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Possible Improvement of Acoustical Climate
Part II: Possible Solutions

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In the paper, the simulation PROP5 program with the road model defined as a noise source and road surroundings model, is used to predict the efficiency of noise protecting means for the chosen building. The appropriate models of verified accuracy have been chosen by comparison of the simulation results with field measurements (Walerian *et al.*, 2010). Here, using the pre-tested simulation program, the possibility of acoustic climate improvement has been analyzed in the ranges of practical variations of the input parameters. The road parameters: its geometry (number of lanes and their positions) and traffic structure over lanes (vehicle flow rates and their average speeds) have been taken under consideration as changeable parameters, that could be corrected to obtain acoustical climate improvement. Moreover, an acoustical screen designing has been considered. The screen efficiency has been evaluated under conditions defined by the input parameters of the road and its surroundings.

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

1. Introduction

In Part I of the paper, after carrying out the field measurement of the sound level over the building façade, the urban system model, appropriate for application in the simulation program PROP5, has been established (Walerian *et al.*, 2010). Here, the program is used for analysis of the acoustical field created within the urban system, and the possibility of its variation resulting in acoustical comfort improvements.

Defining as a goal the acoustical comfort, the appropriate tools for its obtaining have to be used. They are simulation programs that allow prediction and control of noise spread over a building façade by variation of source and environment parameters. Noise abatement means could be divided into two groups: some limit noise emission and others, by modifying the propagation, protect the limited space of the higher acoustical comfort requirements. The available software predicts the sound level at a roadside due to the assumed traffic modeling (Steele, 2001). In this way, they offer tools for observing the noise emission. The programs, which can be used to modify the noise propagation throughout an urban area next to a noisy road, are less popular. Due to complexity of a source such as a road and complexity of propagation in the half-space, with obstacles of different shapes and different acoustical features of their surfaces, the problem is doubly difficult.

Limiting source emission seems to be the most efficient means. In the case of a road emission it is not so simple. The lowered limit of noise emission by a vehicle from 84 to 74 dB(A), in extend since 1966 to 1999, has not resulted in the same lowering of the sound level in built-up area where traffic is a dominating noise source (Grossmann, Ehinger, 1997; Calixto *et al.*, 2008). It is mainly due to growing vehicle number. As a stop in the growing vehicle number cannot be expected, the other means of noise abatement have to be additionally introduced. In limiting noise emission, the traffic organization can be helpful. Moreover, corrections of propagation path can protect some space where acoustical comfort is required. Yet, the means of noise abatement, correcting propagation, act differently in different parts of space, for some parts they can be protectors, for other amplifiers. Thus, their predicted effectiveness, evaluated without consideration of interactions with the whole road surroundings, could be misleading. This is the case of a screen application when the surroundings is not taken into account (Walerian *et al.*, 1999a, 2003; Tang, Li, 2001; Li, Tang, 2003).

Apart from a source silencing and deep shadow creation, the other protecting means could have effectiveness of few decibels order. Thus, the solutions providing acoustical climate improvements should be built upon the detailed description of emission and propagation. Moreover, only a complex solution can provide a noticeable improvement in the subjectively assessed acoustical comfort. The requirements are fulfilled by the here-used software as well as by the HARMONOISE method (Jonasson *et al.*, 2004), prepared to replace the actually used in Europe prediction methods: Nord2000. ISO 9613-2, SRM2, NMPB. The introduced prediction methods undergo field verification (Gołębiewski, Makarewicz, 2009).

The simulation program PROP5 used here belongs to the family of simulation programs that are based on the environmental noise model, which has a source model and propagation model as independent parts (Walerian, 1995; Walerian, Janczur, 1998; Walerian *et al.*, 1999b). The propagation space is a half-space with obstacles whose shapes could be modeled by a set of panels of defined acoustical properties, joined at proper angles. In the propagation model for an omnidirectional point source, a wave undergoes a chain of interactions: transmissions, reflections and diffractions. The pressures of the waves reaching the observation point by different paths are summed. The propagation model, where diffraction is described with acceptable accuracy for distances of a wavelength order (Walerian *et al.*, 2002), has been verified in the scale model experiment (Janczur, 1990; Sakurai *et al.*, 1990). Next, a road model as a noise source, built of point sources, has been introduced (Walerian *et al.*, 2001a, 2001b; Janczur *et al.*, 2001a, 2001b).

In the general environmental noise model, traffic can be divided into an arbitrary number of vehicle classes. Any arbitrary number of lanes on a road is allowed. A vehicle representing the class can be replaced by a set of arbitrary number of point sources, each characterized by its position and emission power with its directivity characteristics. All the parameters can be a function of frequency and vehicle speed. A vehicle movement is represented by the sequence of discrete positions along a vehicle route, what results in the sound exposure calculated as a summation with an adjustable step.

The complex urban system and the complex noise source – road traffic – result in a situation when the observed total sound level depends on a pretty large set of parameters. By adequate modeling of the urban system, the number of input parameters could be limited to these for which the sound level is the most sensitive. In this way, the simulation program can be prepared in the form, which could be efficient in terms of calculating time and the required database. To establish the validation range, the prepared software has been tested in comparison with field measurements. Dealing with the sound level spread over building façade in city center, where the local traffic is mostly composed of passenger cars with participation of public transportation buses, representative sets of the equivalent sources for these two classes of vehicles are of interest. For these two classes of vehicles: light and heavy ones, the single omnidirectional equivalent point sources, one for each class, have been assumed. Based on published data, the MAK2 road model has been introduced. In the PART I of the paper (Walerian *et al.*, 2010), assuming the MAK2 road model, the basic model of the analyzed urban system has been established. By comparison with the field measurement, the basic urban system of a half-plane with the investigated building has been found to be enough accurate to predict the sound level over the building façade.

Here, in Sec. 2, the simulation program architecture is presented with the definitions of input parameters, the variation of which could result in the acoustical climate improvement. After a general analysis of the possible means of noise abatement, a plane screen application is analyzed (Sec. 3). The efficiency of the two screens of different heights is presented in conditions of the basic urban system model. The influence of the fence on the opposite road side, omitted in the basic model, is considered and its effect is analyzed. In Sec. 4, the screen efficiencies are presented for the noise indicator L_{den}.

2. Sound field simulation

The fundamental element of road as a noise source is a moving vehicle. The simulation program PROP5 used here contains the MAK2 model for a road as the noise source (Makarewicz, 1996; Glegg, Yoon, 1990). The single omnidirectional equivalent point sources, representing the class of light (l) and heavy (h) vehicles, have been defined by statistically estimated (Walerian *et al.*, 2010):

- $L_{WA}^{l(h)}\left(v_j^{l(h)}\right)$ – set of source power levels,
- $q_A^{l(h)}(f_w)$ – set of reduced source power spectra,
- $z_0^{l(h)}$ – set of source positions above ground,

which characterize the moving fleet. Other source parameters determining road geometry stem from the analyzed urban system geometry and the assumed method of the sound exposure calculation:

- J – number of lanes,
- $\{y_{0j}\}$ – set of lane positions for the assumed x-axis parallel to a road segment,
- Δx_E – step parametrizing a vehicle x-coordinate along its route (Fig. 1).

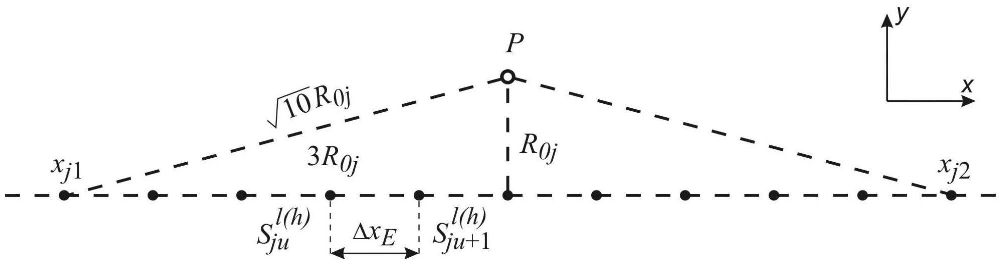

Fig. 1. Discrete vehicle positions along a road during its pass-by.

