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NOISE LEVEL SPREAD IN THE VICINITY OF A CROSSROADS

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In the paper, the PROP10 program is used to present the time-average sound level on façades of buildings in the vicinity of a crossroads. The propagation model within an urban system forming canyon streets includes the wave interaction with obstacles, multi-reflections from building walls and single and double diffraction at their wedges. For the current purpose the program is provided with a road model in which the vehicle route is divided into sub-segments with lengths and linear densities of emitted energy that depend on the traffic organization in the vicinity of the crossroads. The lengths of the sub-segments, where vehicles wait and are forced to a subsequent start and stop, depend on the flow rates on lanes, the equivalent vehicle length, the red and green light times and the speed of leaving a crossroads. The linear energy density at these sub-segments depends on a parameter characterizing the energy emitted during the starting of a vehicle. The time-average sound level is analyzed as a function of the enumerated parameters.

Key words: traffic noise, interrupted movement, canyon street.

1. Introduction

During the last decades, despite that vehicles have become less noisy, this effect has been overwhelmed by growing vehicle flow rates. In cities where traffic noise prevails, possible changes in the time-average sound level are of an order of a single dB(A) what is subjectively noticeable, nevertheless it is observed that an improvement in the acoustical environment has to be of the order of 5 dB(A) to make people move and change dwellings. This substantial improvement can be obtained by a collective application of the means, which applied separately have low effectiveness. The only tools to investigate the existing possibilities could be simulation programs based on an enough detailed source model and a model of propagation in the built-up area.

To analyze the sound level spread along façades of buildings in the vicinity of a crossroads the simulation programs are the best tools. The simulation program PROP10 applied here belongs to the PROP(...) family which is based on the environmental noise model of high accuracy in the wave interaction description [1–3]. During simulation the wave undergoes a chain of interactions: transmissions, reflections, and diffractions. A new concept of diffraction, in which a pure image method is applied, allows an arbitrary order of all three kinds of interactions at any arbitrary place in the chain. Moreover, in PROP(...) programs, the pressures of the waves reaching the observation point by different paths are summed and not the energy.

The simulation program PROP10 used here allows the prediction of the time-average sound level within an urban system. The propagation model is adjusted to describe noise spreading within a city center where canyon streets structure dominates [4–8]. The wave interaction with obstacles includes multi-reflections from building walls and single and double diffractions at their wedges. The program PROP10 is provided with a detailed road model, which allows the analysis of interrupted vehicle flows at crossroads. The crossing of two canyon streets with roads of several lanes at the bottoms is assumed. For noise emitted by an individual vehicle passing-by, the sound exposure is used with limiting the infinite integration boundary and replacing the integral by discrete summation. Since passing a crossroads freely is very rare, a vehicle route is divided into sub-segments. Vehicle streams approaching a crossroads are characterized by flow rates in lanes and cruising speed. There, the linear energy density is determined by the speed-dependent power level and position above the ground of the equivalent source, which represents vehicles [9, 10]. The lengths of sub-segments where vehicles wait and are made to a subsequent start and stop depend on flow rates in the lanes, the equivalent vehicle length, red and green light times, and the speed of leaving a crossroads. The energy linear density at these sub-segments depends on a parameter characterizing the energy emitted during the process of starting a vehicle [11, 12].

In the paper, first the time-average sound level spread on building façades in the vicinity of the symmetric crossroads has been investigated to test the assumed simplified crossroads model validation. Next, an analysis of the sound field in the vicinity of an asymmetric crossroads in relation to the symmetric one has been carried out.

2. Sound field within an urban canyon

In the simulation program PROP10, as a noise source a road of J lanes is introduced, in which move vehicles ascribed to G different classes. Each of the J lanes is divided into I_j sub-segments characteristic of the movement interrupted in the vicinity of a crossroads. Thus, the time-average sound level due to a crossroads for a T-hour period is [1–3]:

$$L_{A\,\mathrm{eq}}(T) = 10\log\left\{\sum_{j=1}^{J}\sum_{i=1}^{I_j}\sum_{g=1}^{G}10^{0.1L_{A\,\mathrm{eq}}{}_j^g(i)}\right\}. \tag{1}$$

The movement of g-class of vehicles at the i-sub-segment of the j-lane generates the time-average sound level

$$L_{A\,\mathrm{eq}}{}_j^g(i) = 10\log\left(S_j^g(i)\Delta x_E \mathcal{N}_j^g(i)\right) + L_j^g\left(U_j(i), P\right). \tag{2}$$

The average speed $v_j^g(i)$ and flow rate $\mathcal{N}_j^g\,(i)$ characterize the traffic during time T at the sub-segment. The ratio

$$S_j^g(i) = \frac{W_A^g\left(v_j^g(i)\right)}{v_j^g(i)} \tag{3}$$

represents the linear density of energy [11] due to the vehicle equivalent source defined by the source position above the ground z_0^g and its power level $L_{WA}\left(v_j^g\,(i)\right)$ with spectrum

$$q_A^g\left(f_w, v_j^g(i)\right) = \frac{W_A^g\left(f_w, v_j^g(i)\right)}{W_A^g\left(v_j^g(i)\right)}. \tag{4}$$

In the procedure applied here for the sound level calculation [Eq. (1)], the integration in the sound exposure level is replaced by a sequence of discrete positions during the passage of a limited road segment, e.g. parallel to the x-axis (x_{j1}, x_{j2}) [5]. The segment (x_{j1}, x_{j2}), depending on the observation point position, cuts a part of a divided into sub-segments j-lane of the length (Fig. 1)

$$x_{j2} - x_{j1} \geq 6R_{j0}, \tag{5}$$

$$R_{j0} = \sqrt{\left(y_{j0} - y_p\right)^2 + \left(z_0^g - z_p\right)^2}. \tag{6}$$

Thus, it can contain only some of j-lane sub-segments. The x-coordinate of discrete vehicle positions depends on the step Δx_E in energy summation along a vehicle route

$$x_0\left(u\right) = u\Delta x_E, \qquad 1 \leq u \leq U_j(i) \tag{7}$$

with the limit

$$\begin{aligned} U_j &= 1 + 2\frac{(x_{j2} - x_{j1})/2 + \varepsilon}{\Delta x_E}, \qquad \varepsilon < \Delta x_E\,, \\ U_j &= \sum_{i=1}^{I_j} U_j(i), \qquad U_j(i) = \text{integer}\left(\frac{l_j(i)}{\Delta x_E}\right), \end{aligned} \tag{8}$$

where $l_j(i)$ is the appropriate sub-segment length. The sound level

$$L_j^g\left(U_j(i), P\right) = 10\log\left(\frac{1}{4\pi}\sum_{w=1}^{10} q_A^g\left(f_w, v_j^g(i)\right) w^g\left(f_w, U_j(i), P\right)\right) \tag{9}$$

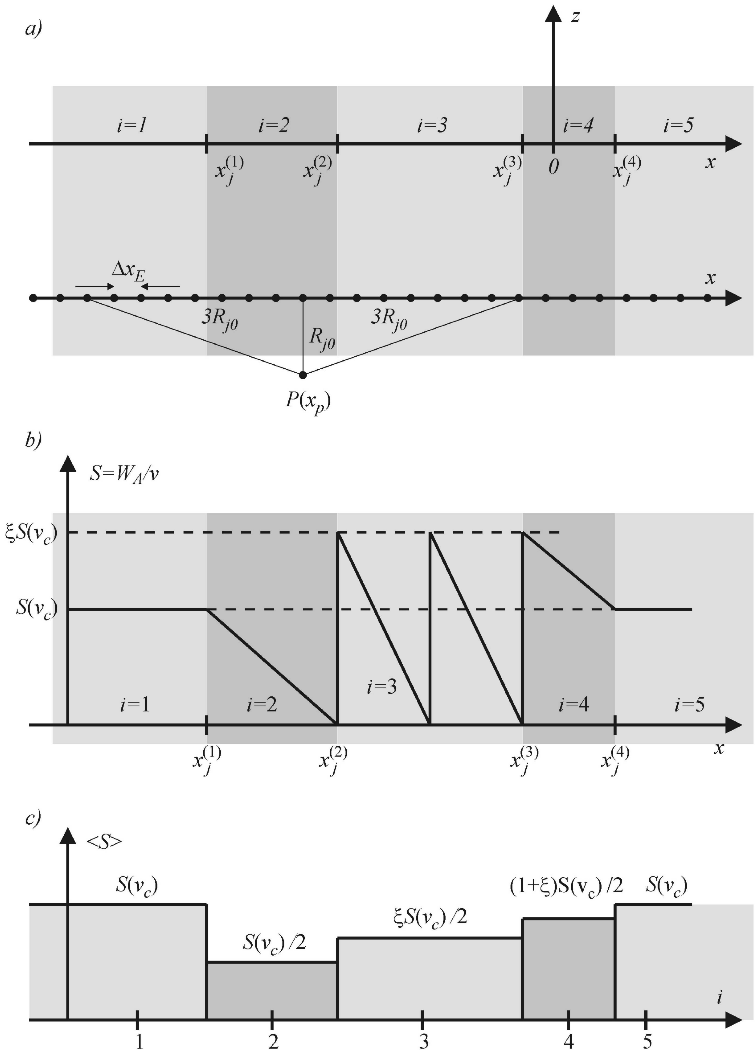

Fig. 1. Separate five sub-segments in j-lane in the vicinity of the crossroads: a) division into appropriate sub-segments and the segment (x_{j1}, x_{j2}) taken in the sound exposure calculation, b) sound energy linear density at separate five sub-segments [11], c) its average value ascribed to the sub-segments.

is the level due to $U_j(i)$ point sources representing a vehicle movement at the i-sub-segment of the j-lane. The average acoustical energy in the w-octave-band due to the set of $U_j(i)$ point sources of the unit strength, emitting simple harmonics of frequencies $f_{wd} \in \left\langle F_w^{(1)}, F_w^{(2)} \right\rangle$

$$w^g(f_w, U_j(i), P) = \frac{1}{D_w} \sum_{d=1}^{D_w} \sum_{u=1}^{U_j(i)} \left| H\left(\mathbf{R}_j^g(u\Delta x_E), f_{wd}\right) \right|^2 \tag{10}$$

is determined by the transfer function of the built-up area $H\left(\mathbf{R}_j^g(u\Delta x_E), f_{wd}\right)$ which, depending on the difference $\mathbf{R}_j^g(u\Delta x_E)$ in the vector position of the g-class vehicle discrete position in the j-lane and observation point position, describes the propagation throughout the half-space with obstacles formed by $n = 1, ..., N$ panels. For a canyon-street [4–7] of a width flanked by infinitely long buildings of height b_1 and b_2 at sides (Fig. 2), only three panels are important: ground $(n = 1)$, and the building façades facing the road $(n = 2, 3)$.

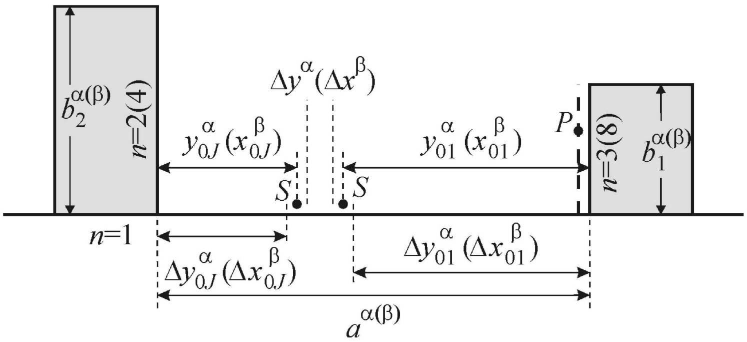

Fig. 2. A vertical sketch of a crossroads.

Thus, in the case under consideration, the crossroads is formed by four one-side limited buildings with the road of two arms α, β (Fig. 3). In the α-arm the movement is parallel to the x-axis while in the β-arm it is parallel to the y-axis. For both arms the road segment description Eqs. (5)–(9) obeys where for the β-arm x has to be replaced by y. The important panels are: the ground $(n = 1)$, and the side walls of buildings facing the road arms $(n = 2 \div 9)$. Thus, the average energy in the w-octave-band [Eq. (10)]:

$$w^g\left(N = 9, f_w, U_j(i), t\right) = w\left(\left(\begin{array}{c} a^{\alpha}, b_1^{\alpha}, b_2^{\alpha}, \left\{y_{j0}^{\alpha}\right\}, x_p^{\alpha}, \\ a^{\beta}, b_1^{\beta}, b_2^{\beta}, \left\{x_{j0}^{\beta}\right\}, y_p^{\beta}, \end{array}\right) t,\right.$$
$$\left.\{\mathcal{R}(n)\}, \{z_0^g\}, \Delta x_E, K, f_w\right), \tag{11}$$

is expressed as a function of the following parameters [4]:

- $a^{\alpha(\beta)} = \Delta y_{01}^{\alpha}\left(\Delta x_{01}^{\beta}\right) + \Delta y_{0J}^{\alpha}\left(\Delta x_{0J}^{\beta}\right) + \Delta y^{\alpha}\left(\Delta x^{\beta}\right) + J^{\alpha(\beta)} \cdot 3.5\,\mathrm{m}$ – canyon-streets widths forming crossroads arms (Fig. 2),
- $b_1^{\alpha(\beta)}$, $b_2^{\alpha(\beta)}$ – side-buildings' heights in crossroads arms,
- $\{\mathcal{R}(n)\}$ – a set of reflection coefficients of panels forming a crossroads,
- x_p^{α}, y_p^{β} – the observation point coordinate along crossroads arms,
- $y_p^{\alpha}(b_1^{\alpha})$, $y_p^{\alpha}(b_2^{\alpha})$, $x_p^{\beta}(b_1^{\beta})$, $x_p^{\beta}(b_2^{\beta})$ – the observation point position at road sides in the crossroads arms,

- $z_p = z_{op} + 3(t-1)$ m – the observation point position at a height of the t-floor's window, with the ground floor position z_{op} and 3 m distance between the floors,
- $\left\{y_{0j}^{\alpha}\right\}$, $\left\{x_{0j}^{\beta}\right\}$ – lanes' positions in crossroads arms,
- $\{z_0^g\}$ – a set of vehicles' equivalent sources positions above the ground,
- Δx_E – a step in energy summation along the vehicle route,
- K – the upper order of interaction.

