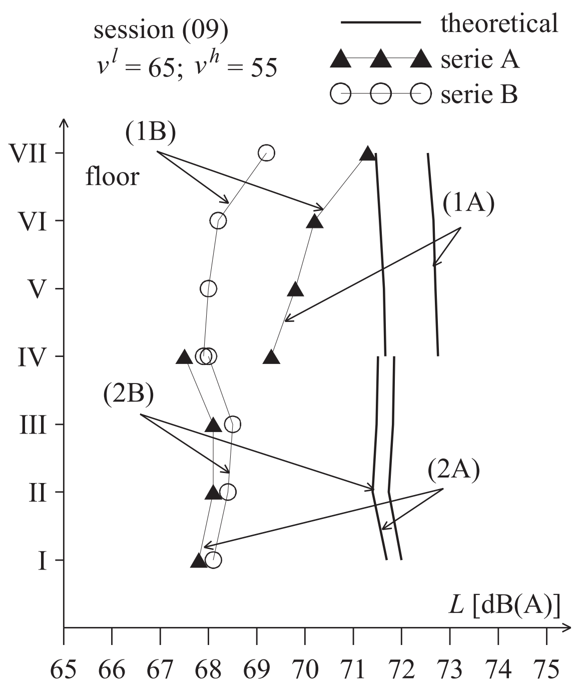
Fig. 7. Comparison of measurement results of the (25)-session with simulation for the simplest urban system model (details in Table 9).

The results of the (09)-session (Fig. 8) are analyzed for rough estimation of vehicle speed (Table 3). Three sets of speeds have been applied: $v_j^l = 60$, $v_j^h = 50$ km/h (Fig. 8a), $v_j^l = 65$, $v_j^h = 55$ km/h (Fig. 8b) and $v_j^l = 55$, $v_j^h = 45$ km/h (Fig. 8c). For the set of the lowest vehicle speeds of $v_j^l = 55$, $v_j^h = 45$ km/h, the agreement with measurements is the best in comparison with the remaining two sets of speeds. The agreement in this case ranges from 2.45 dB(A) on the lowest floors to 0.5 dB(A) on the highest floor. Thus, the observed dependence is the same as that for the (25)-session.

a)


session (09)
$v^l = 60$; $v^h = 50$
theoretical
serie A
serie B
(1B)
floor
(1A)
(2B)
(2A)
VII
VI
V
IV
III
II
I
L [dB(A)]
65 66 67 68 69 70 71 72 73 74 75

b)


session (09)
$v^l = 65$; $v^h = 55$
theoretical
serie A
serie B
(1B)
floor
(1A)
(2B)
(2A)
VII
VI
V
IV
III
II
I
L [dB(A)]
65 66 67 68 69 70 71 72 73 74 75

[Fig. 8a, b]

c)

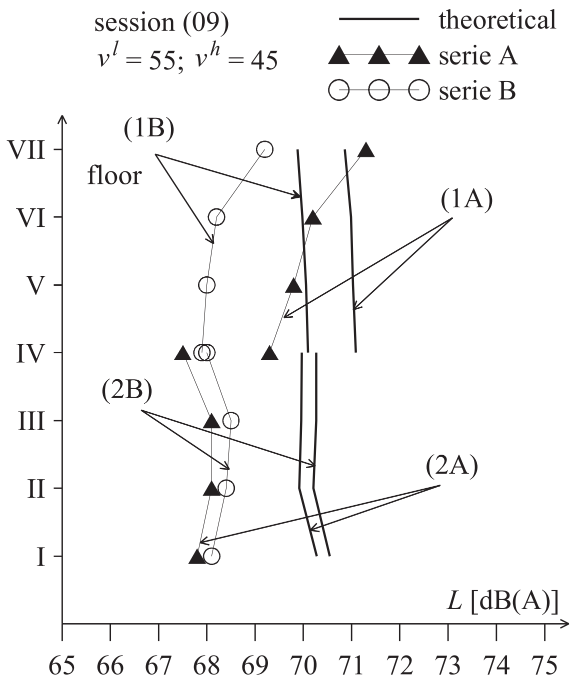


Fig. 8. Comparison of measurement results of the (09)-session with simulation for the simplest urban system model and the real traffic composition of speeds: a) $v_j^l = 60$, $v_j^h = 50$ km/h, b) $v_j^l = 65$, $v_j^h = 55$ km/h, c) $v_j^l = 55$, $v_j^h = 45$ km/h.