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

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

The time-average sound level of T interval due to a road of J lanes, on which move light (l) and heavy (h) vehicles, is given by:

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

The total sound level [Eq. (1)] is the result of summation over the road lanes and the two distinguished classes of vehicles. The contribution to the time-average sound level due to the equivalent source representing light or heavy vehicle moving over the j-lane is given by:

$$L_{Aeq\,j}^{\;l(h)}\left(v_j^{l(h)},\mathcal{N}_j^{l(h)}\right) = L_{WA}^{l(h)}\left(v_j^{l(h)}\right) + 10\log\frac{\Delta x_E}{\Delta x_j^{l(h)}\left(v_j^{l(h)},\mathcal{N}_j^{l(h)}\right)} + L_j^{l(h)}\left(q_A^{l(h)}(v_j^{l(h)},f_w),z_0^{l(h)},U_j,P\right). \tag{2}$$

The first term represents the equivalent source power level, the second – ratio of the step in the emitted energy summation Δx_E (Fig. 1) and spacing:

$$\Delta x_j^{l(h)}\left(v_j^{l(h)},\mathcal{N}_j^{l(h)}\right) = v_j^{l(h)}\Big/\mathcal{N}_j^{l(h)}, \tag{3}$$

which depends on traffic organization defined by the traffic composition: vehicle flow rates $\mathcal{N}_j^{l(h)}$ and their average speeds $v_j^{l(h)}$. The last term in Eq. (2):

$$L_j^{l(h)}\left(q_A^{l(h)}\left(v_j^{l(h)},f_w\right),z_0^{l(h)},U_j,P\right) = 10\ \log\left(\frac{1}{4\pi}\sum_{w=1}^{10} q_A^{l(h)}\left(v_j^{l(h)},f_w\right),\ w^{l(h)}\left(f_w,z_0^{l(h)},U_j\left(x_E\right),P\right)\right), \tag{4}$$

reflects the propagation process defined by the system transfer function. The sound level $L_j^{l(h)}\left(q_A^{l(h)}\left(v_j^{l(h)},f_w\right),z_0^{l(h)},U_j,P\right)$ is the level due to the set of U_j point sources, representing a vehicle movement along the j-lane (sound exposure level). The average acoustical energy in the w-octave-band

$$w^g\left(f_w,z_0^{l(h)},U_j\left(\Delta x_E\right),P\right) = w^g\left(N,\{\mathbf{R}\,(n)\},\{R\,(n)\},\{T\,(n)\},\mathbf{R}\,(P),\left\{\mathbf{R}\left(S_{ju}^g\right)\right\},K,\Delta x_E,f_w,z_0^{l(h)}\right) \tag{5}$$

results from an urban system transfer function of the following parameters:

- K – upper order of interaction,
- N – number of panels creating propagation space as a half-space with obstacles,
- $\{\mathbf{R}\,(n)\}$ – 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,
- $\left\{\mathbf{R}\left(S_{ju}^{l(h)}\right)\right\}$ – set of vectors describing vehicles positions on lanes (Fig. 1).

The above parameters present in the urban transfer function, together with source parameters, create a list of parameters, whose variation can be used for lowering of the sound level over a building façade, resulting in acoustical climate improvement.

3. Possible means of noise abatement

The possibility of acoustical comfort improvement will be analyzed with use of the simulation program PROP5. To perform simulation, the urban system model has to be defined what means the establishment of the list of appropriate input parameters (Sec. 2). These parameters could be modified to achieve the assumed goal of the lower sound level in the chosen area. The simulated sound level is the function of the input parameters belonging to two groups: some describe road surroundings, others the road itself. Surroundings description concerns the number of objects, their position, shape and surface reflection coefficients. The description is completed by the number of reflections K. The road as a noise source is described by the number of lanes, their position and traffic composition over them, and the model of noise emission by a vehicle. The completing parameter is the length of summation step Δx_E (Fig. 1) in calculation of the energy emitted due to vehicle movement (sound exposure).

Possibilities of changing the urban system geometry, concerning the road as well as its surroundings, depend on its status. The whole system could be at the stage of designing or only its existing part is an object of redesigning. Limitation of noise emission by the road could be obtained as a result of long-term policy. In the applied MAK2 ($G = 2$) road model, noise emission by a vehicle is represented by the single equivalent source. The equivalent source power levels $L_{WA}^{l(h)}\left(v_j^{l(h)}\right)$, their spectra $q_A^{l(h)}(f_w)$ (Makarewicz, 1996) and source positions above ground $z_0^{l(h)}$ (Glegg, Yoon, 1990) are permanently loaded in the MAK2 road model. These parameters, characterizing the moving fleet, could be replaced by the current ones when the appropriate changes due to the realized noise abatement policy would be observed. The parameters describing the road geometry: number of lanes J and their positions could undergo variation only as a part of the whole urban system. The parameters of traffic composition, stemming from vehicle flow rates $\mathcal{N}_j^{l(h)}$ and their average speeds $v_j^{l(h)}$ that result in the spacing along lanes $\Delta x_j^{l(h)}$ [Eq. (3)], depend on traffic organization. Possible changes of traffic organization should concern the whole traffic in the city. Despite this, for the defined urban system where protection of the chosen building is analyzed, it is worthwhile to observe the sound level dependence on the traffic composition over lanes and single road lane participation in the total sound level. This would be useful in designing the modification in the road surroundings aiming at lowering of the sound level over the chosen building façade.

For the defined road model, modification in its surroundings can be considered. The road surroundings model defines the propagation space being a half-space with obstacles. The appropriate variations in the road surroundings could yield the sound level lowering in the space, which requires special protection. Corrections in the number of objects, their shapes, surface acoustical features and positions in relation to the road, are reflected in the urban system transfer function [Eq. (5)]. When the urban system is at the stage of designing, the changes in the distance from the road or position to the road axis are possible. A building can be placed in the second row, behind the other building of lower requirement for acoustical comfort. In this way, the building could be situated at a larger distance from the road and could be partly screened by the building in the first row. Moreover, a building position in relation to the road axis and other obstacle positions can also be changed. All these solutions could result in an improvement of acoustical climate (Walerian, Janczur, 1998).

3.1. The model of the analyzed urban system

In the Part I of the paper, the real building has been an object of investigation (Walerian *et al.*, 2010). The measurement of the sound level has been carried out over the building façade, facing the noisy six-lane road. The positions of observation points 1 m from the façade and 1.5 m above each floor of interest, are taken in accordance with the ISO recommendation (ISO, 1996). By comparison of the simulation results with the measurement results, the assumed urban system model has been verified. The criterion of the modeling accuracy is the influence of omitted objects, which has to be below the simulation error due to the vehicle speed estimation.