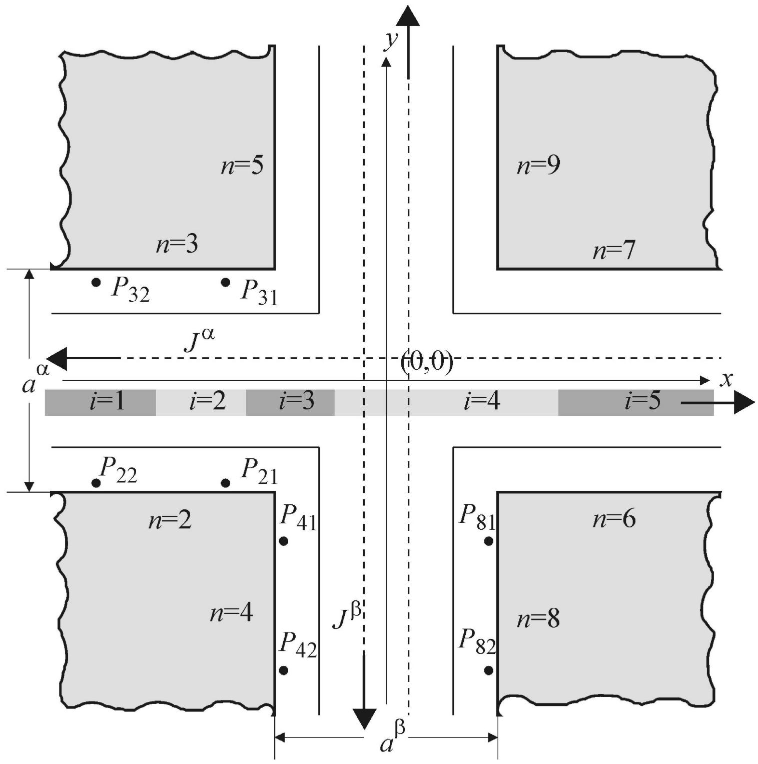

Fig. 3. A sketch of urban canyons forming arms of a crossroads.

The crossroads model as a noise source made up of point sources results in the appearance of vehicle discrete positions along its route in the urban system transfer function [Eqs. (10), (11)]. Apart from this, to calculate the sound level due to a crossroads the following parameters describing the crossroads have to be defined in general:

- G – number of vehicle classes,
- $J = J^{\alpha} + J^{\beta}$ – number of lanes of the crossroads,

and parameters describing the energy emitted by a g-class vehicle at distinguished i-sub-segments of the j-lane:

- $\left\{q_A^g\left(f_w, v_j^g(i)\right)\right\}$ – a set of reduced power spectra [Eq. (4)],
- $\left\{S_j^g(i)\right\}$ – a set of energy linear densities [Eq. (3)].

Other road parameters as a noise source are stemming from traffic organization resulting in:

- $\{I_j\}$ – a set of the number of sub-segments in lanes,
- $\left\{v_j^g(i)\right\}$ – a set of vehicles' average speeds at the road sub-segments in lanes,
- $\left\{\mathcal{N}_j^g(i)\right\}$ – a set of vehicles' flow rates at the road sub-segments in lanes.

3. Simplified model of interrupted vehicle flow

In the vicinity of a crossroads, interrupted movement of an individual vehicle means that it moves subsequently with constant speed, decelerates, stops, waits, starts, accelerates and moves again a with constant speed (Fig. 1). All these phases are characterized by a different source energy linear density $S_j^g(i)$, its spectrum $q_A^g\left(f_w, v_j^g\,(i)\right)$ and flow rate $\mathcal{N}_j^g(i)$. Thus, the vehicle route in the j-lane is divided into five sub-segments of the lengths $l(i),\ i = 1, 2, 3, 4, 5$.

For the simplified crossroads model applied in the PROP10 simulation program, the single vehicle equivalent source representation has been assumed. To this end, the MAK2 $(G = 2)$ model of a road [9] has been used. As in the MAK2 $(G = 2)$ model, the vehicles are divided into two classes: the light and heavy ones $(g = 1 = l,\ \ g = 2 = h)$, and the equivalent source power level and spectrum depend on the vehicle speed, for the heavy vehicle share of 20% $(p_j^l = 0.80,\ p_j^h = 0.20)$ in the j-lane, the average vehicle's stream parameters (Table 1) are calculated as below:

Table 1. Average vehicles' stream parameters for single equivalent source representation.

v^l [km/h]	v^h [km/h]	v_c [km/h]	$\mathcal{N}_j$ [veh/h]	z_0^l [m]	z_0^h [m]	z_0 [m]	L_{WA} [dB(A)]
57	47	$\langle v\rangle_{20\%} = 55$	1200	0.50*	1.20*	$\langle z_0\rangle_{20\%} = 0.64$	$\langle L_{WA}\rangle_{20\%} = 102.82^{**}$ $\langle L_{WA}\rangle_{20\%} = 101.6^{***}$

* [10], ** [9], *** [11].

$$v_j \;=\; \langle v_j\rangle_{20\%} = p_j^l v_j^l + p_j^h v_j^h, \tag{12}$$

$$L_{WA}(v_j) \;=\; \langle L_{WA}(v_j)\rangle_{20\%} = 10\log\left(p^l W_A^l(v_j^l) + p^h W_A(v_j^h)\right), \tag{13}$$

$$q_A(f_w, v_j) \;=\; \langle q_A(f_w, v_j)\rangle_{20\%} = \frac{p^l W_A^l(f_w, v_j^l) + p^h W_A(f_w, v_j^h)}{\sum\limits_{w=1}^{10} p^l W_A^l(f_w, v_j^l) + p^h W_A^h(f_w, v_j^h)}, \tag{14}$$

and from the data of equivalent source positions above the ground [10]:

$$z_0 = \langle z_0\rangle_{20\%} = p^l z_0^l + p^h z_0^h. \tag{15}$$

Apart from the single vehicle representation, it is assumed that the cruising speed with which the vehicle approaches the crossroads is the same in all the lanes $(v_j = v_c)$. Then, in place of Eqs. (1), (2), it is

$$L_{A\,\mathrm{eq}}(T) \;=\; 10\log\left\{\sum_{j=1}^{J}\sum_{i=1}^{5}10^{0.1L_{A\,\mathrm{eq}j}(i)}\right\}, \tag{16}$$

$$L_{A\,\mathrm{eq}}(i) \;=\; 10\log\left(S(i)\delta x_E \mathcal{N}_j(i)\right) + L_j(U_j(i),P). \tag{17}$$

Applying the concept of interrupted movement modeling [11, 12] because of the lack of experimental data, further simplifications have been assumed. The average value of the linear density of the emitted energy is ascribed to each sub-segment. The energy linear density [Eq. (3)] at the sub-segments, where vehicles move with cruising speed v_c

$$S(i=1,5) = \sum_{w=1}^{10}(W_A(f_w,v_c)/v_c) = W_A(v_c)/v_c = S(v_c) \tag{18}$$

is a finite ratio. For the sub-segment where vehicles stop it is ascribed as an average value:

$$S\left(i=2\right) = S\left(v_c\right)/2, \tag{19}$$

for the sub-segment where vehicles wait for green light stopping and starting more than once:

$$S(i=3) = \xi S(v_c)/2, \tag{20}$$

for the sub-segment where vehicles start and achieve the cruising speed:

$$S(i=4) = (1+\xi)S(v_c)/2. \tag{21}$$

The energy linear density $S(i = 2, 3, 4)$ characterizing the interrupted movement is determined by the experimentally established parameter ξ [11]. The linear energy definition [Eqs. (19)–(21)] consumes the total emitted energy variation during the stopping and starting processes, but the spectrum remains unchanged $q_A(f_w, v_j(i))$. Thus, the following approximation obeys:

$$\begin{aligned} L_j\left(U_j(i),P\right) \;&=\; 10\log\left(\frac{1}{4\pi}\sum_{w=1}^{10}q_A\left(f_w,v_j(i)\right)\,w\left(f_w,U_j\left(i\right),P\right)\right) \\ &\cong\; 10\log\left(\frac{1}{4\pi}\sum_{w=1}^{10}q_A\left(f_w,v_j=v_c\right)\,w(f_w,U_j(i),P)\right), \end{aligned} \tag{22}$$

which, introduced to Eq. (17), gives the level $L_{A\,\mathrm{eq}}(i)$ due to the i-sub-segment of the j-lane in the simplified model if the lengths and flow rates at the sub-segments are defined.

The first and fifth sub-segments $(i = 1, 5)$ are one-side unlimited sub-segments. The sub-segment where a vehicle slows down $(i = 2)$ and the sub-segment where, after passing the crossroads, it achieves the cruising speed $(i = 4)$ have constant lengths established according to the traffic observation for the assumed cruising speed [11]. Only the sub-segment where the vehicles wait for passing the crossroads $(i = 3)$ has the length defined in relation to vehicle stream parameters. The length of the third sub-segment in the j-lane occupied by stopped vehicles

$$L_r(j) = l_j(i = 3) = \mathcal{N}_j t_r l_v \tag{23}$$

depends on the flow rate $\mathcal{N}_j$, the time of red light t_r and the equivalent vehicle length l_v which for a 20% participation of heavy vehicles is given by:

$$l_v = \langle l \rangle_{20\%} = p^l l^l + p^h l^h. \tag{24}$$

As only a limiting road segment can be freed during the green light period, the crossroads works as a filter. The length of the road segment that can be freed during the green light time t_f, when the vehicle leaves the crossroads with the speed v_f, is

$$L_f = v_f t_f. \tag{25}$$

For the same leaving speed of all the vehicles and $t_r = t_f$ from the balance $L_r(j) = L_f$, the upper limit of the flow rate can be found for which the third sub-segment is fully freed during the green light period

$$\widetilde{\mathcal{N}} = \frac{v_f}{l_v}\,. \tag{26}$$

In this way the crossroads works as a low-pass filter for the vehicle streams. When $\mathcal{N}_j \geq \widetilde{\mathcal{N}}$ then at the sub-segment $i = 4, 5$ the average flow rate for a full red-green light cycle is

$$\mathcal{N}_j(i = 4, 5) = \widetilde{\mathcal{N}}/2 \tag{27}$$

(Here an ahead movement is assumed, but it consumes also the situation when the half of the stream is ahead and the rest equally turns to the sides.) As the flow rates have to be kept constant on the road, thus, when

$$\mathcal{N}_j(i = 1, 2, 3) = \mathcal{N}_j \tag{28}$$

has to be simultaneously fulfilled with Eq. (27), it has to be realized on the expense of the increase of the length of the third sub-segment of waiting vehicles $(i = 3)$.