3.5. Influence of vehicle noise emission model

The main problem with simulation concerns the overestimation of the sound level on the lower floors, and the experimentally observed effect of the sound level increase with height, instead of the expected decrease due to growing distance from the sources. The observed disagreement in the current investigation of the building with smooth facade seems to be acceptable, as overestimation is only a little larger than the simulation error due to the vehicle average speed estimation. However, in the case of a façade of specific shape with a vertical hollow, the substantial overestimation on the lower floors of 5 dB(A) is observed (Janczur *et al.*, 2009). Therefore, searching for the explanation of the effect is justified.

In city center, traffic is the noise source of the first importance for the sound level spread over building façade. It is mainly composed of passenger cars with some participation of public transportation buses. How large should be the sets of parameters describing the source and specific propagation in densely built-up area, is the question. Due to varying sensitivity of the simulation results to the parameters involved, their number can be limited. Introduced limitations result in a less extended database and make the simulation more efficient in terms of the calculation time.

The propagation model would be sufficiently accurate if the shapes and acoustical feature of objects present in an urban system are accurately modeled. Due to complexity of a road as a noise source, the accuracy of its modeling has to be analyzed in detail. For vehicle streams spread over road lanes, crucial is the description of vehicle noise emission. For the simplest model, a vehicle is represented by a single equivalent point source of the given position above the ground and the power. Below, the justification of the PROP5 simulation program application to the case of the analyzed urban system is presented, together with the results of introduction of more complex road models. Within the framework of complex models, the influence of directivity of noise emission and the equivalent source position above the ground have been tested. Also, the effect of mutual screening by vehicle bodies has been included. Finally, the complex model of four-point sources representing a vehicle has been applied.

The test, performed with use of the PROP5 simulation program, has allowed a definition of the urban system basic model of the half-space with the investigated building. Due to the unimportant influence of the fence on the road's opposite side, its presence has been omitted. For the basic urban system model, dominant interactions are reflections from the ground and the building façade. Thus, the upper reflection order $K = 3$ is proved to be large enough. Moreover, due to the simplicity of the basic model, the source operational parameter – the length of summation step $\Delta x_E = 5$ m – is also proved to be the sufficient one. Therefore, the reason for overestimation has been searched for in the model of noise emission by vehicles.

In the PROP5 simulation, the single omnidirectional equivalent point sources represent vehicles divided into two classes: light and heavy vehicles. Their noise emission dependence on frequency and vehicle speed is taken according to reference (Makarewicz, 1996). The equivalent sources' positions above the ground are taken according to the reference (Glegg, Yoon, 1990). In the present application, the vehicle division into two classes seems to be sufficient; the differences between the results for the standard traffic composition (only light vehicles, higher flow and speed in the inner lanes) and the real traffic are about 1 dB(A) (Fig. 5). In the source power model [Eqs. (12), (13)]

$$L^g_{WA}\left(v^g_j; A^g(f_w), \gamma^g(f_w)\right) = -10\log W_0 + \Delta L_A(f_w) + 10\log\left(A^g(f_w)(v^g_j)^{\gamma^g(f_w)}\right). \tag{11}$$

The values of parameters $A^g(f_w)$, $\gamma^g(f_w)$ (Table 6, Table 7) taken from the literature are decisive. Looking for more adequate source model, it seems unavoidable to check whether the assumed source models, for distinguished vehicle classes, are appropriate for Polish traffic conditions from the viewpoint of the emitted noise spectral dependence, defined by the set of $A^g(f_w)$ coefficients as well as speed dependence, defined by the set of $\gamma^g(f_w)$ coefficients. Since it would require very large and expensive investigation, the adequacy of the MAK2 model has been tested under conditions of the chosen urban systems.