In the PROP5 program with the assumed MAK2 road model, for the loaded real traffic composition, the length of summation step $\Delta x_E = 5$ m (determining the number of considered sources over lane segments) is short enough for the assumed accuracy (Walerian, Janczur, 1998; Walerian *et al.*, 2001b; Janczur *et al.*, 2009). The assumed urban system model and the observation point positions are presented in Fig. 2 and Fig. 3, respectively. Since, in the case under consideration, the buildings neighboring the measurement site are distant, for the assumed accuracy, the road surroundings model simplified to the open half-space where propagation is modified only by the presence of the investigated building. In this basic urban system model, the presence of a long fence on the other side of the road has been omitted. In the interaction description, the upper number of reflections $K = 3$ is assumed, which has been found to be adequate for distances typical in cities, appearance of parallel reflecting planes including (Walerian *et al.*, 2001a; Janczur *et al.*, 2009. Moreover, the reflection coefficients for all the surfaces are assumed to be real, equal to 0.9 (Table 1). The obtained agreement with the measurements of this basic model S(1) with the MAK2 road model is the worst on the lowest floor. The resulting difference with the measurements of 2.5 dB(A) diminishes with height approaching 0.5 dB(A) on the highest floor (Walerian *et al.*, 2010).

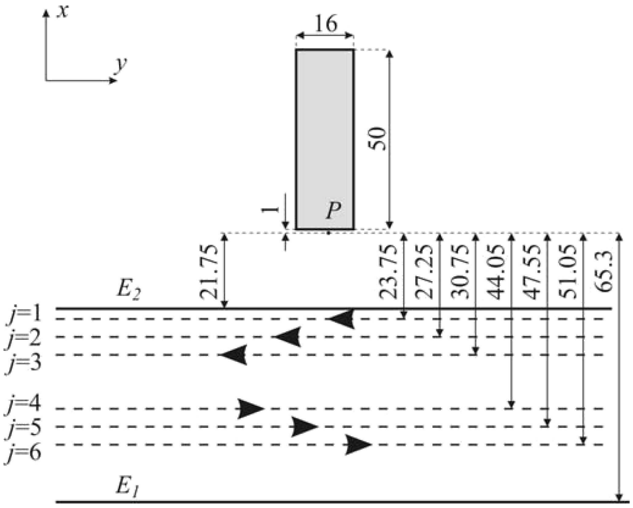

Fig. 2. A horizontal sketch of an urban situation (dimensions in meters).

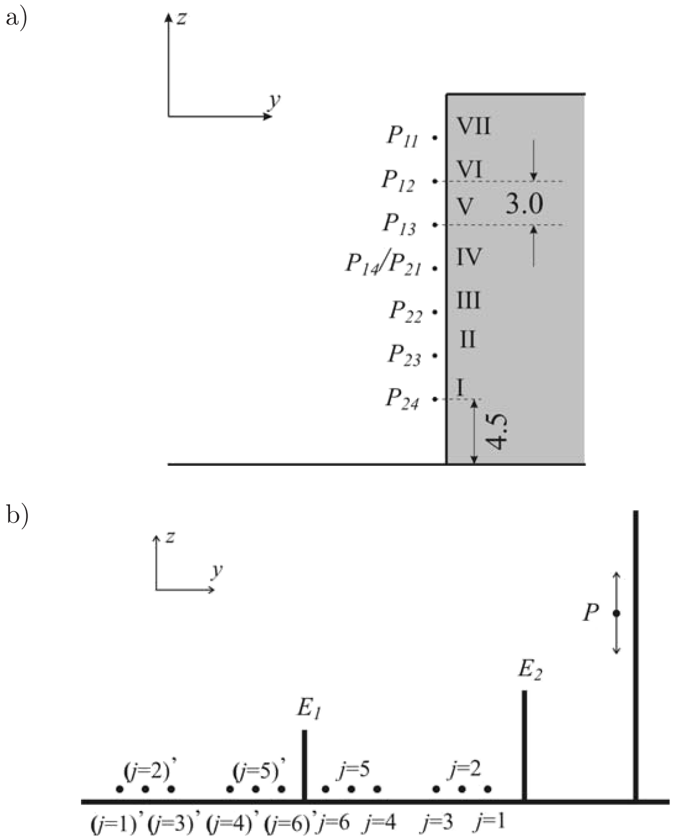

Fig. 3. A vertical sketch of an urban situation with observation point positions (dimensions in meters) (a) and fence E_1 and protecting screen E_2 (b).

Table 1. Parameters of the urban system model.

<table>
<tr><th rowspan="2">model</th><th rowspan="2">objects on the ground</th><th colspan="2">reflection coefficient R</th><th rowspan="2">reflection number</th><th rowspan="2">road lanes number</th><th rowspan="2">summation step Δx_E [m]</th><th rowspan="2">point distance from façade [m]</th></tr>
<tr><th>ground</th><th>walls, fence, screen</th></tr>
<tr><td>S(1)</td><td>building</td><td rowspan="4">0.9</td><td rowspan="4">0.9</td><td rowspan="4">K=3</td><td rowspan="4">$j = 1, 2, 3, 4, 5, 6$ $(J = \sum j = 6)$</td><td rowspan="4">5.0</td><td rowspan="4">1.0</td></tr>
<tr><td>S(2)</td><td>building and fence (E_1)</td></tr>
<tr><td>S(3)</td><td>building with screen (E_2)</td></tr>
<tr><td>S(4)</td><td>building with screen (E_2) and fence (E_1)</td></tr>
</table>

For further investigation, the source description is simplified by replacement of the real traffic composition by the standard traffic composition. In the standard traffic composition only the dominating light vehicle movement is considered, with the higher flow rate and speed over inner lanes ($N^l_{j=1.6} = 400$ veh./h, $v^l_{j=1.6} = 60$ km/h, $N^l_{j=2,3,4,5} = 600$ veh./h, $v^l_{j=2,3,4,5} = 70$ km/h). The influence of the replacement on the simulation results is in the range of ±1 dB(A), and holds in the range of the required accuracy of the urban system modeling, related to the simulation error due to vehicle speed estimation (Walerian *et al.*, 2010).

Below, using the PROP5 simulation program with the assumed urban system model, the analysis of possible acoustical climate improvement is undertaken. The shares of the road lanes in the total acoustical field are analyzed. Next, the effect of variation of propagation space in a form of protective screen is tested.

3.2. Possible variation in sound field due to source parameters changes

Possible changes of traffic organization should be of general character and should concern the whole traffic in the city. The analysis of these possibilities is above the scope of this paper. Yet, in the analyzed case, the knowledge of the sound level dependence on the traffic composition over lanes and single road lane participation in the total sound level, is useful for protecting screen designing.

For standard traffic composition, the sound level due to the single lane and the sound level due to the road of growing number of lanes are presented in Fig. 4. The sound levels are calculated for the basic urban system model S(1) (Table 1) without the fence on the other side of the road and the urban system model S(2), where the previously omitted fence is considered. Due to the distance to the observation points and the large flow rate, the share of the second lane ($j = 2$) in