In the simplified model of a crossroads applied here, the $i = 3$ sub-segment has a length [Eq. (23)] which depends on the stream parameters of the vehicle approaching the crossroads (Table 2), but the ability of leaving a crossroads depends on the vehicle equivalent length l_v and first of all on the speed of leaving the crossroads v_f. Thus, for a situation when $\mathcal{N}_j > \widetilde{\mathcal{N}}$, the traffic jam starts to build up (Table 3). The sub-segment length $l(i=3)$ grows every $T/(t_r+t_f)$ period of red light. Thus, its average length for the red light fraction in the analyzed T-period is

$$l\left(i=3,\, \mathcal{N}_j > \widetilde{\mathcal{N}}\right) = L_r(j) + \frac{t_r}{T}\frac{T}{t_r+t_f}\left(L_r(j) - L_f\right) = \frac{t_r}{2}\left(3\mathcal{N}_j l_v - v_f\right). \qquad (29)$$

Table 2. Average sub-segment parameters of interrupted movement.

sub-segment	end positions	sub-segment length	average energy linear density*	flow rate
$i=1$	$\left(-\infty, x_j^{(1)}\right)$		$S_j(v_c) = S(v_c)$	$\mathcal{N}_j$
$i=2$	$\left(x_j^{(1)}, x_j^{(2)}\right)$	90 m*	$S(v_c)/2$	$\mathcal{N}_j$
$i=3$	$\left(x_j^{(2)}, x_j^{(3)}\right)$ $x_j^{(3)}(\alpha, J^\beta) = \frac{\Delta y^\beta}{2} + \frac{J^\alpha}{2}3.5\ \mathrm{m}$ $x_j^{(3)}(\beta, J^\alpha) = \frac{\Delta y^\alpha}{2} + \frac{J^\alpha}{2}3.5\ \mathrm{m}$	$l_j(i=3) = L_r(j) = \begin{cases} \mathcal{N}_j t_r l_v, & \mathcal{N}_j \le \widetilde{\mathcal{N}}, \\ \frac{t_r}{2}\left(3\mathcal{N}_j l_v - v_f\right), & \mathcal{N}_j > \widetilde{\mathcal{N}} \end{cases}$	$\xi\, S(v_c)/2$	$\mathcal{N}_j$
$i=4$	$\left(x_j^{(3)}, x_j^{(4)}\right)$	90 m*	$(1+\xi)S(v_c)/2$	$\begin{cases} \widetilde{\mathcal{N}}/2, & \mathcal{N}_j \ge \widetilde{\mathcal{N}}/2 \\ \mathcal{N}_j/2, & \mathcal{N}_j < \widetilde{\mathcal{N}}/2 \end{cases}$
$i=5$	$\left(x_j^{(4)}, \infty\right)$		$S(v_c)$	$\begin{cases} \widetilde{\mathcal{N}}/2, & \mathcal{N}_j \ge \widetilde{\mathcal{N}}/2 \\ \mathcal{N}_j/2, & \mathcal{N}_j < \widetilde{\mathcal{N}}/2 \end{cases}$

* for 55 km/h = 916.7 m/min [11].

Table 3. Characteristic parameters of $i=3$ sub-segment.

situation	l^l [m]	l^h [m]	$\langle l\rangle_{20\%} = l_v$ [m]	$t_f = t_r$ [min]	$\mathcal{N}_j$ [veh/min] ([veh/h])	$L_r(j) = \mathcal{N}_j\, t_r\, l_v$ [m]	v_f [m/min] ([km/h])	$L_f = v_f\, t_f$ [m]	$\widetilde{\mathcal{N}}_j = \frac{v_f}{l_v}$ [veh/min] ([veh/h])
normal $\mathcal{N} \le \widetilde{\mathcal{N}}$	3	15	5.4	2	20 (1200)	216	166.7 (10)	333.4	30.87 (1852)
jam $\mathcal{N} > \widetilde{\mathcal{N}}$	3	15	5.4	2	20 (1200)	216	83.3 (5)	166.7	15.44 (926)

The model presented [Eqs. (16)–(22)] divides a road segment in five sub-segments. Depending on the observation point position, the sound level is calculated for the segment given by Eq. (5) (Fig. 1), which cuts out the appropriate part of the lane divided into sub-segments. Thus, depending on the observation point position the cut segment can contain only some of sub-segments

$$l(i=1)+l(i=2)+l(i=3)+l(i=4)+l(i=5)\leq 6R_{j0}. \tag{30}$$

According to Eq. (30), for the observation point position in the vicinity of the $i=3$ sub-segment, the growth of the sub-segment results covering of all the road segments taken in the calculation of the sound exposure level [Eq. (5)] and other sub-segments are found outside this segment (Appendix A).

For an opposite condition when $\mathcal{N}_j<\widetilde{\mathcal{N}}$ at the sub-segment $i=4,5$, the average flow rate for a full red-green light cycle could be

$$\mathcal{N}_j(i=4,5)=\begin{cases}\widetilde{\mathcal{N}}/2, & \widetilde{\mathcal{N}}/2\leq\mathcal{N}_j<\widetilde{\mathcal{N}},\\ \mathcal{N}_j\dfrac{t_r}{t_c+t_r}=\mathcal{N}_j/2, & \mathcal{N}_j<\widetilde{\mathcal{N}}/2.\end{cases} \tag{31}$$

Also, there is a time of free passing the crossroads

$$t_{fs}=\frac{L_f-L_r(j)}{v_f}=\frac{v_f t_f-\mathcal{N}_j t_r l_v}{v_f}=t_f\left(1-\frac{\mathcal{N}_j l_v}{v_f}\right). \tag{32}$$

The time of free passing during green light appears $T/(t_r+t_f)$ times. Thus, the free passing during green light constitutes a fraction of the total period T

$$f_f=\frac{T}{t_f+t_r}\frac{t_{fs}}{T}=\frac{1}{2t_f}t_{fs}=\frac{1}{2}\left(1-\frac{\mathcal{N}_j l_v}{v_f}\right) \tag{33}$$

for which the sound equivalent level [Eq. (16)] has to be calculated for the vehicle free flow as for the sub-segment $i=1$. As the time of the free flow can constitute a substantial part of the analyzing T period (Appendix B), it has to be taken in the calculation of the time-average sound level in the vicinity of a crossroads.

According to the here-applied simplified model of an interrupted movement with parameters gathered in Table 2, the sound level in the vicinity of a crossroads has the following form

$$L_{A\,\mathrm{eq}}(T)=\begin{cases}10\log\left\{f_f\displaystyle\sum_{j=1}^{J}10^{0.1L_{A\,\mathrm{eq}j}(S(v_c))}+(1-f_f)\sum_{j=1}^{J}\sum_{i=1}^{5}10^{0.1L_{A\,\mathrm{eq}j}(i)}\right\}, & \\ & \mathcal{N}_j<\widetilde{\mathcal{N}},\\ 10\log\left\{\displaystyle\sum_{j=1}^{J}\sum_{i=1}^{5}10^{0.1L_{A\,\mathrm{eq}j}(i)}\right\}, & \mathcal{N}_j\geq\widetilde{\mathcal{N}}.\end{cases} \tag{34}$$

The total sound field in Eq. (34) is the result of radiation of point sources spread along lanes in the road arms. The participation of the arm in front of the observation points is due to the lane segments defined by Eq. (5). The participation of the perpendicular arm is limited as the lane segments are screened by buildings corners (Fig. 4). The quantitative effects of the mechanism in the case of an asymmetric crossroad will be presented bellow.

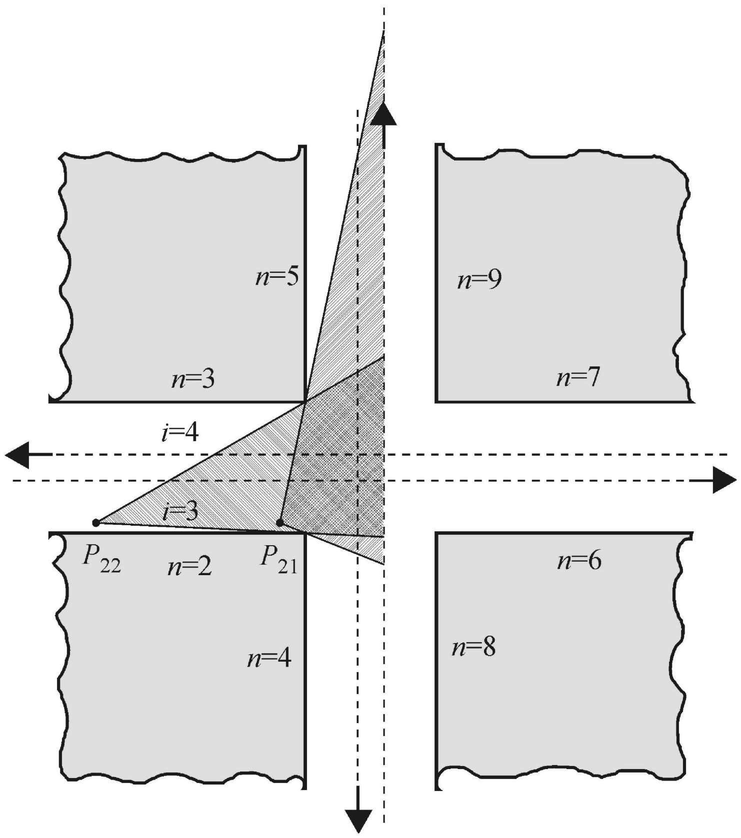

Fig. 4. The part of sub-segments in the perpendicular arm mostly affecting the acoustical field at the observation points.

4. Examples

A simple description of the dependence of the sound level distribution along a building façade on the variation of one or a group of road parameters is not possible. The desired relation could be found only by performing a calculation with use of a simulation program. The examples presented below show what kind of effects can be investigated basing on the ability of the PROP10 program.

The assumed roads forming a crossroads are at the bottoms of canyon-streets of equal heights $b_1^\alpha = b_2^\alpha = b_1^\beta = b_2^\beta = b = 39$ m and cut at the right angle. The average traffic parameters calculated by Eqs. (12)–(15) are given in Table 1. By taking two values of the speed of leaving the crossroads, two situations are analyzed: a normal one for $v_f = 10$ km/h and that resulting in the creation of a traffic jam for $v_f = 5$ km/h (Table 2, Table 3). Here, a relatively gentle driving manner is assumed with 20% of the aggressive starts what results in $\xi = 2$ [11]. Applying the simulation program PROP10 with the summation step $\Delta x_E = 5$ m in the sound exposure calculation and a number of interactions $K = 3$, the sound level in the vicinity of the crossroads has been calculated. The results of the sound level spread over the building façade in the range from the ground to the twelfth floor are presented in figures, while the sound levels at the ground floor $L_{op}^{\alpha(\beta)}$ and their appropriate differences, which show the tendency of growing or diminishing of the sound levels, are presented in tables.

4.1. Symmetric crossroads

The variation in the sound level distribution in the vicinity of a crossroads of two-lane (A) and four-lane streets (B) is investigated (Table 4). For this symmetric crossroads $(J^\alpha = J^\beta = J/2,\ a^\alpha = a^\beta = a)$ the observation points only in one arm of the crossroads have to be taken for the analysis. Here, four points are taken in the α-arm: two at the arriving side and two at the leaving side (Fig. 3, Table 5). The results obtained, presented in relation to the sound level in a single street with fluent movement of the cruising speed $v_c = 55$ km/h, are shown in Fig. 4, while the sound levels at the ground floor L_{op}^{α} and their appropriate differences are presented in Tables 6–8.

Table 4. Geometry and traffic parameters for three different crossroads.

crossroads	a^α [m]	a^β [m]	J^α	J^β	$\mathcal{N}^\alpha = \sum_j \mathcal{N}_j^\alpha$ [veh/h]	$\mathcal{N}^\beta = \sum_j \mathcal{N}_j^\beta$ [veh/h]
A	27	27	2	2	2400	2400
B	34	34	4	4	4800	4800
C	27	34	2	4	2400	4800

In Table 6 the effect of addition of two lanes accompanied by enlarging the existing canyons (Table 4) is shown. The increase of the sound level by about 2.5 dB(A) for all the positions is observed. This is in agreement with the results obtained previously for a single canyon where the addition of two lanes results in a rise of the sound level from 2 to 3 dB(A) depending on the canyon width [6, 7].

The investigation shows that a rise of the speed of leaving a crossroads (Table 7) causes a sound levels rise from about 1 dB(A) to about 2 dB(A) depending on the observation point positions. Moreover, from Fig. 4 it can be seen that for the leaving speed $v_f = 10$ km/h the levels are higher than for a single street of cruising speed $v_c = 55$ km/h, while for the leaving speed $v_f = 5$ km/h they are lower. In detail, these effects of the leaving speed growth are presented in Table 8. Deepening in a crossroads

Table 5. Observation point positions.

point		coordinates in meters	
in the vicinity of panel $n=2$	P_{21}	$x_p^\alpha(b_2^\alpha) = -\frac{a^\beta}{2} - 5,$	$y_p^\alpha(b_2^\alpha) = -\frac{a^\alpha}{2} + 0.5$
	P_{22}	$x_p^\alpha(b_2^\alpha) = -\frac{a^\beta}{2} - 50,$	$y_p^\alpha(b_2^\alpha) = -\frac{a^\alpha}{2} + 0.5$
in the vicinity of panel $n=3$	P_{31}	$x_p^\alpha(b_1^\alpha) = -\frac{a^\beta}{2} - 5,$	$y_p^\alpha(b_1^\alpha) = \frac{a^\alpha}{2} - 0.5$
	P_{32}	$x_p^\alpha(b_1^\alpha) = -\frac{a^\beta}{2} - 50,$	$y_p^\alpha(b_1^\alpha) = \frac{a^\alpha}{2} - 0.5$
in the vicinity of panel $n=4$	P_{41}	$x_p^\beta(b_2^\beta) = -\frac{a^\beta}{2} + 0.5,$	$y_p^\beta(b_2^\beta) = -\frac{a^\alpha}{2} - 5$
	P_{42}	$x_p^\beta(b_2^\beta) = -\frac{a^\beta}{2} + 0.5,$	$y_p^\beta(b_2^\beta) = -\frac{a^\alpha}{2} - 50$
in the vicinity of panel $n=8$	P_{81}	$x_p^\beta(b_1^\beta) = \frac{a^\beta}{2} - 0.5,$	$y_p^\beta(b_1^\beta) = -\frac{a^\alpha}{2} - 5$
	P_{82}	$x_p^\beta(b_1^\beta) = \frac{a^\beta}{2} - 0.5,$	$y_p^\beta(b_1^\beta) = -\frac{a^\alpha}{2} - 50$

Table 6. Sound level on the ground floor: effect of enlarging streets.

v_f [km/h]	point	$J = J^\alpha + J^\beta$ $\xi_3 = \xi_4 = 2$	L_{op}^α [dB (A)]		
5	P_{21}	4	77.68	$\Delta = -2.40$	arriving side
		8	80.08		
	P_{22}	4	76.80	$\Delta = -2.53$	
		8	79.33		
	P_{31}	4	77.42	$\Delta = -2.33$	leaving side
		8	79.75		
	P_{32}	4	76.74	$\Delta = -2.59$	
		8	79.33		
10	P_{21}	4	79.05	$\Delta = -2.42$	arriving side
		8	81.47		
	P_{22}	4	78.10	$\Delta = -2.51$	
		8	80.61		
	P_{31}	4	79.12	$\Delta = -2.45$	leaving side
		8	81.57		
	P_{32}	4	78.17	$\Delta = -2.44$	
		8	80.61		

arm (Table 8a) shows a decrease (?) from about 0.5 dB(A) to 1 dB(A). It was found by comparing the arriving and leaving sides (Table 8b) that the leaving side starts to be noisier when the leaving speed grows.