The measurements in the close proximity of a four-lane road, for high traffic density have shown the agreement with the MAK2 model in the range of 1.5 dB(A), while the error due to speed estimation has been of ±1 dB(A) (Walerian *et al.*, in press in Applied Acoustics). Although, the relative sound level spread has shown the specific behavior of the spectral components. The 1 kHz component is almost independent of the observation point height, while the 0.5 kHz component decreases with height and the 2 kHz one increases. Due to the fact that the observed magnitude of the differences in the relative spread of the field components holds in the range of ±1 dB, the MAK2 road model, with the omnidirectional equivalent point sources representing a vehicle, is not challenged in the road proximity. The situation could change after interactions during propagation process, as it is in the case of the building façade with the vertical hollow.

In the previous investigation, the source directivity has been tested for the measured single vehicle pass-by and low flow rate on a road (Walerian *et al.*, 2006a; 2006b). In the simulation, for a light vehicle pass-by, the two positions above ground: 0.5 m and 0.2 m have been taken, each with three different directivity characteristics prevailing the smaller angles above the ground. Likewise the directivity, the lowering of the equivalent source position makes the sound level higher on the lowest floors. It means that they work in opposite direction than the desired one, expected to lower the sound level on the lowest floors. Interesting are the results obtained for traffic of low flow rates and vehicle movement over all the four road lanes. For the relative sound level spread, with the reference value on the lowest floor, the omnidirectional equivalent point source application leads to the fully satisfying agreement between the simulation and measurements. The overestimation in the sound level magnitude of about 2 dB(A) is still observed. The introduction of directivity worsens the agreement. The effect found seems to be due to mutual canceling of the individual features of emission directivity, in the case of vehicles moving simultaneously over all four road lanes during the measurement time interval.

The explanation of the overestimation in the simulation could be the process which blocks the noise emission, e.g. in the case of mutual screening by vehicle bodies. It appears for high flow rates when vehicles are moving in the form of clusters. The recent study has confirmed that taking into account the effect of mutual screening by vehicle bodies, leads to the awaited improvement (Walerian *et al.*, 2009). Yet, the obtained improvement, due to the mutual screening application in the MAK2 model, is not fully satisfying in magnitude which in extreme is of about 0.5 dB(A).

As another attempt to remove disagreement between the simulation and measurement, the MAK2 model, of the single omnidirectional equivalent point sources representing a vehicle class, has been replaced by the HARMONOISE model (Jonasson *et al.*, 2004b). In the HARMONOISE model, a vehicle class is represented by a set of four point sources (Table 5). In the case of light vehicles, rolling noise is represented by the point source at 0.01 m above the ground, emitting

80% of the energy, and the point source at 0.3 m above the ground emitting the rest of energy. For propulsion, 80% of the energy is emitted by the source at 0.3 m above the ground and the rest by the source at 0.01 m above the ground. For heavy vehicles, the different position of the upper source of 0.75 m appears in the set of sources representing the vehicle class. The functional dependence of the source power level on speed and frequency [Eq. (11)] is the same as in the MAK2 model, but the sets of coefficients are different. The relative spectrum [Eq. (2)] of energy emitted by light and heavy vehicles of different speeds in the MAK2 and the HARMONOISE road model are presented in Fig. 9. There is no substantial difference between the spectra. Characteristic is the weak dependence of the spectra on vehicle speed in both cases.

Table 5. Vehicle parameters for standard traffic composition.