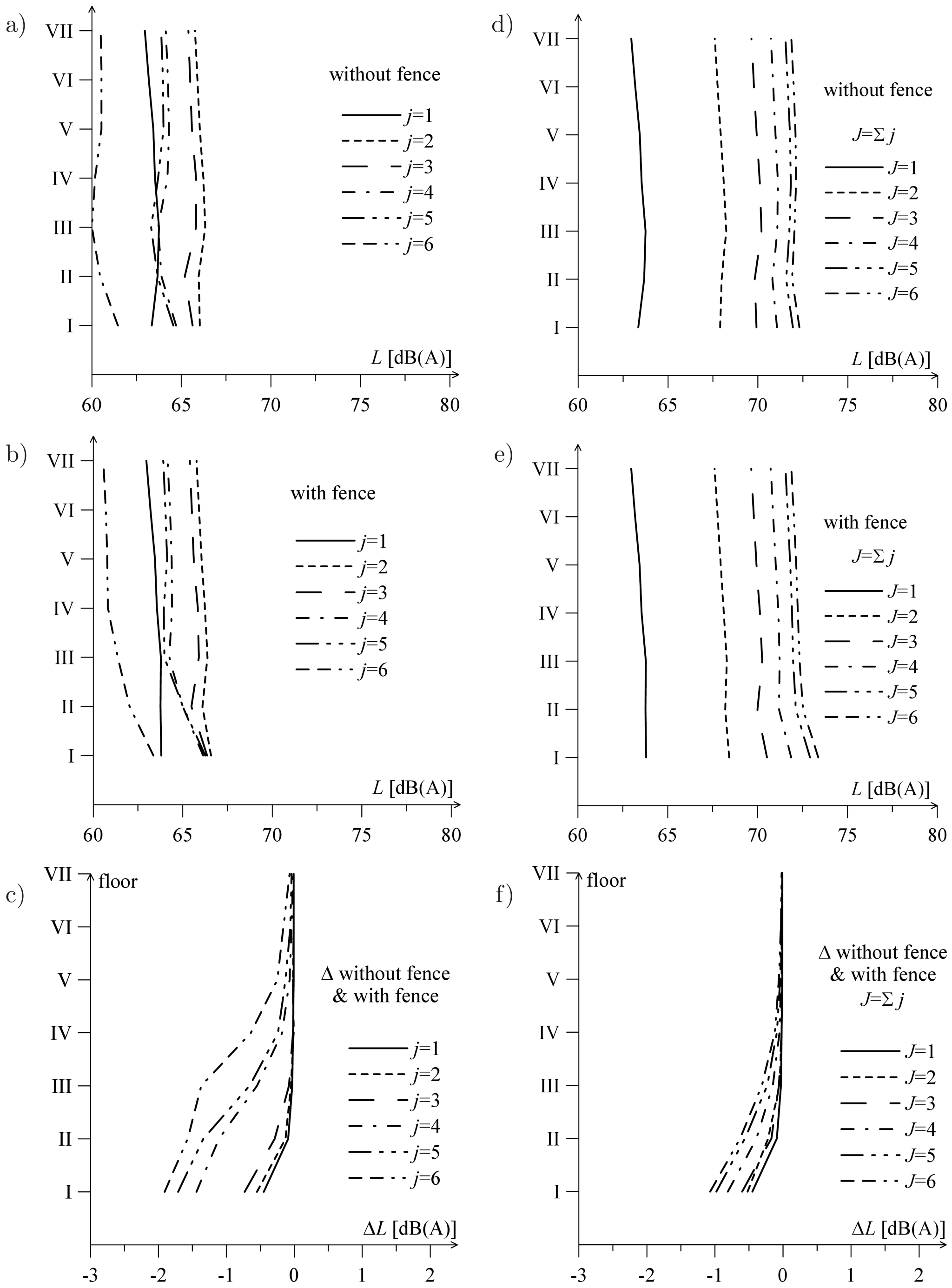

Fig. 4. For standard traffic composition the sound level due to the single lane: a) without a fence on the opposite road side, b) with a fence, c) the effect of a fence, and the sound level due to road of growing number of lanes: d) without a fence, e) with a fence, f) the effect of a fence.

the total sound level is the largest regardless of the fence presence. The order of participation in the total sound level is the following. The inner lanes of higher flow rates $j = 2$, 3 and $j = 4$, 5 give larger shares than the outer lanes $j = 1$, 6 of lower flow rates. When the sound level due to the road of growing number of lanes is observed, it can be noticed that the subsequent addition of a lane results in diminishing growth of the sound level. It is a consequence of the fact that the energy emitted by the subsequent lane, being at growing distance from the observation points, is added to the larger energy of the previously considered lanes.

Comparing the results obtained for the basic urban system model S(1) with the results of the S(2) model with the fence on the other side of the road, we find the effect of presence of the fence. It is the largest at the lowest floor and the lane nearest to the fence. For the nearest lane ($j = 6$) at the lowest floor, it reaches 1.91 dB(A) and decreases with height above the ground. The sound level due to the road of growing number of lanes, when the added lanes approach the fence, is less sensible to the fence presence than it is in the case of single lanes. For the all six lanes ($J = 6$), the extreme effect on the lowest floor equals 1.07 dB(A).

The obtained information of the sound level spread over the building façade shows the direction of further investigation and confirms the general rules. The most effective in the total sound level reduction is lowering of the highest component. Besides, all the performed tests have confirmed the fact that the physics of phenomenon of propagation in the half-space, where propagation is modified by the building presence and the fence on the opposite side, is described properly in accordance with expectation.

3.3. Possible variation in sound field due to changes in a road surroundings

For the analyzed urban system with the defined traffic composition and the existing building, the changes in the distance from the road or position to the road axis are impossible. As there is relatively large space between the building and the road, the possible means of noise abatement could be a plane screen.

The screen efficiency is predicted for the standard traffic composition. Applying the simulation program PROP5, the influence of the factors changing propagation in the road surroundings is observed. In Eq. (2), giving the contribution to the sound level due to vehicle moving in the j-lane, the first two terms remain unchanged while the change in surroundings is reflected by variations of the third term. To obtain the total sound level after modification in the road surroundings, the summation over lanes has to be performed [Eq. (1)], while the summation over vehicle classes disappears since in the standard traffic composition, only light vehicles are considered.

For the assumed basic urban system model S(1) (Table 1), the building is modeled as a shoe-box and only its side walls are considered, since for the sources position near the ground only sidewalls participate in propagation. Thus, in the basic urban system model of the building placed on the ground, there are $N = 5$ panels. The protecting screen application in the S(3) model results in $N = 6$ panels appearance. Consideration of the fence on the road opposite side in the S(2) model without screen, means appearance of $N = 6$ panels. After the screen application in the S(4) model with the fence, the present panels number is $N = 7$. The detailed analysis of the screen efficiency under conditions of these road surroundings models, is presented in the following section.

3.4. Efficiency of a plane screen application

The screen efficiency is defined as the difference between the sound level [Eq. (1)] at the observation point in the urban system without and with a screen. To the set of the input parameters, defining the urban system model, the screen position, its height and the kind of its surface and insulation properties have to be added.

The screen introduction, apart from the geometrical shadow creation, causes the additional interactions with existing objects. First of all, it concerns the façade of protected building and the screen surface. Other existing objects, as the fence on the other side of the road, which has been omitted in the basic model of the road surroundings, also participate in interactions. Before the screen application, the largest effect of the fence presence of 1.91 dB(A) appears at the lowest floor for the sixth lane ($j = 6$), the one nearest to the fence, while for the whole six-lane road it equals 1.07 dB(A) (Fig. 4). The protecting screen application could change the situation and the fence could appear important for the created acoustical field. For this reason, the screen efficiency will be calculated for the urban system models S(1), S(3) without the fence and the S(2), S(4) models containing the fence (Table 1). In current analysis, the fence and the screen have been assumed in the form of infinitely long panels, placed perpendicularly to the ground and parallel to the road. The protecting screen is placed in front of the building near the road curb (Fig. 2, Fig. 3). Both the screen and the fence are fully isolating and have reflection coefficients $R = 0.9$.

As the road consists of six lanes, it seems reasonable to take as the first option the screen height, which provides protection for the whole façade against the lane giving the largest share to the total field. For the $j = 2$ lane of the largest share, the 5 m screen is the one, which creates the geometrical shadow of the boundary at the 25 m height, equal to the building height (Table 3). Thus, protection for the whole façade against the second lane has been provided. For comparison, the results of the 3 m screen are also presented. The 3 m screen is taken under consideration as its erection is technically easier than the erection of the 5 m screen and, in consequence, it is cheaper.