Table 7. Sound level on the ground floor: effect of raising cruising speed.

$J = J^{\alpha} + J^{\beta}$ $\xi_3 = \xi_4 = 2$	point	v_f [km/h]	L_{op}^{α} [dB (A)]		
4	P_{21}	5	77.68	$\Delta = -1.37$	arriving side (less affected)
		10	79.05		
	P_{22}	5	76.80	$\Delta = -1.30$	
		10	78.10		
	P_{31}	5	77.42	$\Delta = -1.70$	leaving side
		10	79.12		
	P_{32}	5	76.74	$\Delta = -1.43$	
		10	78.17		
8	P_{21}	5	80.08	$\Delta = -1.39$	arriving side
		10	81.47		
	P_{22}	5	79.33	$\Delta = -1.28$	
		10	80.61		
	P_{31}	5	79.75	$\Delta = -1.82$	leaving side
		10	81.57		
	P_{32}	5	79.33	$\Delta = -1.28$	
		10	80.61		

An analysis of the observation point positions (Table 5) in relation to the sub-segments shows that the acoustical field there is due mostly to the third and fourth sub-segments (Fig. 5). Points P_{21}, P_{31} are 5 m from the building corners, points P_{22}, P_{32} – 50 m further, while the third sub-segment extends from the crossroads center to a distance of about 200 m (Table 3, Appendix A) and the fourth one from the crossroads center to a distance of about 100 m (Table 2). Thus, the arriving side $(P_{21},\, P_{22})$ is affected mostly by the third sub-segment, the leaving side $(P_{31},\, P_{32})$ – by the fourth sub-segment (Fig. 5). The energy emitted by the sub-segments [Eqs. (17)–(22)] depends on their defined lengths $l_j(i = 3) \approx 200$ m, $l_j(i = 4) \approx 100$ m, linear density $S(i = 3) = \xi S(v_c)/2$, $S(i = 4) = (\xi + 1)S(v_c)/2$, and the flow rate $\mathcal{N}_j(i = 3) = \mathcal{N}_j$, $\mathcal{N}_j(i = 4) = \widetilde{\mathcal{N}}(v_f)/2$ (Table 2). Here the present parameter ξ has an observed value which varies from $\xi = 1.5$ for a normal operation to $\xi = 4.0$ for an aggressive one [11]. Assuming that the aggressive start constitutes 20%, a single value $\xi = 2.0$ is ascribed to all the sub-segments. For these conditions, the energy linear density is the highest at the fourth sub-segment (Fig. 6). Nevertheless, it seems reasonable to assume, especially for the leaving speed $v_f = 10$ km/h, that at the fourth sub-segment the ξ value is higher than at other sub-segments.

Taking this into account, the simulation has been carried out for $v_f = 10$ km/h and $\xi(i = 3) = \xi_3 = 2$, $\xi(i = 4) = \xi_4 = 4$ (Fig. 7, Tables 9–10). It can be seen that the more aggressive driving rises the sound levels from about 1 dB(A) to 1.5 dB(A) depending on observation points positions in the crossroads arms (Table 9). A detailed

Table 8. Sound level on the ground floor.

a. Effect of deepening in arm.

<table>
<tr><th>v_f
[km/h]</th><th>$J = J^\alpha + J^\beta$
$\xi_3 = \xi_4 = 2$</th><th>point</th><th colspan="3">L_{op}^α
[dB (A)]</th></tr>
<tr><td rowspan="8">5</td><td rowspan="4">4</td><td>P_{21}</td><td>77.68</td><td rowspan="2">$\Delta = 0.88$</td><td rowspan="2">arriving side</td></tr>
<tr><td>P_{22}</td><td>76.80</td></tr>
<tr><td>P_{31}</td><td>77.42</td><td rowspan="2">$\Delta = 0.68$</td><td rowspan="2">leaving side</td></tr>
<tr><td>P_{32}</td><td>76.74</td></tr>
<tr><td rowspan="4">8</td><td>P_{21}</td><td>80.08</td><td rowspan="2">$\Delta = 0.75$</td><td rowspan="2">arriving side</td></tr>
<tr><td>P_{22}</td><td>79.33</td></tr>
<tr><td>P_{31}</td><td>79.75</td><td rowspan="2">$\Delta = 0.42$</td><td rowspan="2">leaving side</td></tr>
<tr><td>P_{32}</td><td>79.33</td></tr>
<tr><td rowspan="8">10</td><td rowspan="4">4</td><td>P_{21}</td><td>79.05</td><td rowspan="2">$\Delta = 0.95$</td><td rowspan="2">arriving side</td></tr>
<tr><td>P_{22}</td><td>78.10</td></tr>
<tr><td>P_{31}</td><td>79.12</td><td rowspan="2">$\Delta = 0.95$</td><td rowspan="2">leaving side</td></tr>
<tr><td>P_{32}</td><td>78.17</td></tr>
<tr><td rowspan="4">8</td><td>P_{21}</td><td>81.47</td><td rowspan="2">$\Delta = 0.86$</td><td rowspan="2">arriving side</td></tr>
<tr><td>P_{22}</td><td>80.61</td></tr>
<tr><td>P_{31}</td><td>81.57</td><td rowspan="2">$\Delta = 0.96$</td><td rowspan="2">leaving side</td></tr>
<tr><td>P_{32}</td><td>80.61</td></tr>
</table>

b. Arriving side versus leaving one.

<table>
<tr><th>v_f
[km/h]</th><th>$J = J^\alpha + J^\beta$
$\xi_3 = \xi_4 = 2$</th><th>point</th><th colspan="4">L_{op}^α
[dB (A)]</th></tr>
<tr><td rowspan="8">5</td><td rowspan="4">4</td><td>P_{21}</td><td>77.68</td><td rowspan="2">$\Delta = 0.26$</td><td rowspan="2">near</td><td rowspan="4">arriving side noisier</td></tr>
<tr><td>P_{31}</td><td>77.42</td></tr>
<tr><td>P_{22}</td><td>76.80</td><td rowspan="2">$\Delta = 0.06$</td><td rowspan="2">further</td></tr>
<tr><td>P_{32}</td><td>76.74</td></tr>
<tr><td rowspan="4">8</td><td>P_{21}</td><td>80.08</td><td rowspan="2">$\Delta = 0.33$</td><td rowspan="2">near</td><td rowspan="4">arriving side noisier or equal</td></tr>
<tr><td>P_{31}</td><td>79.75</td></tr>
<tr><td>P_{22}</td><td>79.33</td><td rowspan="2">$\Delta = 0$</td><td rowspan="2">further</td></tr>
<tr><td>P_{32}</td><td>79.33</td></tr>
<tr><td rowspan="8">10</td><td rowspan="4">4</td><td>P_{21}</td><td>79.05</td><td rowspan="2">$\Delta = -0.07$</td><td rowspan="2">near</td><td rowspan="4">leaving side noisier</td></tr>
<tr><td>P_{31}</td><td>79.12</td></tr>
<tr><td>P_{22}</td><td>78.10</td><td rowspan="2">$\Delta = -0.07$</td><td rowspan="2">further</td></tr>
<tr><td>P_{32}</td><td>78.17</td></tr>
<tr><td rowspan="4">8</td><td>P_{21}</td><td>81.47</td><td rowspan="2">$\Delta = -0.10$</td><td rowspan="2">near</td><td rowspan="4">leaving side noisier or equal</td></tr>
<tr><td>P_{31}</td><td>81.57</td></tr>
<tr><td>P_{22}</td><td>80.61</td><td rowspan="2">$\Delta = 0$</td><td rowspan="2">further</td></tr>
<tr><td>P_{32}</td><td>80.61</td></tr>
</table>

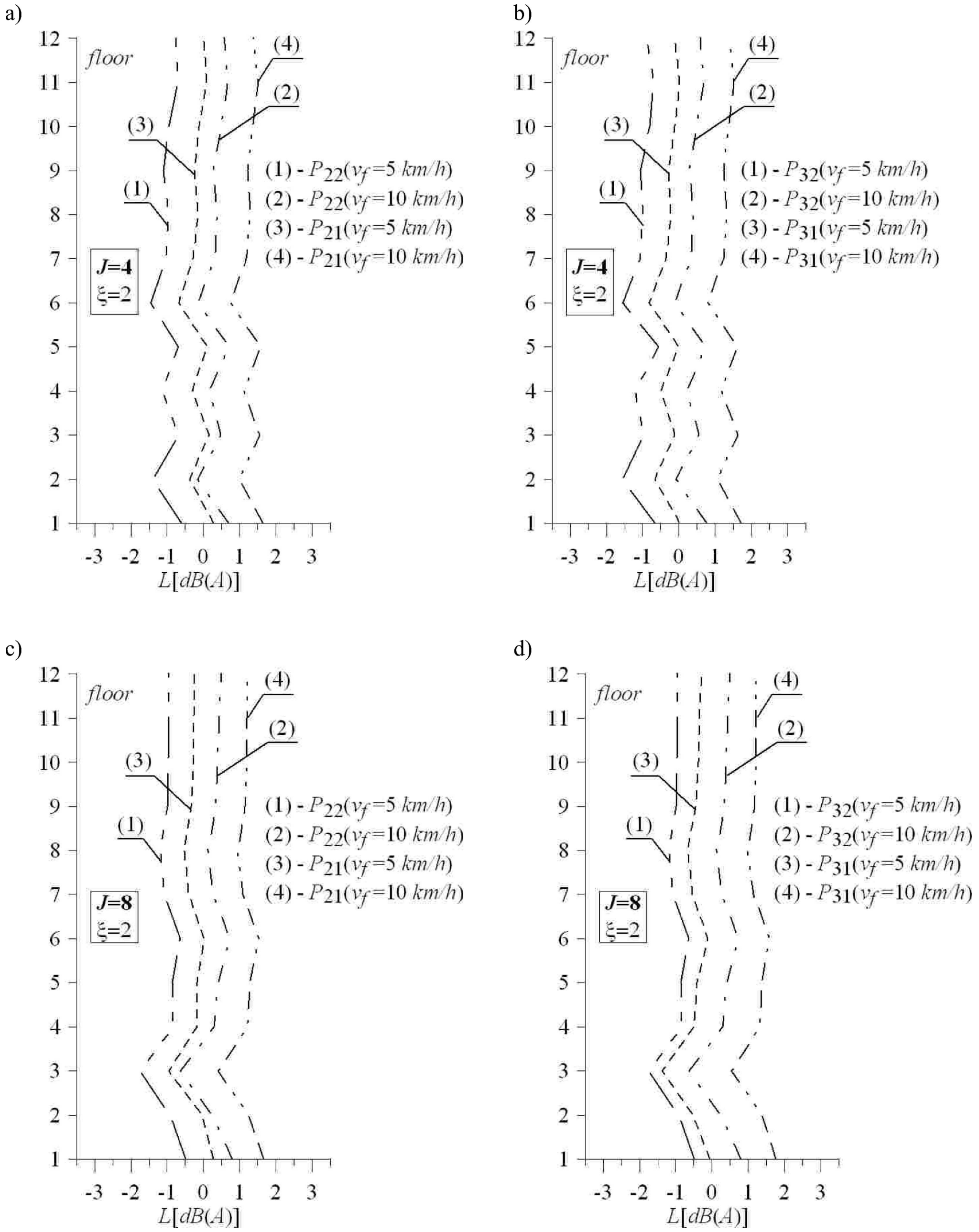

Fig. 5. The sound level distribution (Table 4, Fig.3) in relation to the single street ($v_c = 55\text{km/h}$): a) arriving side in the vicinity of the A-crossroads, b) leaving side in the vicinity of the A-crossroads, c) arriving side in the vicinity of the B-crossroads, d) leaving side the in vicinity of the B-crossroads.