<table>
<tr><td colspan="2">MAK2 road model</td><td colspan="2">HARMONOISE road model</td></tr>
<tr><td>source power level* L^l_{WA} v^l [dB(A)]</td><td>position above ground** [m]</td><td>source power level*** L^l_{WA} v^l [dB(A)]</td><td>position above ground*** [m]</td></tr>
<tr><td colspan="2">total</td><td colspan="2">propulsion</td></tr>
<tr><td rowspan="3">$L^l_{WA}\,(60) = 101.70$
$L^l_{WA}\,(70) = 103.73$</td><td rowspan="3">$z^l_0 = 0.50$</td><td>$L^l_{WA}\,(60) = 95.60$
$L^l_{WA}\,(70) = 95.90$</td><td>$z^l_0\,(80\%) = 0.30$
$z^l_0\,(20\%) = 0.01$</td></tr>
<tr><td colspan="2">rolling</td></tr>
<tr><td>$L^l_{WA}\,(60) = 91.50$
$L^l_{WA}\,(70) = 93.60$</td><td>$z^l_0\,(80\%) = 0.01$
$z^l_0\,(20\%) = 0.30$</td></tr>
</table>

*(Makarewicz, 1996), **(Glegg, Yoon, 1990), ***(Jonasson *et al.*, 2004b).

The HARMONOISE model has been applied for the urban system of the current investigation. Comparing the simulation results of the MAK2 model and the HARMONOISE model, the same shape of sound level spread over the building has been found without the experimentally observed growth with height at the lower floors (Figs. 10, 11). Moreover, the HARMONOISE model gives the sound level higher than the MAK2 model. In Fig. 10, the comparison of the simulation results for the standard traffic involves only light vehicles noise emission. The observed difference decreases slightly with height, the highest one of 1.5 dB(A) is on the lowest floors. The comparison of the simulation results for the real traffic composition of the (25)-session involves both vehicle classes (Fig. 11). The difference of 3 dB(A) on the lowest floors also decreases a little with the height. Lowering of the source position means approaching of the source to the reflecting ground. Thus, the lower equivalent source positions in the HARMONOISE model have resulted in larger sound levels than those of the MAK2 model application, what has caused a higher disagreement between the simulation and measurement results.

Summing up the investigation results concerning vehicle noise emission, it has been found that the proper estimation of power levels of the equivalent sources

