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Statistical model for traffic noise prediction in signalised roundabouts

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Abstract. The existing traffic noise prediction models in road intersections relate mainly to the typical solutions of intersection geometry and traffic organisation. There are no models for large and more complex intersections such as signalised roundabouts. This paper presents the results of studies on the development of a traffic noise prediction model for this type of intersection. The model was developed using a multiple regression method based on the results of field measurements of traffic parameters and noise levels in the vicinity of signalised roundabouts in Poland. The obtained model consists of two groups of variables affecting noise levels at the intersection. The first group determines in detail the influence of traffic and geometry of the closest entry. The second group shows the influence of more distant noise sources (traffic at the three remaining entries of the intersection) and the influence of the dimensions of the entire intersection. The developed model was verified through additional field measurements, as well as compared to the results of two methods of traffic noise prediction: the French 'NMPB-Routes-2008' and the German 'RLS-90'. The obtained results confirmed a higher accuracy of calculations performed using the developed model in the range of: −1.2 dB ÷ +1.0 dB, while the 'NMPB-Routes-2008' and 'RLS-90' calculate precision were respectively: −2.8 dB ÷ +1.3 dB, and +0.8 dB ÷ +5.2 dB. Therefore, the developed model allows for a more accurate prediction of noise levels in the vicinity of signalised roundabouts in a flat terrain without buildings and noise barriers.

Key words: traffic noise, noise prediction, intersection, signalised roundabout.

1. Introduction

Road intersections, due to their varied geometry and traffic organisation, as well as traffic structure, make the process of assessing and predicting traffic noise more difficult. For these reasons, many research centres are conducting studies in order to design models allowing to predict noise levels in the vicinity of intersections more precisely. This paper also deals with this problem. One of the first designed models was the Gilbert's model which took into account the interrupted traffic at intersections [1]. However, this model featured a relatively high standard estimation error $S_e = 2.7$ dB and its usage was limited mainly to city centres. Further studies on the development of noise prediction models in intersections were characterised by various approaches to the issue and varied accuracy of the developed dependencies.

The first group of noise prediction models for road intersections are empirical models which were based on field measurements of noise levels in various points located mainly along the entries and exits of intersections. Such models feature a fairly good replication of the real values of sound levels but their application is often limited to specific cases and locations of the points of sound measurement. This is especially visible in the case of regression models, where the choice of the variables results from the local conditions and often does not take into account the mechanisms of sound generation. Such models were designed by the researchers listed below:

- Samuels – the Interrupted Traffic Flow Noise Simulation model, which enabled the prediction of noise in the vicinity of a simple intersection with traffic lights [2].
- Jraiw – two models depending on the type of terrain and the allowed vehicle speed characterised by a prediction error of ±2.5 dB [3].
- Mohammed – a noise prediction model for interrupted traffic enabling the introduction of constant values of acceleration and deceleration of traffic in a simple intersection with traffic lights [4].
- Pamanikabud – two models of noise prediction: for intersection exits (acceleration) and intersection entries (deceleration or stopping traffic); prediction error ±1.5 dB and ±0.5 dB respectively [5].
- Bohatkiewicz – two models which, apart from the basic traffic parameters, take into account the average delays (time loss by vehicles crossing the intersection) and the volume to capacity ratio at entries; prediction error: ±1.5 dB [6, 7].
- Abu-Qudais and Alhiary – a model taking into account the BPN surface friction coefficient (British Pendulum Number), number and width of lanes and the distance from stop lines; prediction error ±2 dB [8, 9].
- Rajakumara and Mahalinge Gowda – a model taking into account elements such as the length of the queue of stopped vehicles at entry [10].
- Akgüngör and Demirel – a model which includes the traffic data of 4 vehicle groups: passenger cars; delivery trucks; motorcycles; HGVs + buses [11].

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- Bazaras and Jotautiene – a model designed based on measurements conducted during green traffic signal and taking into account only the variable related to the traffic volume; prediction error ±5 dB [12].
- Agarwal – a modified version of the FHWA TNM model based on the accounting for the level of an intersection's capacity usage (volume to capacity ratio); prediction error before modification: from 5 to 15 dB, after modification: ±3 dB [13].
- Salomons – a model based on the data on traffic processed from video recordings in order to determine the traffic volume, traffic composition and the L_{mov} indicator (vehicle movement level), which allow to estimate the noise level with 89% accuracy [14].
- Quiñones-Bolaños – a model which modifies the CoRTN method, characterised by an error of ±1 dB, while the original model had ±5 dB [15].