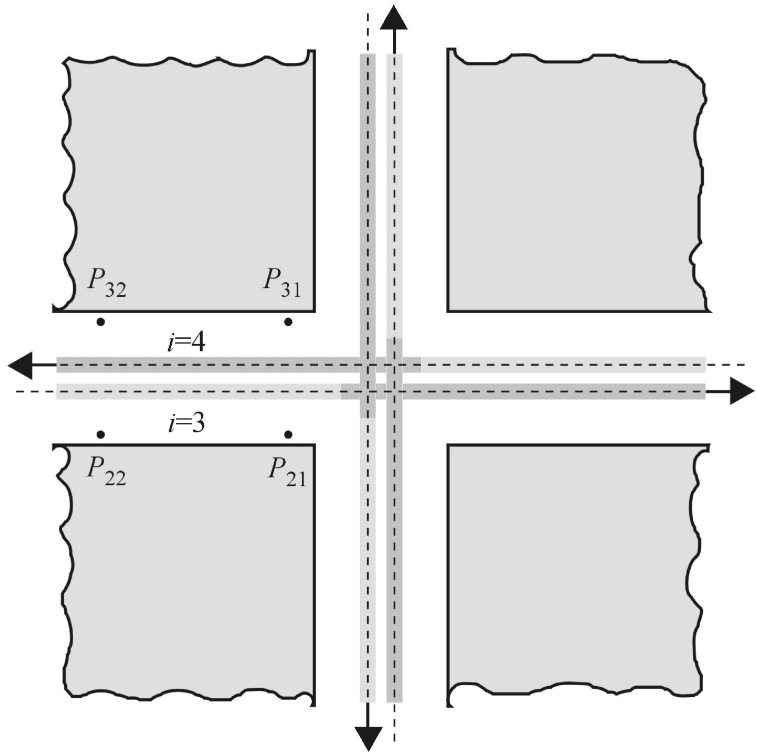

Fig. 6. The sub-segments mostly affecting the acoustical field at the observation points.

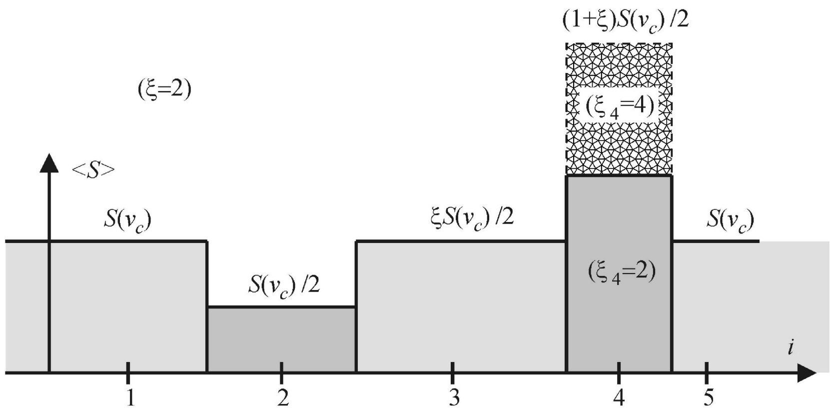

Fig. 7. Energy linear density for $\xi = 2$ and two different values at the fourth sub-segment $\xi(i = 4) = \xi_4 = 2, 4$.

investigation shows that deepening in the crossroads arm shows a decrease (?) from about 1 dB(A) to 1.5 dB(A) (Table 10a) which is higher than for less aggressive driving (Table 8a). Moreover, the leaving side becomes a little noisier (Table 10b) than in the case of less aggressive driving (Table 8b).

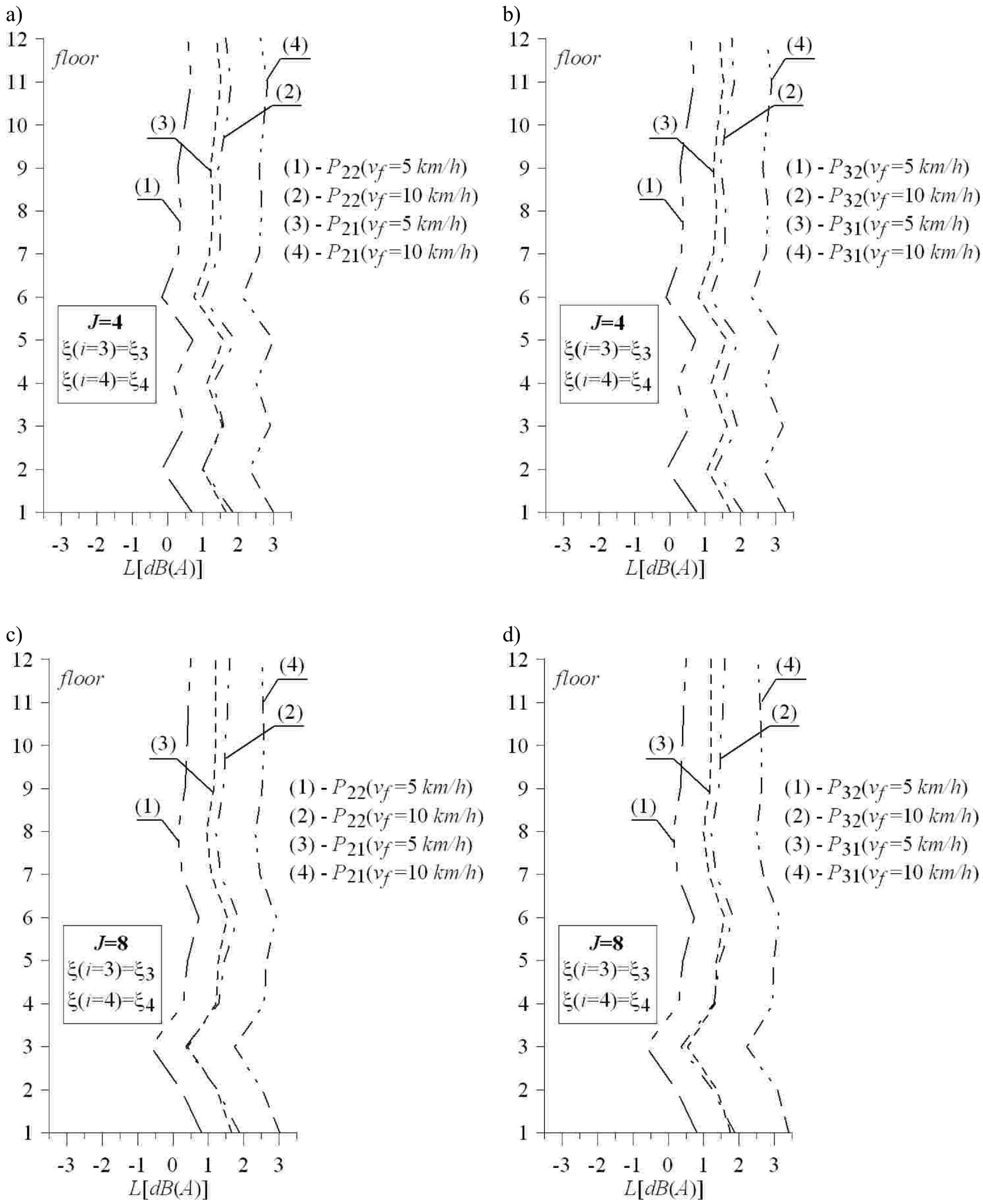

Fig. 8. The sound level distribution (Table 4, Fig. 3) for more aggressive driving (Fig. 6) in relation to the single street ($v_c = 55$ km/h): a) arriving side in the vicinity of the A-crossroads, b) leaving side in the vicinity of the A-crossroads, c) arriving side in the vicinity of the B-crossroads, d) leaving side in the vicinity of the B-crossroads.

Table 9. Sound level on the ground floor: effect of more aggressive driving.

v_f [km/h]	$J = J^\alpha + J^\beta$	point	$\xi(i=3)=\xi_3$ $\xi(i=4)=\xi_4$	L^α_{op} [dB (A)]	
10	4	P_{21}	$\xi_3 = 2, \quad \xi_4 = 2$	79.05	$\Delta = -1.34$
			$\xi_3 = 2, \quad \xi_4 = 4$	80.39	
		P_{22}	$\xi_3 = 2, \quad \xi_4 = 2$	78.10	$\Delta = -1.15$
			$\xi_3 = 2, \quad \xi_4 = 4$	79.25	
		P_{31}	$\xi_3 = 2, \quad \xi_4 = 2$	79.12	$\Delta = -1.56$
			$\xi_3 = 2, \quad \xi_4 = 4$	80.68	
		P_{32}	$\xi_3 = 2, \quad \xi_4 = 2$	78.17	$\Delta = -1.30$
			$\xi_3 = 2, \quad \xi_4 = 4$	79.47	
	8	P_{21}	$\xi_3 = 2, \quad \xi_4 = 2$	81.47	$\Delta = -1.35$
			$\xi_3 = 2, \quad \xi_4 = 4$	82.82	
		P_{22}	$\xi_3 = 2, \quad \xi_4 = 2$	80.61	$\Delta = -1.09$
			$\xi_3 = 2, \quad \xi_4 = 4$	81.70	
		P_{31}	$\xi_3 = 2, \quad \xi_4 = 2$	81.57	$\Delta = -1.64$
			$\xi_3 = 2, \quad \xi_4 = 4$	83.21	
		P_{32}	$\xi_3 = 2, \quad \xi_4 = 2$	80.61	$\Delta = -1.09$
			$\xi_3 = 2, \quad \xi_4 = 4$	81.70	

Table 10. Sound level on the ground floor.

a. Effect of deepening in arm.

v_f [km/h]	$J = J^\alpha + J^\beta$ $\xi_3 = 2, \ \xi_4 = 4$	point	L^α_{op} [dB (A)]		
10	4	P_{21}	80.39	$\Delta = 1.14$	arriving side
		P_{22}	79.25		
		P_{31}	80.68	$\Delta = 1.21$	leaving side
		P_{32}	79.47		
	8	P_{21}	82.82	$\Delta = 1.12$	arriving side
		P_{22}	81.70		
		P_{31}	83.21	$\Delta = 1.51$	leaving side
		P_{32}	81.70		

Table 10. Sound level on the ground floor.

b. Arriving side versus leaving one.

v_f [km/h]	$J = J^{\alpha} + J^{\beta}$ $\xi_3 = 2,\ \xi_4 = 4$	point	L_{op}^{α} [dB (A)]			
	4	P_{21}	80.39	$\Delta = -0.29$	near	leaving side noisier
		P_{31}	80.68			
		P_{22}	79.25	$\Delta = -0.22$	further	
		P_{32}	79.47			
	8	P_{21}	82.82	$\Delta = -0.39$	near	leaving side noisier or equal
		P_{31}	83.21			
		P_{22}	81.70	$\Delta = 0.00$	further	
		P_{32}	81.70			

4.2. Asymmetric crossroads

The asymmetric crossroads (C) of two lanes in the α-arm and four lanes in the β-arm (Table 4) will be compared with the symmetric crossroads of two-lanes (A) and four-lanes (B) in both the arms. As expected, it can be seen in Figs. 9–12 that the field in the asymmetric crossroads arm of two lanes approaches that of the symmetric one of two lanes, while that in the asymmetric crossroads arm of four lanes approaches that of the symmetric one of four lanes. The decrease of the sound level in the range from the ground to the twelfth floor is about 3.5 dB(A). As the curve giving the sound level spread over the building façade for different crossroads and the leaving speeds are parallel, a quantitative comparison can be made for the sound levels on the ground floor $L_{op}^{\alpha(\beta)}$. The tested C-crossroads can be created by addition of two lanes in the β-arm of the A-crossroads or subtraction of two lanes in the α-arm of the B-crossroads. Thus, presenting the results, the consequences of the variation in the crossroads geometry are observed all the time at the points in the arm changing and in the perpendicular arm. The appropriate differences are presented in Tables 11–15.