For standard traffic composition, the sound levels due to the single lane after the screens application are presented in Fig. 5. The sound levels are calculated for the S(3) urban system model with the protecting screen without the fence on the opposite road side, and the S(4) urban system model where in addition to

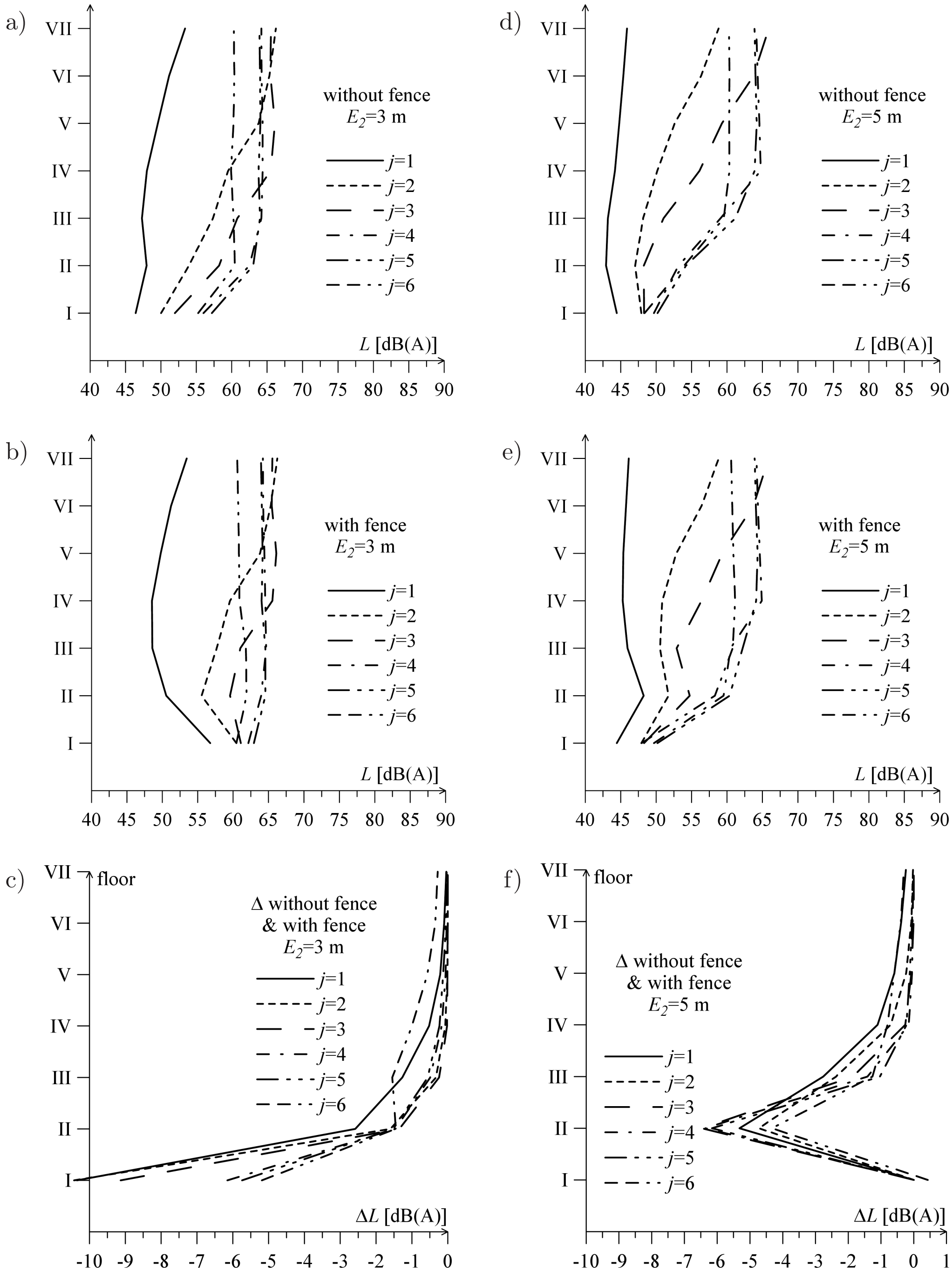

Fig. 5. For standard traffic composition the sound level due to the single lane after $E_2 = 3$ m screen introduction: a) without a fence, b) with a fence, c) the effect of a fence; and after $E_2 = 5$ m screen introduction: d) without a fence, e) with a fence, f) the effect of a fence.

the screen, the fence also is considered (Table 1). Due to the screen action, the share of the first lane ($j = 1$) in the total sound level is the lowest, regardless of the fence presence. For comparison, in the field before the screen application, the lowest share has been due to the sixth lane (Fig. 4). The sound level reduction due to screening is observed in the shadow zone, which is the largest for the lanes closest to the screen and decreases with the lane growing distance from the screen. Like before the screen introduction (Fig. 4), the effect of the fence presence appears on the lowest floors but this time it is stronger.

The efficiency of the 3 m and 5 m protecting screens without and with the fence on the opposite side is presented in Fig. 6. Apart from the efficiency against the whole six-lane road ($J = 6$), the efficiency against the $j = 2$ lane and against the $j = 6$ lane are presented. Their roles are important in explanation of the differences between the efficiencies of the protecting screen in the urban system without and with the fence. The $j = 2$ lane is that, which delivers the highest field component. The component due to $j = 6$ lane is mostly affected by the fence presence.

Comparing the screen efficiencies it can be seen that, as it was expected, these of the 5 m screen are larger than those of the 3 m screen. The shadow boundary of the 5 m screen for the whole road is above the building height (Table 3), but for the 3 m screen the effects connected with the shadow boundary can be observed. For the whole road it appears somewhere between the fourth and fifth floors. There, the 3 m screen efficiency equals the value characteristic for the shadow boundary of 3 dB(A). The same position has the shadow boundary for the $j = 2$ lane. This means that the shadow boundary for the whole road is defined by the lane of the largest share in the total field. In this case it is the second lane. The less screened further lanes account for diminishing of the screen efficiency against the whole road on the floors below the shadow boundary.

In the range of the first two floors, the screen efficiency has reflected the complex character of the field created due to the three parallel surfaces: building façade, protecting screen and fence. The influence of the fence presence in the range of the lowest floors shows the different character for the two heights of the screens. The substantial degradation of the efficiency for the 3 m screen is observed on the lowest floor. For the 5 m screen, the local degradation on the second floor appears.

In the range of the lowest floors, reflections from the ground and the two parallel surfaces of the building façade and the screen, participate in the field creation. In the case of the fence presence on the opposite road side, the third parallel surface of the fence joins the chains of the reflection processes taken up to the third order (Table 1, $K = 3$).