The second group of noise prediction models for intersections are analytical models which are based on mathematical dependencies between the characteristic of the road geometry and physical phenomena related to the traffic movement. This allows to model various cases, although due to numerous assumptions and simplifications, the accuracy of these calculations is often far lower than that of empirical models. Such models for intersections were designed by:

- Makarewicz – a model which introduces an additional factor related to the traffic dynamics and the drivers' driving style (careful, normal, aggressive), and allows to take into account the influence of acceleration and deceleration in vehicle movement and the speed in normal movement [16]. Makarewicz also designed a model of predicting the noise level in the vicinity of roundabouts, which uses significant simplifications such as uniform movement of vehicles in the entire intersection, traffic volume and its distribution identical at all entries, all vehicles stopping and starting their movement from the central point of the intersection with constant values of acceleration and deceleration during movement [17].
- Piddubniak – a model for calculating 3-entry intersections taking reflections and influence of wind on noise levels into account [18].
- Paoprayoon – a model which allows to take into account the constant values of acceleration and deceleration coefficients in vehicle movement, as well as their changing values depending on the speed-distance relation; the average prediction error is 2 dB when variable coefficients of accelerations and decelerations are chosen [19].
- Stoilova and Stoilov – a model which takes into account the influence of traffic lights and the number of vehicles in queue at the entry; the established dependencies enable to calculate the sound level depending on the participation of the green light in the traffic lights cycle [20].

In recent years, other analytical methods of traffic noise prediction have started to be developed. These methods are based either on genetic algorithms [21, 22] or on neuron networks [23, 24].

The third group of noise prediction models in the vicinity of intersections are models based on a computer microsimulation of traffic which use or modify the existing models of emission or propagation of traffic noise. Such models allow to conduct complex analyses, which could not have been solved using analytic or empirical methods. A microsimulation of traffic movement allows to calculate sound emissions from individual vehicles based on their location, speed and other parameters which describe movement dynamics. The verification of the current simulation models showed differences in the results of field measurements in the range of 1÷2 dB. These models, however, require a large amount of detailed data on the behaviours of drivers and traffic movement to be taken into account, as well as the calibration of this data with the results of field measurements [25–36].

Apart from the listed research into noise prediction models, work is being conducted to constantly monitor and improve the functioning of intersections due to the traffic noise criterion [37–44].

Current research work on the noise prediction models in the vicinity of intersections relate mainly to typical geometrical solutions of intersections and traffic organisation. There are no models for larger and more complex intersections such as signalised roundabouts known in Poland as 'intersections with a central island'. A signalised roundabout is formed through spreading apart the carriageways of intersecting streets and building an oval island in the centre with a diameter of 30 to 60 m (Fig. 1). This causes the forming of large areas for left-turn traffic movement accumulation inside the intersection with a capacity of 200÷800 veh/h [45, 46].

Regarding traffic organisation, a signalised roundabout is a set of 4 coordinated intersections of one-direction roads, so called sub-intersections (sub. 'A', sub. 'B', sub. 'C', sub. 'D').