The investigation shows that a change in the speed of leaving the crossroads, which means a difference between the normal ($v_f = 10$ km/h and jam situations ($v_f = 5$ km/h, lowers the sound level at the ground floor by about 1.5 dB(A) (Tables 11). In Table 11a the C-crossroads is presented as the result of addition of two lanes in the β-arm of the A-crossroads, while Table 11b presents the crossroads as the result of subtraction of two lanes in the α-arm of the B-crossroads. These effects of addition and subtraction of two lanes at points in the arm perpendicular to the arm of the change and in the arm of the change is presented in Table 12 and Table 13. The tables contain an explanation of the results in Tables 11. It is seen that for addition or subtraction of two lanes, despite that the added or subtracted energy is the same, the absolute values of level changes are higher for addition than for subtraction. This is due to the

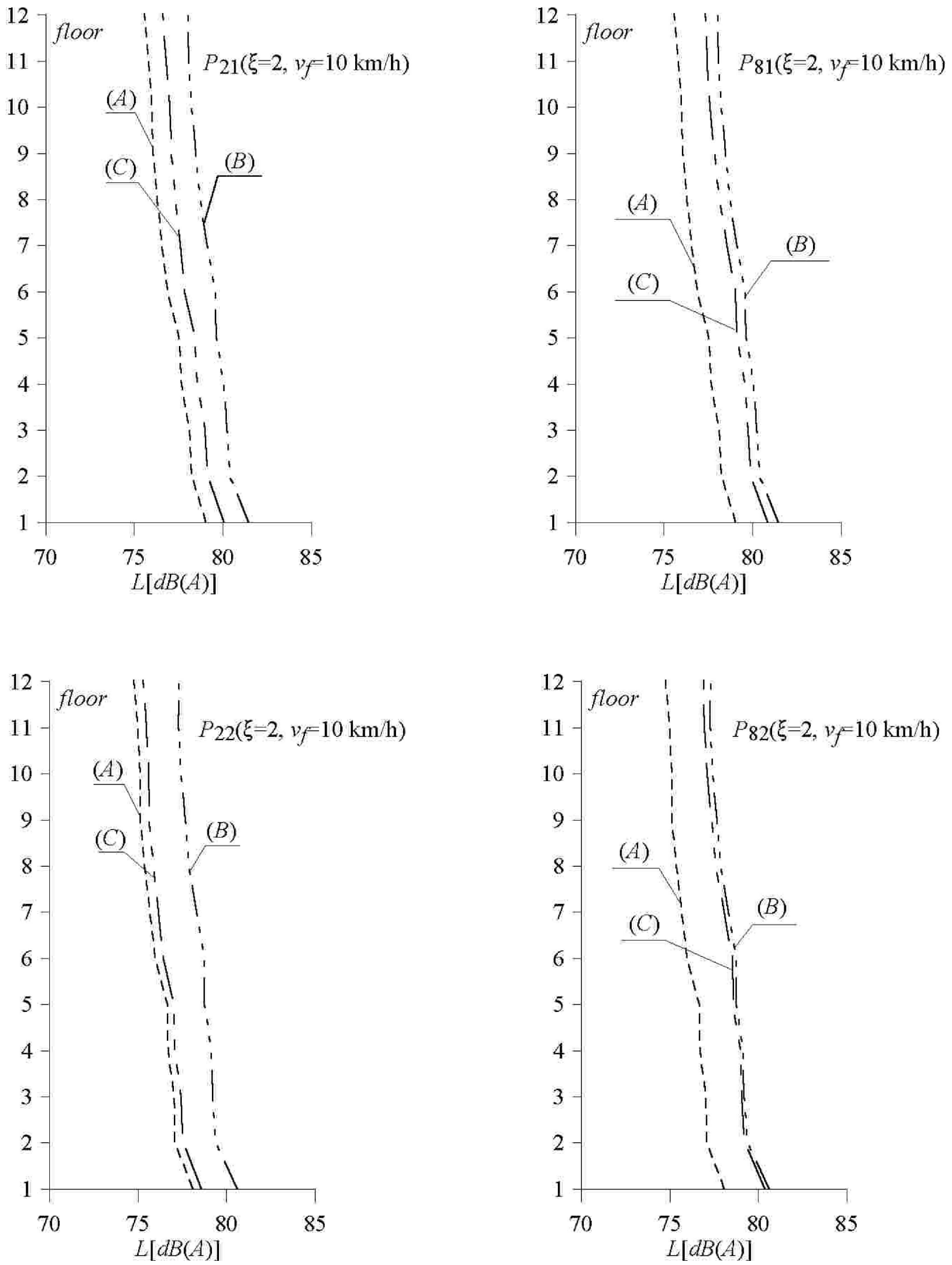

Fig. 9. The sound level distribution at the arriving side in the vicinity of the A-crossroads, B-crossroads and C-crossroads (Table 5, Fig. 3) for a normal situation (Table 4).

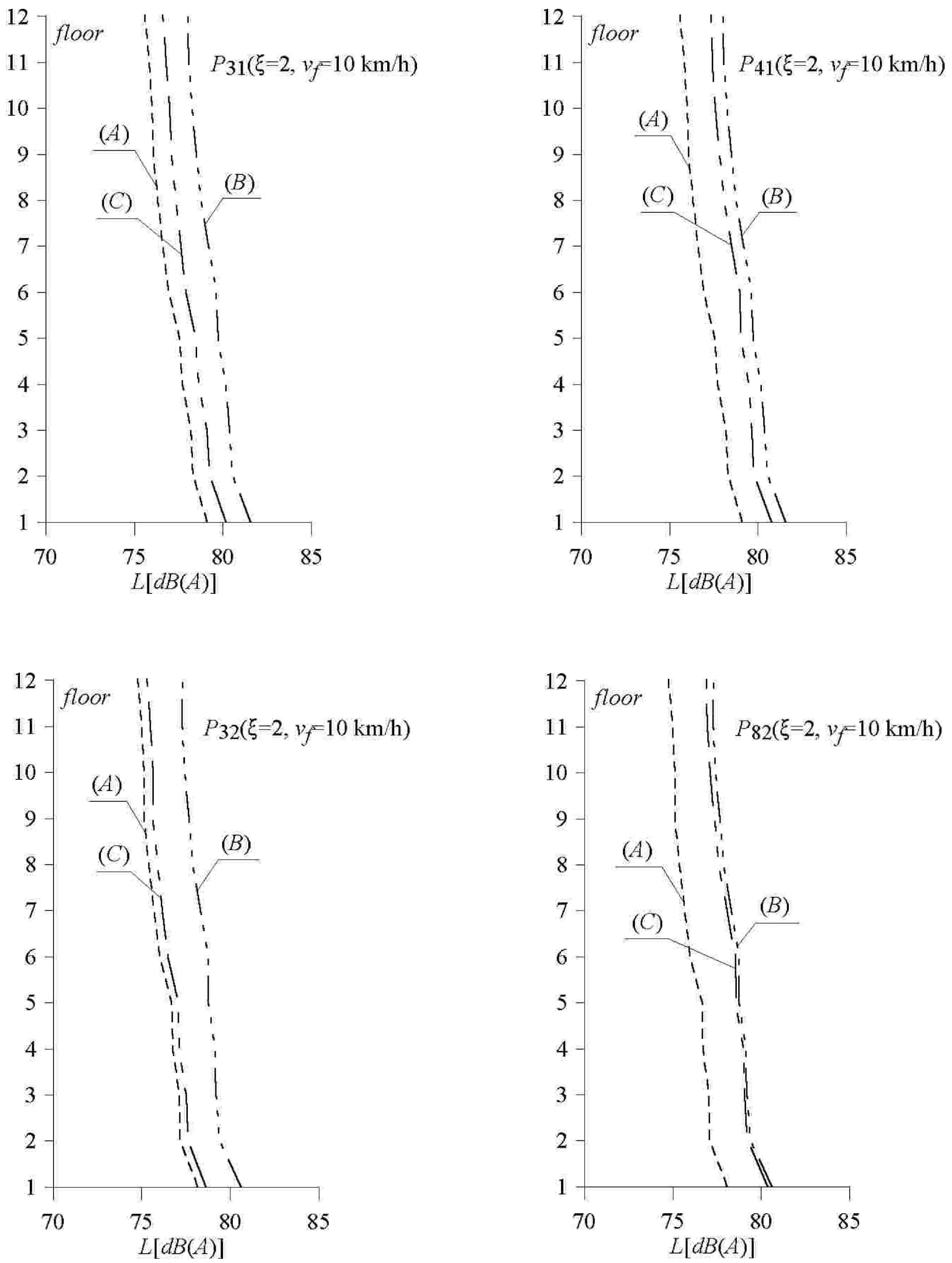

Fig. 10. The sound level distribution at the leaving side in the vicinity of the A-crossroads, B-crossroads and C-crossroads (Table 5, Fig. 3) for a normal situation (Table 4).

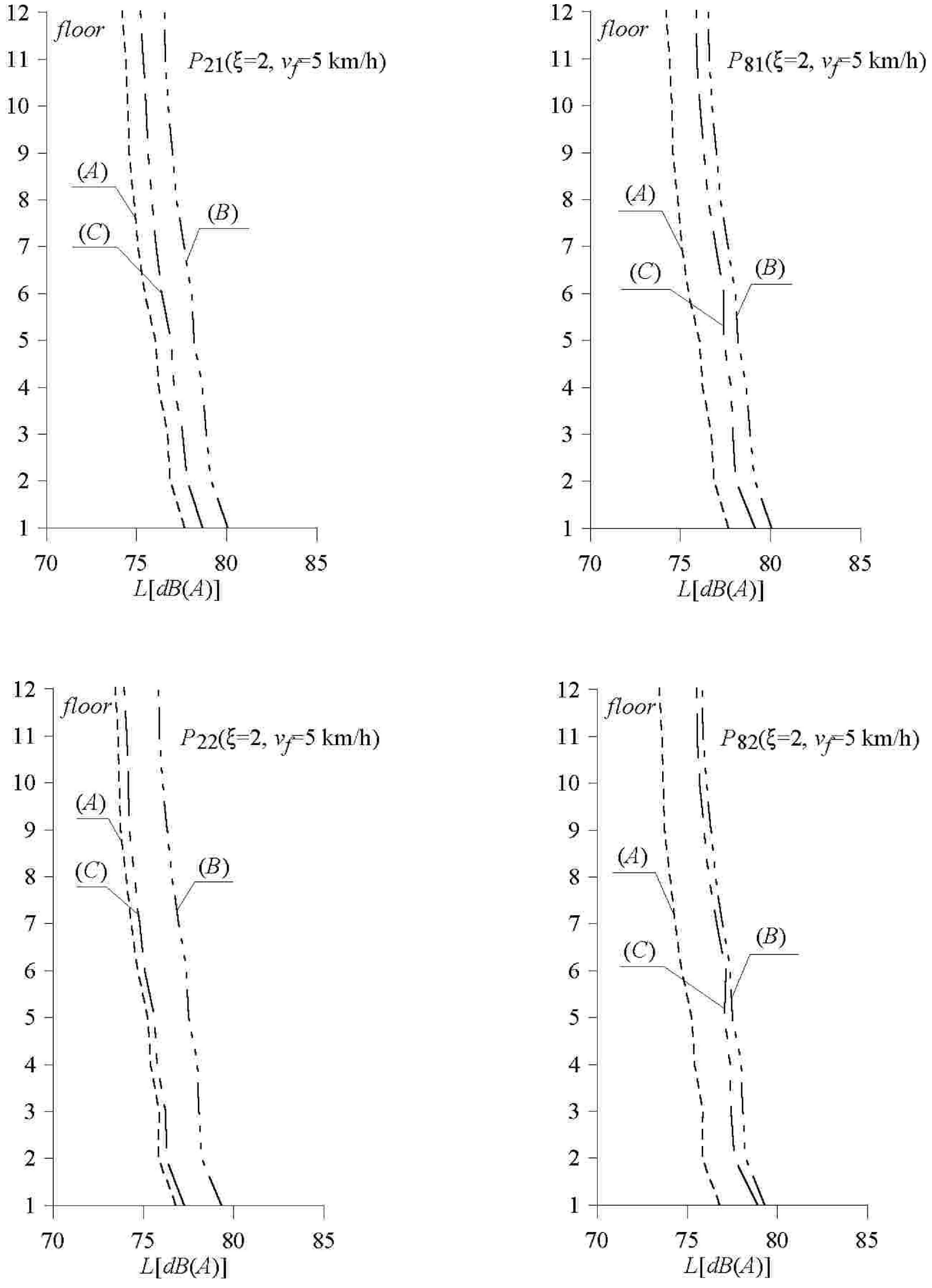

Fig. 11. The sound level distribution at the arriving side in the vicinity of the A-crossroads, B-crossroads and C-crossroads (Table 5, Fig. 3) for traffic jam (Table 4).