The waves once reflected on the fence, represented by the image sources (Fig. 3b), belong to the most important field components resulting due to the fence presence. The direct waves due to these image sources have the range of existence defined by the limited height of the fence equal to 2.3 m (Table 3). As the screen action reduces more the field components due to the sources of positions

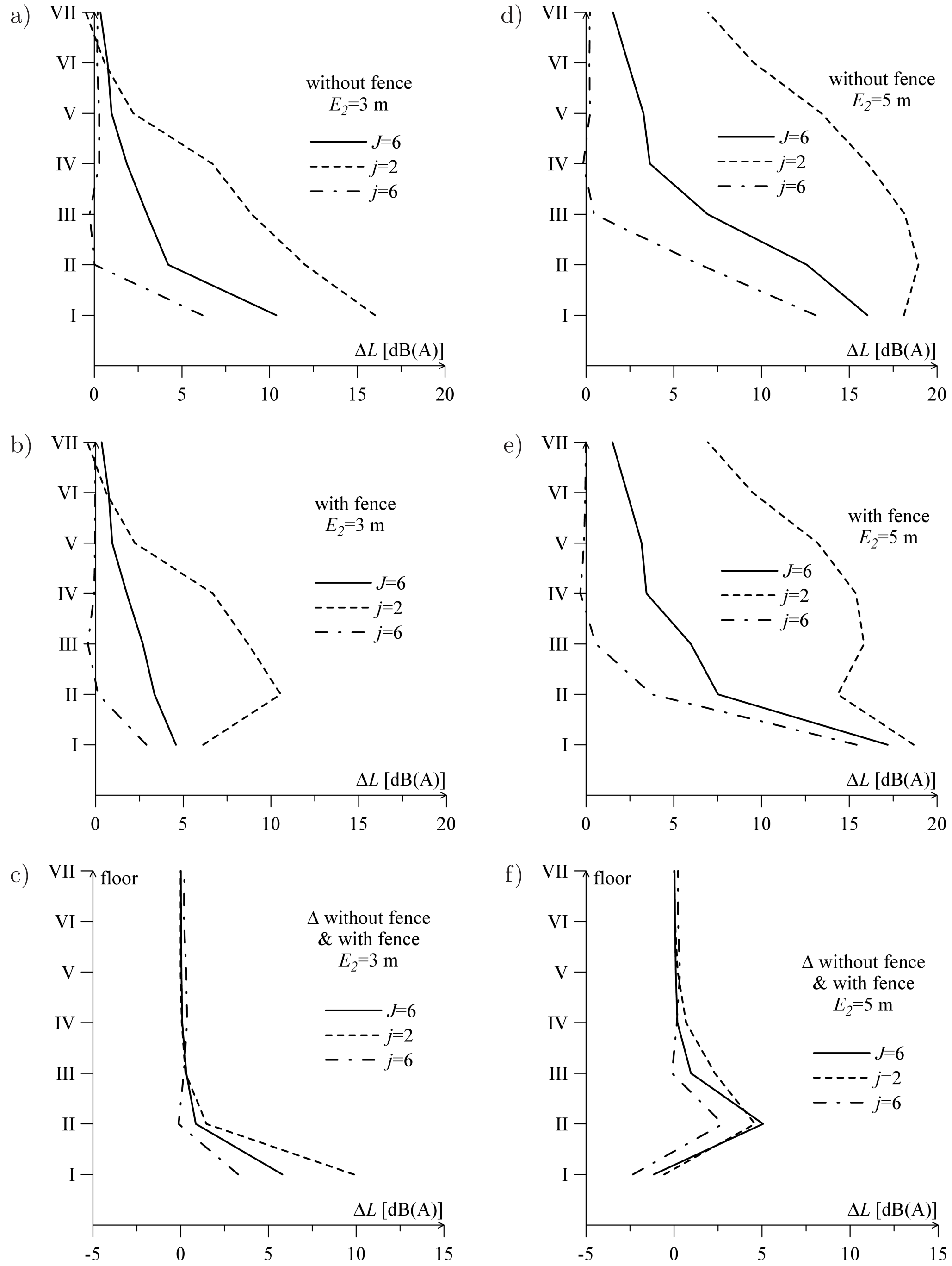

Fig. 6. The efficiency of the protecting screen $E_2 = 3$ m: a) without a fence on opposite side, b) with a fence, c) the effect of a fence, and the efficiency of the protecting screen $E_2 = 5$ m: d) without a fence, e) with a fence, f) the effect of a fence.

closer to the protecting screen, the proportions between the field components become different from those before the screen application (Fig. 5).

In the case of the 3 m screen, the sound levels due to the $j = 2$ lane in the urban systems S(1), S(3) without the fence and the S(2), S(4) system with the fence are shown in Table 4. On the lowest floor when the fence is absent, in the S(1) system without the protecting screen, as well as in the S(3) system with the protecting screen, the field components due to the $j = 2$ lane dominate. On the lowest floor, in the range of geometrical shadow of the protecting 3 m screen, the screen efficiency equals 16 dB(A) (Fig. 6a).

The fence presence has changed the situation. For the image sources resulting due to single reflection in the fence, the protecting screen creates the shadows below the first floor (Table 4). Thus, the screen does not change the range of floors where the waves due to these sources exist. The image source $(j = 2)'$, representing reflection in the fence, being at the large distance from the protecting screen, is only slightly affected by the screen presence. In contrast with this, the real $j = 2$ lane is effectively screening due to its position in the screen proximity. In this way, the sound levels due to the image sources dominate the real sources' component. The screen efficiency against the whole road on the lowest floor equals 6 dB(A). For the observation point position on the first floor, the fence presence lowers the protecting screen efficiency by about 10 dB(A) and by less than 2 dB(A) on the second floor. For the higher floors the fence influence is hardly visible.

In the case of the 5 m screen, the most important field components due to the fence presence $(j = 6)'$, $(j = 5)'$, $(j = 4)'$ are cut out on the first floor (Table 3). Thus, the screen efficiency only slightly differs from this presence unaffected by the fence. Regardless the protecting screen application, all these components are present on the second floor and only there, since the ranges of their existence are limited by the fence height. These components, in contrast to the real sources components, are only slightly affected by the protecting screen. Due to them, the screen efficiency observed on the second floor is lower than this in the case of the fence absence.

4. Acoustical climate evaluation

The above analysis of the sound level over the building façade has been performed for the standard traffic being a simplified form of traffic composition observed during measurements. Below, the appropriate simulation has been carried out for the noise indicator L_{den}. According to the European Union recommendations, the noise indicator L_{den}

$$L_{\text{den}} = 10 \log \left\{ \frac{1}{T_{\text{total}}} \left(T_{\text{day}} 10^{0.1 L_{\text{day}}} + T_{\text{evening}} 10^{0.1\left(L_{\text{evening}}+5\right)} + T_{\text{night}} 10^{0.1\left(L_{\text{night}}+10\right)} \right) \right\} \tag{6}$$

should be used in order to evaluate the acoustical climate (DIRECTIVE 2002). In the above definition L_{day} is the sound level of daytime from 7 a.m. to 7 p.m., L_{evening} of time from 7 p.m. to 11 p.m. and L_{night} of time from 11 p.m. to 7 a.m. Thus for the total time interval T_{total} of 24 h, it results in

$$L_{\text{den}} = 10 \log \left\{ \frac{1}{24} \left(12 \cdot 10^{0.1 L_{\text{day}}} + 4 \cdot 10^{0.1 \left(L_{\text{evening}} + 5 \right)} + 8 \cdot 10^{0.1 \left(L_{\text{night}} + 10 \right)} \right) \right\}$$
$$= 10 \log \left\{ \left(\frac{1}{2} 10^{0.1 L_{\text{day}}} + \frac{1}{6} 10^{0.1 \left(L_{\text{evening}} + 5 \right)} + \frac{1}{3} 10^{0.1 \left(L_{\text{night}} + 10 \right)} \right) \right\}. \quad (7)$$

Using the simulation program PROP5 and loading the traffic compositions characteristic for the appropriate time intervals (Table 2), the indicator L_{den} of acoustical climate can be predicted. Similarly as in the standard traffic compositions, the traffic compositions are a simplified form of the real traffic observed for the interval of 24 h. The traffic is reduced to light vehicle movement with the appropriate proportion between flow rates for the distinguished time interval. In Table 2, apart from traffic composition for the whole day, the compositions characteristic for the morning rush hours (a.m.) and afternoon rush hours (p.m.) are given. During the morning rush hours, the dominant vehicle flows are in the direction to the city center, while during afternoon rush hours – from the center. In Fig. 7, the indicator L_{den} and the modified indicators L_{den} (a.m), L_{den} (p.m) obtained for the basic urban system S(1) (Table 1) are presented. The indicator L_{den} and the modified indicators: L_{den} (a.m), L_{den} (p.m) are almost the same. The sound level L_s of the standard traffic composition, added for comparison, is a little higher than this for the noise indicators.