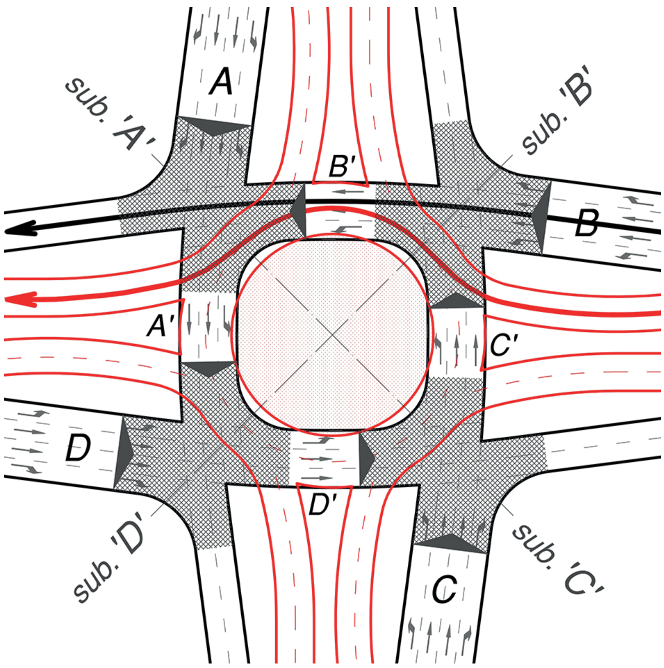

Fig. 1. A comparison of the geometries of a classic roundabout (red line) and a signalised roundabout (black line); (A–D: entries; A′–D′: inner areas of accumulation)

The proper connection of their geometry and the programming of traffic lights in relation to traffic volume allows to obtain a capacity of 4000 to 8500 veh/h [47]. The basic features differentiating this type of intersections from classic roundabouts are [48]:

- One-direction carriageways pass tangentially to the central island (black line in Fig. 1), differently than in classic roundabouts where the vehicle path is deflecting around the central island causing lower speeds (red line in Fig. 1) [49].
- Traffic lights at entries and inner areas of accumulation.

The studies conducted by the authors on the acoustic climate in the vicinity of signalised roundabouts in Bialystok (Poland), allowed to determine that there is a dependency between the noise level, the geometry of the intersection and the traffic parameters such as volume, composition and distribution [50]. Therefore, the purpose of this paper is to develop a statistical model based on a multiple regression analysis, which would enable the prediction and assessment of sound level in the vicinity of signalised roundabouts based on the traffic data and the geometry of the intersection.

2. Methodology

The data base for the conducted analyses were the results of equivalent sound level (L_{Aeq}) and traffic volume measurements performed by the authors at 4 intersections in Bialystok (Poland), labelled W2, W3, W5 and W6 (Fig. 2).