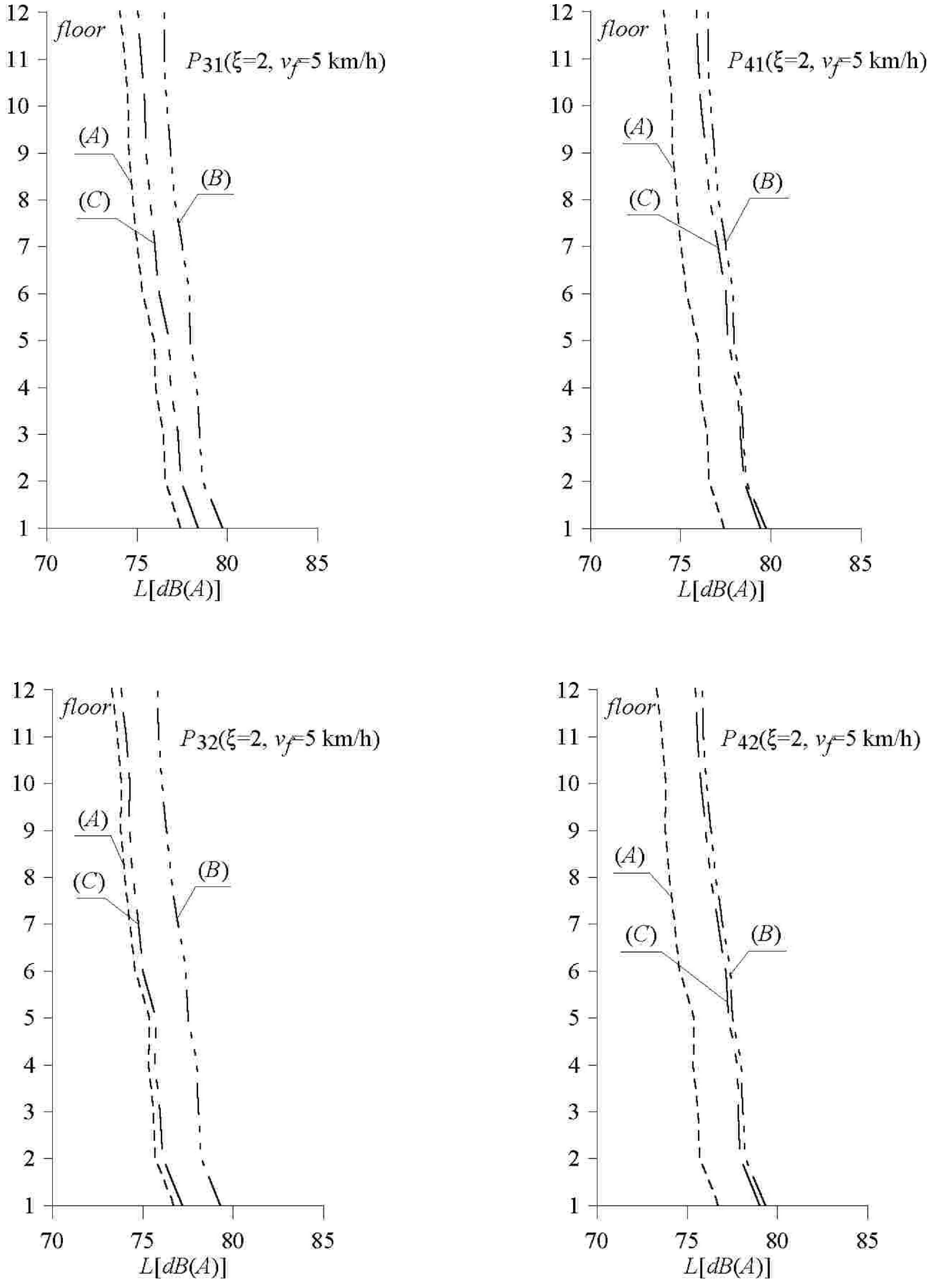

Fig. 12. The sound level distribution at the leaving side in the vicinity of the A-crossroads, B-crossroads and C-crossroads (Table 5, Fig. 3) for traffic jam (Table 4).

application of a logarithmic scale, where function dependence becomes weaker with growing argument. Here, the levels for the A-crossroads are lower than for the B-crossroads. Thus, addition of two lanes to the A-crossroads causes changes in the sound level of higher absolute values than subtraction of two lanes from the B-crossroads.

Table 11. Sound level on the ground floor: effect of rising the leaving speed.

a. Comparison between C-crossroads and A-crossroads.

cross-roads	J^{α}	J^{β}	point	v_f [km/h]	L_{op}^{α} [dB (A)] (changes in perpendicular arm)		L_{op}^{β} [dB (A)] (changes in front of points)	
A	2	2	P_{21}/P_{81}	5	77.68	$\Delta = -1.37$	77.68	$\Delta = -1.37$
				10	79.05		79.05	
			P_{22}/P_{82}	5	76.80	$\Delta = -1.30$	76.80	$\Delta = -1.30$
				10	78.10		78.10	
			P_{31}/P_{41}	5	77.42	$\Delta = -1.70$	77.42	$\Delta = -1.70$
				10	79.12		79.12	
			P_{32}/P_{42}	5	76.74	$\Delta = -1.43$	76.74	$\Delta = -1.43$
				10	78.17		78.17	
C	2	4	P_{21}	5	78.69	$\Delta = -1.39$		
				10	80.08			
			P_{22}	5	77.28	$\Delta = -1.31$		
				10	78.59			
			P_{31}	5	78.39	$\Delta = -1.77$		
				10	80.16			
			P_{32}	5	77.21	$\Delta = -1.44$		
				10	78.65			
			P_{81}	5			79.14	$\Delta = -1.74$
				10			80.88	
			P_{82}	5			78.92	$\Delta = -1.47$
				10			80.39	
			P_{41}	5			79.45	$\Delta = -1.35$
				10			80.80	
			P_{42}	5			79.03	$\Delta = -1.25$
				10			80.28	

arriving side   leaving side

This also explains why in Tables 11 more noticeable changes are observed all the time in the β-arm.

In Tables 14 one can see that moving from the crossroads and deepening in its arm not always results in lowering of the sound levels. The complexity of the sound field

Table 11. Sound level on the ground floor: effect of rising the leaving speed.

b. Comparison between C-crossroads and B-crossroads.

cross-roads	J^α	J^β	point	v_f [km/h]	L^α_{op} [dB (A)] (changes in front of points)		L^β_{op} [dB (A)] (changes in perpendicular arm)	
B	4	4	P_{21}/P_{81}	5	80.08	$\Delta = -1.39$	80.08	$\Delta = -1.39$
				10	81.47		81.47	
			P_{22}/P_{82}	5	79.33	$\Delta = -1.28$	79.33	$\Delta = -1.28$
				10	80.61		80.61	
			P_{31}/P_{41}	5	79.75	$\Delta = -1.82$	79.75	$\Delta = -1.82$
				10	81.57		81.57	
			P_{32}/P_{42}	5	79.33	$\Delta = -1.28$	79.33	$\Delta = -1.28$
				10	80.61		80.61	
C	2	4	P_{21}	5	78.69	$\Delta = -1.39$		
				10	80.08			
			P_{22}	5	77.28	$\Delta = -1.31$		
				10	78.59			
			P_{31}	5	78.39	$\Delta = -1.77$		
				10	80.16			
			P_{32}	5	77.21	$\Delta = -1.44$		
				10	78.65			
			P_{81}	5			79.14	$\Delta = -1.74$
				10			80.88	
			P_{82}	5			78.92	$\Delta = -1.47$
				10			80.39	
			P_{41}	5			79.45	$\Delta = -1.35$
				10			80.80	
			P_{42}	5			79.03	$\Delta = -1.25$
				10			80.28	

arriving side   leaving side

Table 12. Sound level on the ground floor.

a. Effect of addition of two lanes in β-arm of A-crossroads, perpendicular to observation points.

v_f [km/h]	point	cross-roads	J^α	J^β	L_{op}^{α} [dB (A)]		L_{op}^{β} [dB (A)]	
5	P_{21}	A	2	2	77.68	$\Delta = -1.01$		
		C	2	4	78.69			
	P_{22}	A	2	2	76.80	$\Delta = -0.48$		
		C	2	4	77.28			
	P_{31}	A	2	2	77.42	$\Delta = -0.97$		
		C	2	4	78.39			
	P_{32}	A	2	2	76.74	$\Delta = -0.47$		
		C	2	4	77.21			
10	P_{21}	A	2	2	79.05	$\Delta = -1.03$		
		C	2	4	80.08			
	P_{22}	A	2	2	78.10	$\Delta = -0.49$		
		C	2	4	78.59			
	P_{31}	A	2	2	79.12	$\Delta = -1.04$		
		C	2	4	80.16			
	P_{32}	A	2	2	78.17	$\Delta = -0.48$		
		C	2	4	78.65			

b. Effect of subtraction of two lanes in α-arm of B-crossroads, perpendicular to observation points.

v_f [km/h]	point	cross-roads	J^α	J^β	L_{op}^{α} [dB (A)]		L_{op}^{β} [dB (A)]	
5	P_{81}	B	4	4			80.08	$\Delta = 0.94$
		C	2	4			79.14	
	P_{82}	B	4	4			79.33	$\Delta = 0.41$
		C	2	4			78.92	
	P_{41}	B	4	4			79.75	$\Delta = 0.34$
		C	2	4			79.45	
	P_{42}	B	4	4			79.33	$\Delta = 0.30$
		C	2	4			79.03	
10	P_{81}	B	4	4			81.47	$\Delta = 0.59$
		C	2	4			80.88	
	P_{82}	B	4	4			80.61	$\Delta = 0.22$
		C	2	4			80.39	
	P_{41}	B	4	4			81.57	$\Delta = 0.77$
		C	2	4			80.80	
	P_{42}	B	4	4			80.61	$\Delta = 0.33$
		C	2	4			80.28	

arriving side   leaving side

Table 13. Sound level on the ground floor.

a. Effect of addition of two lanes in β-arm of A-crossroadsin front of observation points.

v_f [km/h]	point	cross-roads	J^α	J^β	L^α_{op} [dB (A)]		L^β_{op} [dB (A)]	
5	P_{81}	A	2	2			77.68	$\Delta = -1.46$
		C	2	4			79.14	
	P_{82}	A	2	2			76.80	$\Delta = -2.12$
		C	2	4			78.92	
	P_{41}	A	2	2			77.42	$\Delta = -1.93$
		C	2	4			79.45	
	P_{42}	A	2	2			76.74	$\Delta = -2.29$
		C	2	4			79.03	
10	P_{81}	A	2	2			79.05	$\Delta = -1.83$
		C	2	4			80.88	
	P_{82}	A	2	2			78.10	$\Delta = -2.29$
		C	2	4			80.39	
	P_{41}	A	2	2			79.12	$\Delta = -1.68$
		C	2	4			80.80	
	P_{42}	A	2	2			78.17	$\Delta = -2.11$
		C	2	4			80.28	

b. Effect of subtraction of two lanes in α-arm of B-crossroads in front of observation points.

v_f [km/h]	point	cross-roads	J^α	J^β	L^α_{op} [dB (A)]		L^β_{op} [dB (A)]	
5	P_{21}	B	4	4	80.08	$\Delta = 1.39$		
		C	2	4	78.69			
	P_{22}	B	4	4	79.33	$\Delta = 2.05$		
		C	2	4	77.28			
	P_{31}	B	4	4	79.75	$\Delta = 1.36$		
		C	2	4	78.39			
	P_{32}	B	4	4	79.33	$\Delta = 2.12$		
		C	2	4	77.21			
10	P_{21}	B	4	4	81.47	$\Delta = 1.39$		
		C	2	4	80.08			
	P_{22}	B	4	4	80.61	$\Delta = 2.02$		
		C	2	4	78.59			
	P_{31}	B	4	4	81.57	$\Delta = 1.41$		
		C	2	4	80.16			
	P_{32}	B	4	4	80.61	$\Delta = 1.96$		
		C	2	4	78.65			

arriving side   leaving side

Table 14. Sound level on the ground floor.

a. Effect of deepening in arm, comparison between C-crossroads and A-crossroads.

v_f [km/h]	cross-roads	J^α	J^β	point	L_{op}^{α} [dB (A)] (changes in perpendicular arm)			L_{op}^{β} [dB (A)] (changes in front of points)		
5	A	2	2	P_{21}/P_{81}	77.68	$\Delta = 0.88$	$\uparrow$	77.68	$\Delta = 0.88$	$\uparrow$
				P_{22}/P_{82}	76.80			76.80		
				P_{31}/P_{41}	77.42	$\Delta = 0.68$		77.42	$\Delta = 0.68$	
				P_{32}/P_{42}	76.74			76.74		
	C	2	4	P_{21}	78.69	$\Delta = 1.41$	$\uparrow$			
				P_{22}	77.28					
				P_{31}	78.39	$\Delta = 1.18$				
				P_{32}	77.21					
				P_{81}				79.14	$\Delta = 0.22$	$\downarrow$
				P_{82}				78.92		
				P_{41}				79.45	$\Delta = 0.42$	
				P_{42}				79.03		
10	A	2	2	P_{21}/P_{81}	79.05	$\Delta = 0.95$	$\updownarrow$	79.05	$\Delta = 0.95$	$\updownarrow$
				P_{22}/P_{82}	78.10			78.10		
				P_{31}/P_{41}	79.12	$\Delta = 0.95$		79.12	$\Delta = 0.95$	
				P_{32}/P_{42}	78.17			78.17		
	C	2	4	P_{21}	80.08	$\Delta = 1.49$	$\downarrow$			
				P_{22}	78.59					
				P_{31}	80.16	$\Delta = 1.51$				
				P_{32}	78.65					
				P_{81}				80.88	$\Delta = 0.49$	$\downarrow$
				P_{82}				80.39		
				P_{41}				80.80	$\Delta = 0.52$	
				P_{42}				80.28		

arriving side (white) leaving side (grey)

account for this since it results from radiation of point sources spread along the lanes which undergoes multiple reflections from the canyon walls, and the participation of the perpendicular arm becomes weaker with deepening due to the growing distance and screening by the building corners (Fig. 4). Here the simulation is made for the same flow rates in all directions. In reality, depending on daytime of interest, different directions

Table 14. Sound level on the ground floor.

b. Effect of deepening in arm, comparison between C-crossroads and B-crossroads.

v_f [km/h]	cross-roads	J^α	J^β	point	L_{op}^{α} [dB (A)] (changes in front of points)			L_{op}^{β} [dB (A)] (changes in perpendicular arm)		
5	B	4	4	P_{21}/P_{81}	80.08	$\Delta = 0.75$	↑	80.08	$\Delta = 0.75$	↑
				P_{22}/P_{82}	79.33			79.33		
				P_{31}/P_{41}	79.75	$\Delta = 0.42$		79.75	$\Delta = 0.42$	
				P_{32}/P_{42}	79.33			79.33		
	C	2	4	P_{21}	78.69	$\Delta = 1.41$	↑			
				P_{22}	77.28					
				P_{31}	78.39	$\Delta = 1.18$				
				P_{32}	77.21					
				P_{81}				79.14	$\Delta = 0.22$	↓
				P_{82}				78.92		
				P_{41}				79.45	$\Delta = 0.42$	
				P_{42}				79.03		
10	B	2	4	P_{21}/P_{81}	81.47	$\Delta = 0.86$	↓	81.47	$\Delta = 0.86$	↓
				P_{22}/P_{82}	80.61			80.61		
				P_{31}/P_{41}	81.57	$\Delta = 0.96$		81.57	$\Delta = 0.96$	
				P_{32}/P_{42}	80.61			80.61		
	C	2	4	P_{21}	80.08	$\Delta = 1.49$	↓			
				P_{22}	78.59					
				P_{31}	80.16	$\Delta = 1.51$				
				P_{32}	78.65					
				P_{81}				80.88	$\Delta = 0.49$	↓
				P_{82}				80.39		
				P_{41}				80.80	$\Delta = 0.52$	
				P_{42}				80.28		

arriving side   leaving side

prevail which can result in a situation in which in these directions a traffic jam appears, while in opposite directions the movement is fluent. The same concerns the comparison made between arriving versus leaving sides (Tables 15). It can be seen that for equal flow rates in lanes, the leaving side becomes noisier with addition of lanes and making the leaving speed higher.