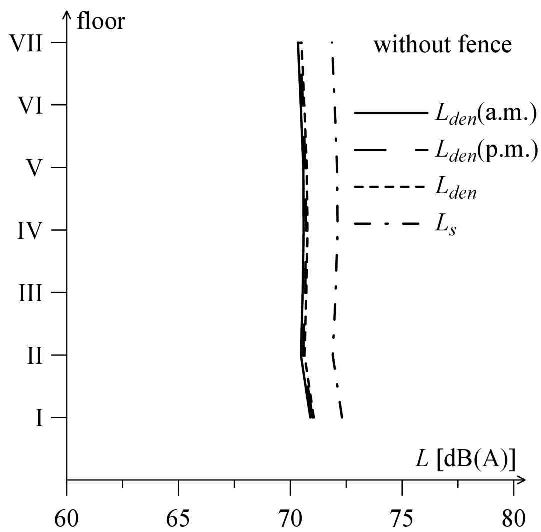

Fig. 7. The noise indicator L_{den} for the characteristic traffic composition in the defined time intervals (Table 2) and the sound level L_s for standard traffic composition in the S(1) urban system model without fence on the opposite side (Table 1).

Table 2. The traffic composition for L_{den} calculation.

time interval	lane j	flow rate [veh/h] N_j^l	speed [km/h] v_j^l
a.m.	1	500	50
	2	500	
	3	500	
	4	1000	40
	5	1000	
	6	1000	
p.m.	1	1000	40
	2	1000	
	3	1000	
	4	500	50
	5	500	
	6	500	
day 7 a.m. – 7 p.m.	1	750	45
	2	750	
	3	750	
	4	750	
	5	750	
	6	750	
evening 7 p.m. – 11 p.m.	1	100	80
	2	300	
	3	150	
	4	150	
	5	300	
	6	100	
night 11 p.m. – 7 a.m.	1	10	80
	2	30	
	3	15	
	4	15	
	5	30	
	6	10	

The efficiency of the protecting screen defined for the noise indicator L_{den} in the urban system model without and with the fence on the opposite side (Table 1), is presented in Fig. 8. The efficiencies are the same as these calculated for the standard traffic compositions (Fig. 6). The protecting screen efficiency for the afternoon rush hours (ΔL_{den} (p.m)), when the most intensive vehicle movement is in the lanes closest to the protecting screen, is expected to be higher than for the morning rush hours. Moreover, for the morning rush hours, when the

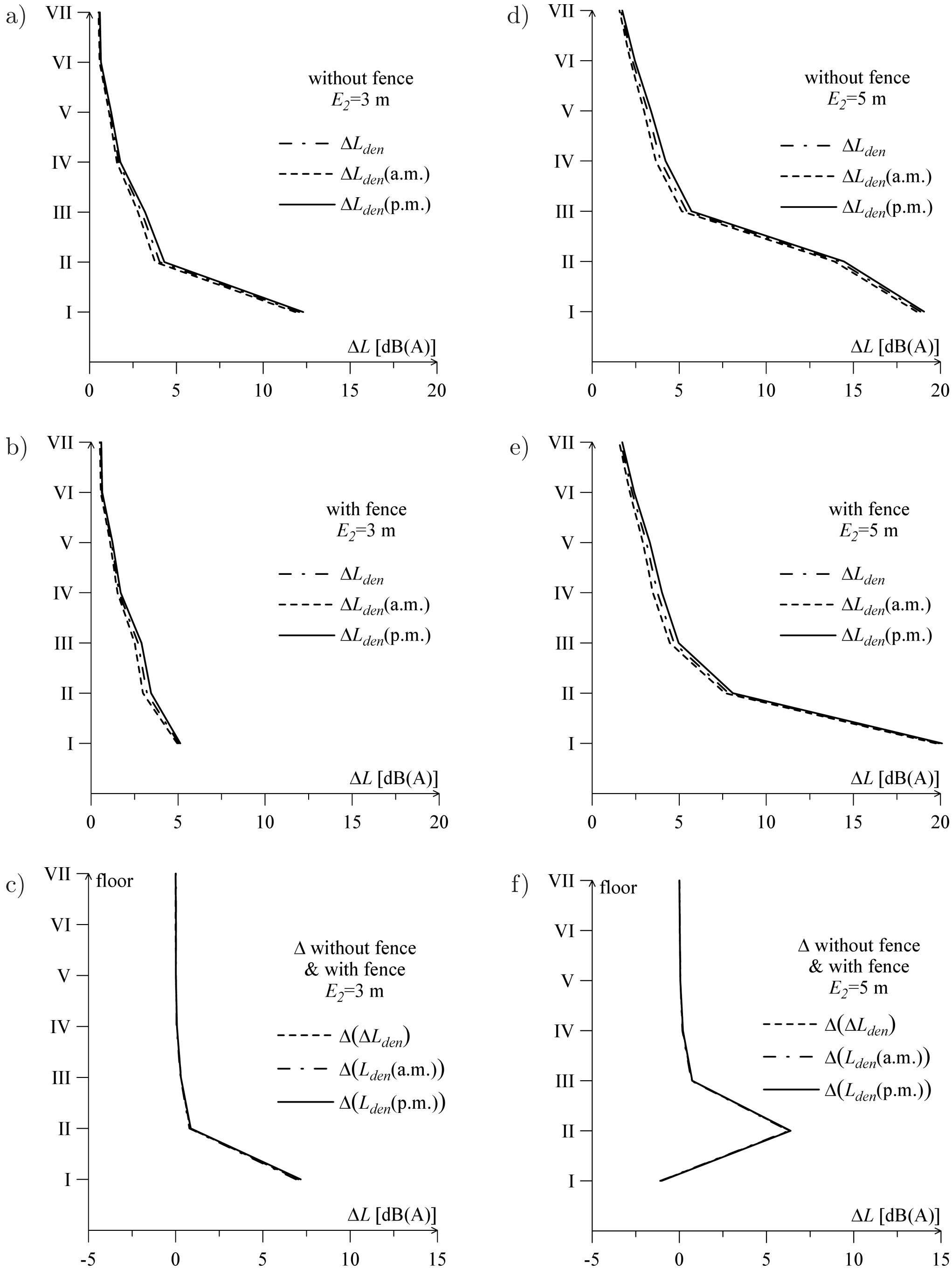

Fig. 8. For the noise indicator L_{den} the efficiency of the protecting screen $E_2 = 3$ m: a) without a fence on opposite side, b) with a fence, c) the effect of a fence, and the efficiency of the protecting screen $E_2 = 5$ m: d) without a fence, e) with a fence, f) the effect of a fence.

most intensive vehicle movement is on the lanes closest to the fence, the fence effect is expected to be stronger than for the afternoon rush hours. The expected effects are not observed due to the fact that higher flow rates are accompanied by the lower vehicle speed (Table 2). The doubled flow rates result in the sound level growth by 3 dB, while the speed lowered from 50 km/h to 40 km/h results in diminishing of the light vehicle source level by 2.84 dB (Table 5). Thus, the difference between the morning and afternoon rush hours has disappeared.

5. Final analysis

The example of designing of an acoustic screen has been presented. The screen is to be applied in an urban system as a protector against traffic noise. Depending on the accuracy of the designing tool used, the screen efficiency can be predicted with different accuracy and can be a function of a larger or smaller set of input parameters. The presented example has illustrated what kind of effect can be expected and how they can overlap each other.