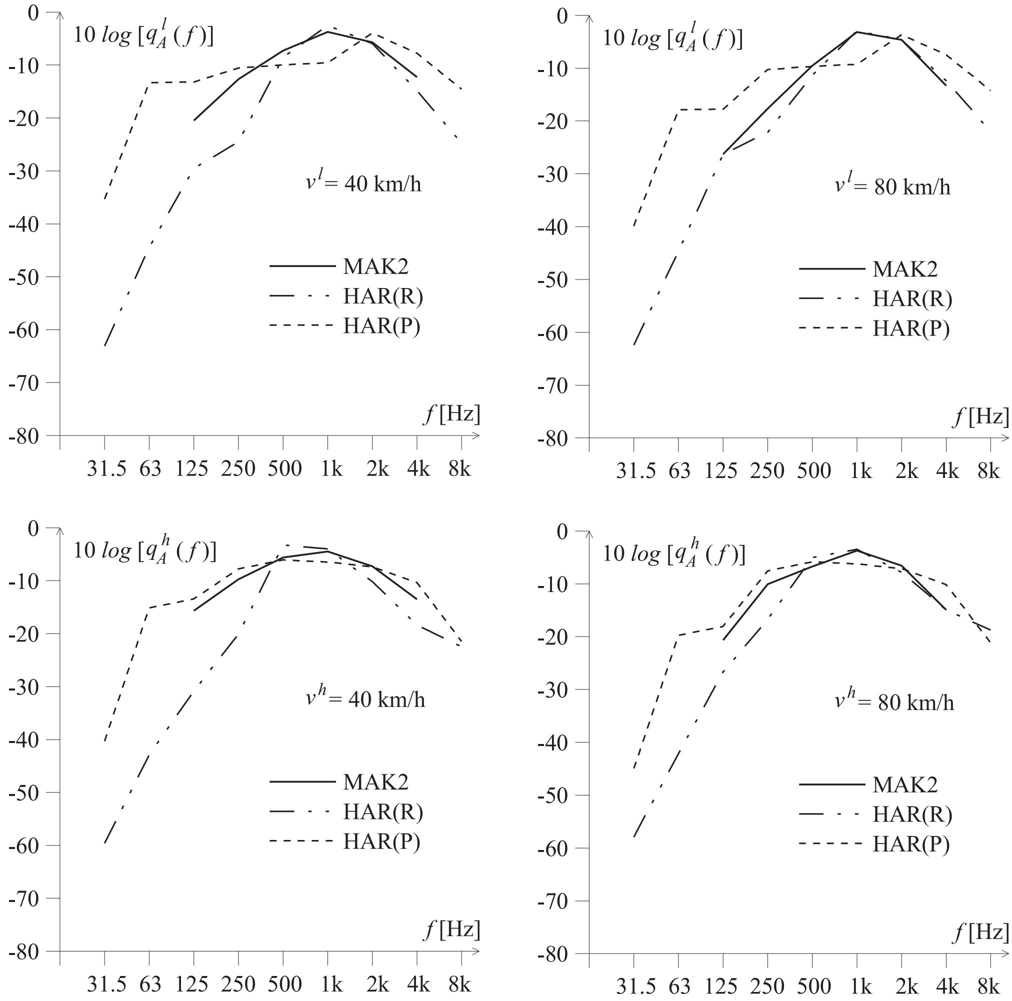


Fig. 9. The source power relative spectrum [Eq.(2)] of energy emitted by light and heavy vehicle of different speed in MAK2 and HARMONOISE road model, with HAR(P) – propulsion noise and HAR(R) – rolling noise.

representing vehicles [Eq. (11)] is mostly responsible for the magnitude of the sound level, observed over a building façade. As traffic can have some local specific features, there is a problem of obtaining the reliable, statistically established parameters describing noise emission by vehicles during city driving. Finding the representative set of the equivalent sources representing the local fleet could provide more accurate sound levels.

For the assumed MAK2 model of two vehicle classes, according to the undertaken investigation, the directivity of vehicle noise emission as well as the lower equivalent source position, have been excluded as the causes of the sound level overestimation on the lowest floors (Walerian *et al.*, 2006a; 2006b). Also, re-

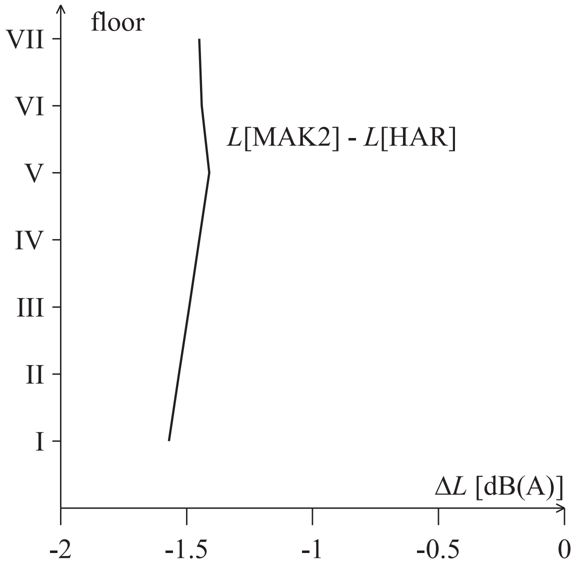


Fig. 10. Comparison of simulation results for the standard traffic and applied MAK2 or HARMONOISE road model.

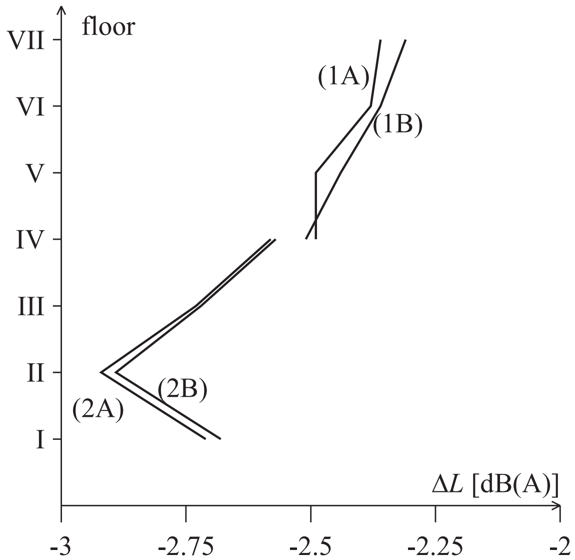


Fig. 11. Comparison of simulation results for real traffic composition of the (25) session and applied MAK2 or HARMONOISE road model.

placement of the MAK2 road model by the HARMONOISE model of the four equivalent sources of lower positions above the ground than in the MAK2 model (Table 5), only enlarges the disagreement with the measurements. Moreover, both models have not reflected the phenomenon of sound level growth with height.