Table 15. Sound level on the ground floor.

a. Arriving versus leaving side, comparison between C-crossroads and A-crossroads.

v_f [km/h]	cross-roads	J^α	J^β	point	L_{op}^{α} [dB (A)] (changes in perpendicular arm)			L_{op}^{β} [dB (A)] (changes in front of points)		
5	A	2	2	P_{21}/P_{81}	77.68	$\Delta = 0.26$		77.68	$\Delta = 0.26$	
				P_{31}/P_{41}	77.42			77.42		
				P_{22}/P_{82}	76.80	$\Delta = 0.06$		76.80	$\Delta = 0.06$	
				P_{32}/P_{42}	76.74			76.74		
	C	2	4	P_{21}	78.69	$\Delta = 0.30$				
				P_{31}	78.39					
				P_{22}	77.28	$\Delta = 0.07$				
				P_{32}	77.21					
				P_{81}				79.14	$\Delta = -0.31$	leaving side noisier
				P_{41}				79.45		
				P_{82}				78.92	$\Delta = -0.11$	
				P_{42}				79.03		
10	A	2	2	P_{21}/P_{81}	79.05	$\Delta = -0.07$	leaving side noisier	79.05	$\Delta = -0.07$	leaving side noisier
				P_{31}/P_{41}	79.12			79.12		
				P_{22}/P_{82}	78.10	$\Delta = -0.07$		78.10	$\Delta = -0.07$	
				P_{32}/P_{42}	78.17			78.17		
	C	2	4	P_{21}	80.08	$\Delta = -0.08$				
				P_{31}	80.16					
				P_{22}	78.59	$\Delta = -0.06$				
				P_{32}	78.65					
				P_{81}				80.88	$\Delta = 0.08$	
				P_{41}				80.80		
				P_{82}				80.39	$\Delta = 0.11$	
				P_{42}				80.28		

arriving side   leaving side

Table 15. Sound level on the ground floor.

b. Arriving versus leaving side, comparison between C-crossroads and B-crossroads.

v_f [km/h]	cross-roads	J^α	J^β	point	L_{op}^{α} [dB (A)] (changes in front of points)			L_{op}^{β} [dB (A)] (changes in perpendicular arm)		
5	B	4	4	P_{21}/P_{81}	80.08	$\Delta = 0.33$		80.08	$\Delta = 0.33$	
				P_{31}/P_{41}	79.75			79.75		
				P_{22}/P_{82}	79.33	$\Delta = 0.00$		79.33	$\Delta = 0.00$	
				P_{32}/P_{42}	79.33			79.33		
	C	2	4	P_{21}	78.69	$\Delta = 0.30$				
				P_{31}	78.39					
				P_{22}	77.28	$\Delta = 0.07$				
				P_{32}	77.21					
				P_{81}				79.14	$\Delta = -0.31$	leaving side noisier
				P_{41}				79.45		
				P_{82}				78.92	$\Delta = -0.11$	
				P_{42}				79.03		
10	B	4	4	P_{21}/P_{81}	81.47	$\Delta = -0.10$	leaving side noisier	81.47	$\Delta = -0.10$	leaving side noisier
				P_{31}/P_{41}	81.57			81.57		
				P_{22}/P_{82}	80.61	$\Delta = 0.00$		80.61	$\Delta = 0.00$	
				P_{32}/P_{42}	80.61			80.61		
	C	2	4	P_{21}	80.08	$\Delta = -0.08$				
				P_{31}	80.16					
				P_{22}	78.59	$\Delta = -0.06$				
				P_{32}	78.65					
				P_{81}				80.88	$\Delta = 0.08$	
				P_{41}				80.80		
				P_{82}				80.39	$\Delta = 0.11$	
				P_{42}				80.28		

arriving side   leaving side

5. Application of the simplified model of interrupted vehicle flow

The basic idea of the model of vehicle movement interrupted by a crossroads is the segmentation of lanes in appropriate sub-segments defined by the following parameters:

- $\{l_j(i)\}$ – a set of sub-segments lengths,
- $\{S_j(i)\}$ – a set of energy linear densities,
- $\left\{\mathcal{N}_j^{\alpha(\beta)}(i)\right\}$ – a set of vehicles' flow rates at the lane sub-segments.

The parameters are functions of traffic organization parameters:

- $v_j = v_c$ – cruising speed with which vehicles approach the crossroads,
- l_v – equivalent vehicle length,
- t_r, t_c – red/green light time,
- ξ – parameter of energy emitted by starting vehicles,
- v_f – speed with which vehicles leave the crossroads.

From the viewpoint of the traffic organization it is expected that the vehicle movement has to be fluent. For a defined composition of traffic approaching a crossroads (flow rates, cruising speed, heavy vehicles participation), this can be obtained by making the speed v_f,with which the vehicles leave the crossroads, higher. Nevertheless, by the calculation examples it has been shown that the normal movement $v_f = 10$ km/h results in a higher sound level than in a situation in which $v_f = 5$ km/h and a traffic jam occurs. Thus, a fluent movement does not mean a lower the sound level.

In general, the number of lanes results from the urban system geometry, while the flow rates, cruising speed, heavy vehicles participation, which can be modified by legislation, determine the sound level in the vicinity of a crossroads and partly affects the ability of leaving the crossroads by lowering the vehicle equivalent length l_v. The latter is possible by diminishing the heavy vehicles participation, but there are limitations in removing heavy vehicles from city centers since they are mostly busses of the public transportation service. There are yet two parameters: the speed with which vehicles leave the crossroads v_f and the ξ parameter describing the energy emitted by the starting vehicle which straight stem from the driving manner. The latter one affects only the sound level, while the former one affects both: the sound level and the ability of fluent leaving a crossroads. Thus, the prediction of acoustical consequence of the traffic parameters modification can be obtained only by performing an appropriate simulation, especially when a more complex case of an asymmetric crossroads is dealt with and the daytime variation of the flow rate in the lanes is taken into account. Also, a decision has to be made what is more desired: a more fluent vehicle movement, or a lower sound level as they are not occurring simultaneously.

6. Conclusions

The tests of the simplified model of a crossroads as the noise source have shown that the sound level grows according to expectation founded on everyday experiences although some specific relations have been found. The two parameters related to the driving manner have been found to be important for the sound level values observed on the building façades. These are the ξ parameter describing the energy emitted during the starting of a vehicle and the speed of leaving the crossroads. In the simplified crossroads model, these two parameters have been treated as independent although they are not independent. The speed of leaving the crossroads describes the ability of leaving the crossroads during the green light time and stems from the distance in which the first waiting vehicle can travel during the green light time making room for the other waiting vehicles. But a waiting driver, more than having in mind to drive as far as possible, is inclined to drive in an aggressive way because he is nervously waiting for the start. Despite the simplifications and lack of precision in the estimation of the input parameters, the performed tests offer a knowledge of the range of possible variations in the sound level in the vicinity of a crossroads. Also, basing on the results of the performed tests, the conditions which are conducive to the sound level growth can be analyzed.

The simulation program PROP10 predicting the sound level in a built-up area with the model of vehicle movement interrupted by a crossroads has been prepared. The verification of the PROP9 simulation program on which PROP10 is based has enough well confirmed the precision of the propagation model [13], but the open problem is the modeling of a vehicle as the noise source. The sound exposure gives the energy emitted by a passing-by vehicle. The applied approximated way of the sound exposure calculation with a limited road segment and discrete vehicle movement seems to be enough accurate [5]. In the case of need, the segment length and step between the vehicle discrete positions can be easily adjusted. Thus, in the road modeling as noise source the vehicle model is crucial. Assuming a single equivalent point source for a vehicle, the two basic parameters: the source power level and the position above the ground have to be established for the existing local conditions concerning the moving fleet, driving manner and state of maintenance. This requirement is an urgent need for all the applied manners of the sound level predicting due to the traffic parameters. Having a vehicle model as the noise source, an appropriate segmentation of roads in the vicinity of the crossroads could be introduced with adequate values of the substantial parameters: the sub-segments lengths and the energy linear density.

The time-average sound level spread on the building facade has been analyzed for flow rates equally divided between the lanes where the canyon-street width for the assumed pavement width is directly correlated with the number of lanes. The results of the examples presented show that the prediction where and when it will be noisier cannot be based on the ground of a simple qualitative analysis. Since the situation in the vicinity of a crossroads is pretty complex, only computer simulation programs can provide information on the sound level spread on the building façade and the ability of its possible modification by variation of changeable parameters.

For example, having an enough accurate description of the vehicle as the noise source, only the vehicle flow rates are needed to perform a simulation for busy crossroads where it seems reasonable to evaluate the acoustical climate for such specific periods as the morning and evening rush hours.

Appendix A.

The $l(i = 3)$ sub-segment average length for red light fraction in the analyzed T-period [Eq. (29)] for the typical data in Table 3 is

$$l\left(i = 3, \mathcal{N}_j = 20 \text{ veh/min}, \ \widetilde{\mathcal{N}} = 15.44 \text{ veh/min}\right) \\ = \frac{2 \text{ min}}{2}\left(3 \cdot 20 \frac{\text{veh}}{\text{min}} 5.4 \text{ m} - 83.3 \ \frac{\text{m}}{\text{min}}\right) = 240.7 \text{ m}. \qquad \text{(A1)}$$

For $x_j^{(3)}$ (Table 2) showing the rim of the crossroads and the observation point position nearest to the crossroads (Table 5) on the side of arriving vehicle, the inequality

$$l(i = 1) + l(i = 2) + l(i = 3) < 3R_{j0} \qquad \text{(A2)}$$

has to be fulfilled to take into the sound equivalent level calculation all the three sub-segments. For a flow rate $\mathcal{N}_j > \widetilde{\mathcal{N}}$ the traffic jam start to build up and the $l(i = 3)$ sub-segment length grows every period of red light. According to Eq. (A2) the growth of the $l(i = 3)$ sub-segment moves the sub-segments $l(i = 1) + l(i = 2)$ outside the road segment taken in the calculation of the sound exposure level [Eq. (5)]. It would be after the time

$$t_{rs} = (t_f + t_r)\frac{3R_{j0}}{L_r(j) - L_f} = 3R_{j0} = \frac{(t_f + t_r)}{\mathcal{N}_j t_r l_v - v_f t_f} = \frac{6R_{j0}}{\mathcal{N}_j l_v - v_f}. \qquad \text{(A3)}$$

For $L_{\text{eq}}(T = 1 \text{ h})$, the time of covering the road segment Eq. (5) by waiting vehicles constitutes a fraction of the total period

$$f_r = \frac{t_{rs} \text{ [min]}}{60 \text{ min}}. \qquad \text{(A4)}$$

For the typical data in Table 3 it is

$$f_r(\mathcal{N}_j = 20 \text{ veh/min}, \widetilde{\mathcal{N}}_j = 15.44 \text{ veh/min}, R_{j0} = 20 \text{ m}) = \frac{4}{60}\frac{60}{49.3} = 0.08. \qquad \text{(A5)}$$

Appendix B.

For $L_{\text{eq}}(T = 1 \text{ h})$, the time of free passing during green light [Eq. (32)], which appears 30 times, constitutes a fraction of the total period

$$f_r = 30\frac{t_{rs} \text{ [min]}}{60 \text{ min}} \qquad \text{(B1)}$$

for which the sound equivalent level has to be calculated for vehicle free flow as for the sub-segment

$$f_r(\mathcal{N}_j = 20 \text{ veh/min}, \widetilde{\mathcal{N}}_j = 30.87 \text{ veh/min}, = \frac{1}{2}\frac{117.4}{166.7} = 0.35. \qquad \text{(B2)}$$

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