The simulation program used here requires loading of the urban system model and the acting source model. The modeling accuracy could be arbitrarily high. The limits come from the limited database and requirement of reasonable simulation time. The sensitivity of the final results to the input parameters is the basis for the establishment of the required degree of the modeling accuracy. In the Part I of the paper, the basic urban system model with the MAK2 road model has been established as accurate enough to predict the sound level measured over the investigated building façade. To predict the protecting screen efficiency, the basic urban system of the half-plane with the investigated building has to be modified. The fence on the road opposite side, omitted in the basic model, has to be considered due to its importance in the urban system with the protecting screen. The simplest model of noise emission by a vehicle, in the form of the single omnidirectional equivalent point source, and the traffic composition reduced to the standard composition, has been assumed.

The assumed road model as a noise source and road surroundings model have appeared enough accurate to present specific features of the acoustical field resulting due to the protecting screen application in the analyzed urban system, with the assumed accuracy of ±1 dB(A). Sometimes, the observed features of the acoustical field could be difficult for explanation based on the assumed source and its surroundings models. Then, in the source model a vehicle can be represented by more than one equivalent source with the appropriate directivity characteristic. Number of surrounding objects can be enlarged; their shapes and acoustical features can be more accurately defined. Whether it is the reasonable step depends on individual analyzed case, the possessed database including.

Here, according to the applied models, the screen efficiency depends on the positions of the elementary sources representing vehicles moving over the road lanes.

For a single point source representing a vehicle of movement modeled as a sequence of adequate point sources spread along vehicle route, the screen efficiency is a function of road lane number and lane positions. The varying traffic composition over lanes results in the screen efficiency, which changes in accordance to the traffic variation. However, this general dependence without the detailed analysis could be misleading. This has happened in the case of the noise indicator L_{den} defined for the distinguished time intervals. The expected lowering of the screen efficiency due to the shift of the most intensive traffic to the more remote lanes, which simultaneously are nearer to the reflecting fence, has not appeared. This is due to the fact that higher flow rates have been accompanied by lowering of the vehicle speed. Thus, the screen efficiency for these traffic compositions appears similar to the one established for the overall daytime with the averaged traffic compositions.

Based on the applied road surroundings model, the influence of the fence on the opposite side on the screen efficiency could be observed. In the range of lower floors, after the protecting screen application, the fence presence results in local extremes in the sound level spread. As the ranges of the geometrical shadows and the existence ranges of the waves reflected in the fence surfaces overlap, there is not a well-defined shadow boundary below which the sound level steadily decreases. Thus, the sound level spread over the building façade as well as the screen efficiency requires the detailed presentation over the whole façade.

6. Conclusions

Generally, analyzing the possibilities of improving of the acoustical comfort for people living in buildings close to the noisy road, limiting of noise emission and growing of the distance between a building and a source, are taken into account. In the special case of the building 2 Klonowicza street, the noise emission as well as the urban system geometry have to be treated as unchangeable. Since there is enough space between the road and the building, the erection of an acoustical screen could be deliberated. The screen erection is an expensive investment; thus, the screen designing has to be carefully worked out to offer the maximal sound level lowering at minimal cost.

The presented designing procedure demonstrates the importance of screen interactions with surrounding objects for the screen effectiveness. Thus, any simplified designing method, which does not take into account the road lane structure and screen interactions with surroundings, could be misleading. The social response, in the best case, is disappointment when the promised acoustical comfort improvement is not obtained. The worst case is when, for some space, the increase of the sound level appears. It could happen when parallel screens are placed in the area where high-rise buildings are flanking the road. The dissatisfaction of people living on the floors of worsened comfort results in a large number of registered complaints.

Appendix A.

Table 3. The range of existence of the direct geometrical waves due to different sources.

source		without protecting screen		for protecting screen $E_2 = 3$ m		for protecting screen $E_2 = 5$ m	
real	reflected in fence	existence boundary $h_e(z)$ [m]	floors affected	shadow boundary $h_s(z)$ [m]	floors affected	shadow boundary $h_s(z)$ [m]	floors affected
$j = 1$		$\propto$	all	30.19	none	53.94	none
$j = 2$		$\propto$	all	14.13	V–VII	25.02	none
$j = 3$		$\propto$	all	9.04	III–VII	15.88	V–VII
$j = 4$		$\propto$	all	5.44	II–VII	9.39	III–VII
$j = 5$		$\propto$	all	5.11	II–VII	8.79	III–VII
$j = 6$		$\propto$	all	4.89	II–VII	8.34	III–VII
	$(j = 1)'$	5.13	I	3.64	I	6.15	none
	$(j = 2)'$	5.39	I	3.67	I	6.20	none
	$(j = 3)'$	5.70	I	3.69	I	6.25	none
	$(j = 4)'$	7.83	I–II	3.84	I–II	6.51	II
	$(j = 5)'$	8.92	I–II	3.89	I–II	6.60	II
	$(j = 6)'$	10.55	I–III	3.94	I–III	6.69	II–III

Table 4. The sound level due to different sources.

<table>
<tr><th>model</th><th>objects on the ground</th><th>point position</th><th colspan="3">field</th><th>sound level [dB(A)]</th><th>screen efficiency [dB(A)]</th></tr>
<tr><td>S(1)</td><td>building</td><td>first floor</td><td colspan="3">total due to $j = 2$</td><td>66.03</td><td rowspan="2">16.01</td></tr>
<tr><td>S(3)</td><td>building with screen $E_2 = 3$ m</td><td>first floor</td><td colspan="3">total due to $j = 2$</td><td>50.02</td></tr>
<tr><td>S(2)</td><td>building and fence (E_1)</td><td>first floor</td><td colspan="3">total due to $j = 2$</td><td>66.58</td><td rowspan="2">6.13</td></tr>
<tr><td>S(4)</td><td>building with screen $E_2 = 3$ m and fence (E_1)</td><td>first floor</td><td colspan="3">total due to $j = 2$</td><td>60.45</td></tr>
<tr><td></td><td></td><td></td><td colspan="3">component due to</td><td></td><td></td></tr>
<tr><td rowspan="3">S(4)</td><td rowspan="3">building with screen $E_2 = 3$ m and fence (E_1)</td><td rowspan="3">first floor</td><td>real $j = 2$</td><td></td><td></td><td>44.89</td><td></td></tr>
<tr><td></td><td>$(j = 2)'$ reflected in fence</td><td></td><td>52.36</td><td></td></tr>
<tr><td></td><td></td><td>real $j = 2$ and $(j = 2)'$ reflected in fence</td><td>53.08</td><td></td></tr>
</table>

Table 5. Parameters of light (l) and heavy (h) vehicles and source power level speed dependence in accordance with MAK2 road model as noise source.

position above ground** [m]		speed [km/h]	source power level* [dB(A)]		$\Delta L_{WA} = L_{WA}(v + 10\,[\text{km/h}]) - L_{WA}(v)$ [dB(A)]	
z_0^l	z_0^h	v	$L_{WA}^l(v)$	$L_{WA}^h(v)$	$L_{WA} = L_{WA}^l$	$L_{WA} = L_{WA}^h$
0.50	1.20	40	96.51	104.32		
		45	98.00	106.01		
		50	99.35	107.53	2.84	3.21
		55	100.57	108.91		
		60	101.70	110.18	2.35	2.65
		65	102.75	111.34		
		70	103.73	112.43	2.03	2.25
		75	104.64	113.44		
		80	105.49	114.39	1.76	1.96
		85	106.30	115.28		
		90	107.07	116.12	1.58	1.73
		95	107.79	116.92		
		100	108.48	117.68	1.41	1.56
		105	109.14	118.40		
		110	109.76	119.09	1.28	1.41
		115	110.37	119.75		
		120	110.94	120.38	1.18	1.29

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

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