On the other side, despite the measurements close to the road have shown the agreement with the MAK2 model in the range of the error due to vehicle average speed estimation, the behavior of low and high frequency spectral components is observed (Walerian *et al.*, in press in Applied Acoustics). This observation, together with the results of consideration in the MAK2 model of the mutual screening by vehicles bodies, which only slightly improve the agreement with measurements (Walerian *et al.*, 2009), suggests direction of searching for a new noise emission model. In the HARMONOISE model, the source of rolling noise placed near the ground is enriched by higher frequency components, and the source of propulsion noise of higher position is enriched by lower frequency components. Thus, a vehicle representation, combining these two types of sources with mutual screening by vehicle bodies, looks promising for the road model reflecting the acoustic field feature observed for the lowest floors.

4. Conclusions

The undertaken investigation has been carried out with two goals in mind. First of all, the analyzed urban system model is searched for as a base for further investigation of possibilities to improve the acoustical climate conditions. Simultaneously, the adequate model of a road as noise source is looked for.

The road model searched for as a noise source, has to remove the overestimation of the sound level on the lower floors, which becomes substantial in the case of a building of a specific shape with a vertical hollow. The model, apart from removing the sound level overestimation, has to give the sound level spread with some increase of height in the range of the lowest floors that also appears in a building of a smooth façade. Due to complexity of noise emission by the road, the second goal has not been obtained up to now. Only the direction of further investigation has been proposed.

Despite this, application of the simulation program PROP5 with the MAK2 road model for the case under investigation of the building of the smooth façade, seems acceptable since the prediction overcomes only a little the simulation error due to the vehicle average speed estimation. Thus, the defined basic model of the urban system under the current investigation, despite being not fully satisfying on the lowest floors, can be applied for investigation of the acoustic climate improvement. The results of this investigation will be presented in the Part II of this paper.

Appendix A.

The source spectral power level is defined as below (Makarewicz, 1996)

$$\begin{aligned} L^g_{WA}(v^g_j, f_w) &= 10\log\frac{W^g_A(v^g_j, f_w)}{W_0} = 10\log\frac{\alpha_A(f_w)P^g(v^g_j, f_w)}{W_0} \\ &= -10\log W_0 + \Delta L_A(f_w) + 10\log P^g(v^g_j, f_w), \end{aligned} \tag{12}$$

$$P^g(v_j^g, f_w) = A^g(f_w)(v_j^g)^{\gamma^g(f_w)}, \tag{13}$$

with the appropriate values of the parameters $A^l(f_w)$, $\gamma^l(f_w)$ for light and $A^h(f_w)$, $\gamma^h(f_w)$ for heavy vehicles given in Tables 6–8. Thus, the source power level $L_{WA}^g(v_j^g)$ and relative power spectrum $q_A^g(v_j^g, f_w)$ [Eq. (1), Eq. (2)] are:

$$L_{WA}^g(v_j^g) = 10\log\frac{\sum\limits_{w=1}^{6} 10^{0.1L_{WA}^g(v_j^g,f_w)}}{W_0} = 10\log\frac{10^{0.1L_{WA}^g(v_j^g)}}{W_0}, \tag{14}$$

$$\begin{aligned} q_A^g(v_j^g, f_w) &= \frac{W_A^g(v_j^g, f_w)}{\sum\limits_{w=1}^{6} W_A^g(v_j^g, f_w)} = \frac{W_0 10^{0.1L_{WA}^g(v_j^g,f_w)}}{W_0\sum\limits_{w=1}^{6} 10^{0.1L_{WA}^g(v_j^g,f_w)}} \\ &= \frac{10^{0.1L_{WA}^g(v_j^g,f_w)}}{10^{0.1L_{WA}^g(v_j^g)}} = \frac{\alpha_A(f_w)A^g(f_w)(v_j^g)^{\gamma^g(f_w)}}{\sum\limits_{w=1}^{6}\alpha_A(f_w)A^g(f_w)(v_j^g)^{\gamma^g(f_w)}}. \end{aligned} \tag{15}$$

Table 6. Source model parameters [Eqs. (12), (13)] for light vehicles $g = l$.

f_w [Hz]	$A^l(f_w)$	$\gamma^l(f_w)$
125	$3.31 \cdot 10^{-5}$	1.05
250	$1.48 \cdot 10^{-5}$	1.32
500	$4.13 \cdot 10^{-7}$	2.25
1000	$1.64 \cdot 10^{-8}$	3.16
2000	$4.08 \cdot 10^{-9}$	3.35
4000	$1.28 \cdot 10^{-8}$	2.63

Table 7. Source model parameters [Eqs. (12), (13)] for heavy vehicles $g = h$.

f_w [Hz]	$A^h(f_w)$	$\gamma^h(f_w)$
125	$5.93 \cdot 10^{-5}$	1.68
250	$1.47 \cdot 10^{-7}$	3.24
500	$4.13 \cdot 10^{-7}$	2.96
1000	$1.65 \cdot 10^{-8}$	3.60
2000	$7.40 \cdot 10^{-9}$	3.58
4000	$2.32 \cdot 10^{-8}$	2.88

Table 8. A-weighting correction.

f_w [Hz]	$10 \log \alpha_A(f_w) = \Delta L_A(f_w)$
125	−16
250	−9
500	−3
1000	0
2000	+1
4000	+1

Appendix B.

Detailed results of the (25) session of measurements.

Table 9. Comparison of calculated and measured sound levels.

floor	point	theoretical for basic urban system (Table 1, S(1))					measured				theoretical versus measured
		real composition (Table 2, $J = 6$)			standard composition (Table 4, $J = 6$)						
		series	level [dB(A)]	ΔL [Eq.(11)] [dB(A)]	level [dB(A)]	ΔL [Eq.(11)] [dB(A)]	level [dB(A)]	$\Delta L = L_A - L_B$	ΔL [Eq.(11)] [dB(A)]		
VII	P_{11}	2A	71.86 ± 0.91	−0.25	71.86	−0.26	71.4	0.8	0.60		0.46
		2B	71.27 ± 0.91	−0.28			70.6		0.50		0.67
VI	P_{12}	2A	72.00 ± 0.91	−0.11	71.99	−0.13	71.4	0.8	0.60		0.60
		2B	71.38 ± 0.90	−0.17			70.6		0.50		0.78
V	P_{13}	2A	72.06 ± 0.91	−0.05	72.09	−0.03	71.1	0.8	0.30		0.96
		2B	71.48 ± 0.90	−0.07			70.3		0.20		1.18
IV	P_{14}	2A	72.11 ± 0.91		72.12		70.8	0.7			1.31
		2B	71.55 ± 0.90				70.1				1.45
IV	P_{21}	3A	72.37 ± 0.91	−0.18	72.12	−0.19	70.6	0.6	1.00		1.77
		3B	71.39 ± 0.90	−0.21			70.0		0.80		1.39
III	P_{22}	3A	72.32 ± 0.90	−0.23	72.03	−0.28	70.4	0.7	0.80		1.92
		3B	71.34 ± 0.89	−0.26			69.7		0.50		1.64
II	P_{23}	3A	72.21 ± 0.88	−0.34	71.90	−0.41	69.8	0.5	0.20		2.41
		3B	71.24 ± 0.86	−0.36			69.3		0.10		1.94
I	P_{24}	3A	72.55 ± 0.85		72.31		69.6	0.4			2.95
		3B	71.60 ± 0.83				69.2				2.40

Simulation error due to speed estimation accuracy 10%.

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