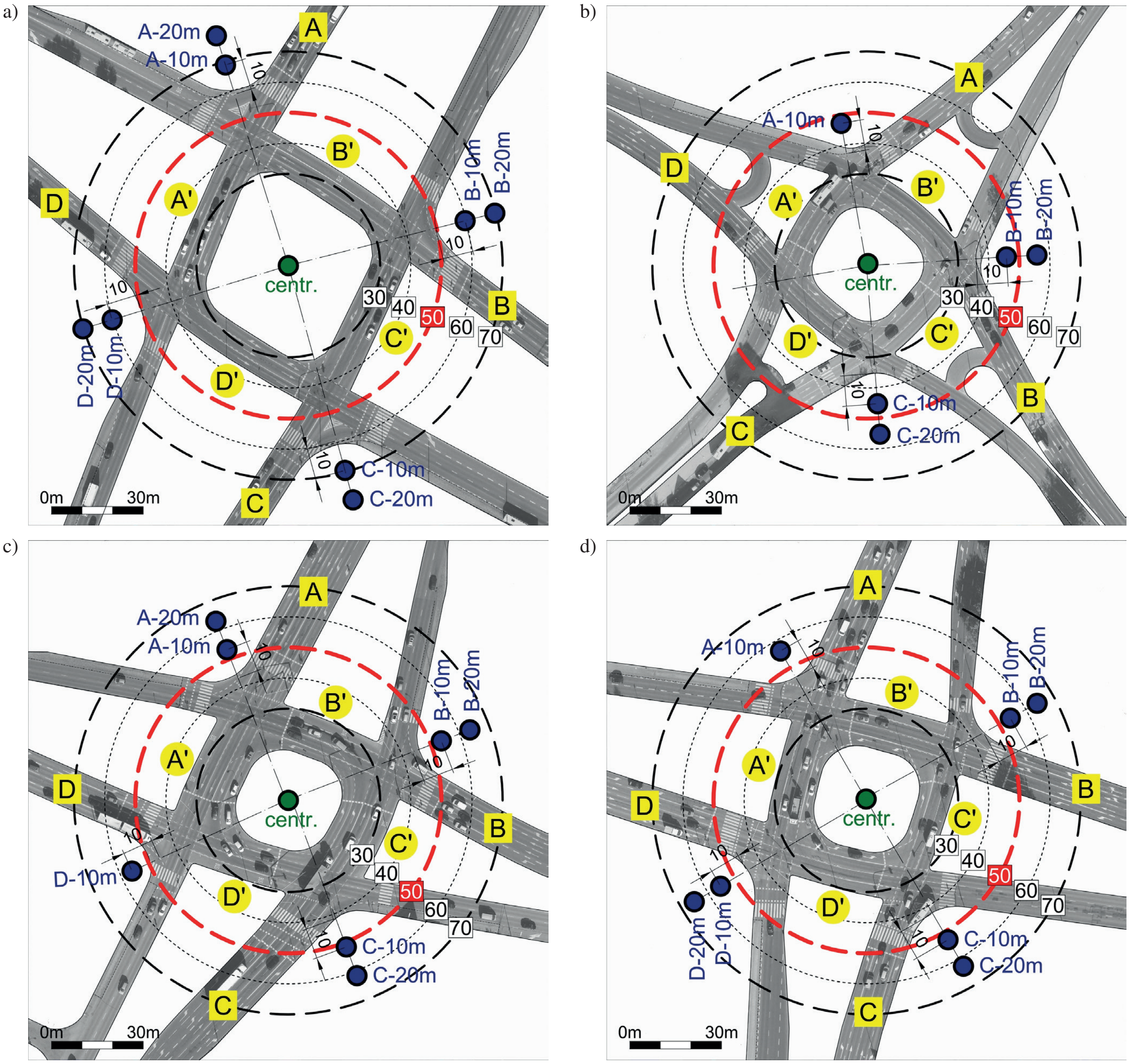

Fig. 2. The geometry of the intersections and the location of noise level measurement points: a) W2, b) W3, c) W5, d) W6 (A–D: entries, A′–D′: inner areas of accumulation, centr. = midpoint of central island)

In the city of Bialystok there are eight signalised roundabouts, numbered from W1 to W8. Intersections W1, W4, W7 and W8 were not included in the analysis due to sound reflections caused by buildings located too close to the intersection or the placement of the intersection within a two-level road junction.

The L_{Aeq} measurements were conducted in each of the four selected intersections over one hour periods using five 1st class sound level Sonopan DSA-50 meters. The measurement points were located in the midpoint of the central island and between intersection arms, radially to the central point of the intersection, at a height of 1.5 m above street level (L_{Aeq} measurements in the midpoint and in the 4 other points were conducted at the same time). For the height of 1.5 m, it was considered that the absorption of sound waves by the grassy ground would not be significant for further analysis. Distances of 10 m and 20 m from the edge of the outer traffic lane were chosen as basic (Fig. 2). Unfortunately, the objects in the vicinity of the intersections (buildings, adverse terrain slopes) made it impossible to measure the noise level in all 8 predefined points. In some cases, when the terrain allowed it, additional measurements were also conducted at distances of 30 m and 40 m from the outer lane edge.

The traffic parameters measurements were conducted simultaneously with the noise measurements, at each entry of the intersection (traffic volume, distribution and composition). These measurements were conducted by video recording or manual counting of vehicles.

In the conducted measurements an assumption was made to omit instances of negative traffic conditions, which can create additional, and sometimes hard to determine, negative factors influencing the noise level, such as: interrupted traffic flow (so called stop and go); aggressive or dynamic driving style; sound signals; mutual shielding of vehicles waiting in a queue on multilane entries. The determining of the influence of these negative conditions on noise levels is the subject of many studies which have not yet solved this issue entirely [7, 51, 52]. According to 'HCM' [53], traffic conditions are classified using levels of service (LOS) labelled from A to F, where A means the best conditions and F – the worst conditions. The basic criterion for assessing the LOS at intersections are the values of the average delays d experienced by vehicles crossing the intersection. Their ranges for intersection with traffic lights are: LOS A: $d < 10$ s/veh; B: $d = 10 \div 20$ s/veh; C: $d = 20 \div 35$ s/veh; D: $d = 35 \div 55$ s/veh; E: $d = 55 \div 80$ s/veh; F: $d > 80$ s/veh.

In order to determine favourable traffic conditions in the analysed intersections, additional field measurements were conducted for a variable traffic load. The measurements were conducted using 22 to 30 cameras which registered the traffic at all entries and lanes of the intersection simultaneously. Based on these recordings, the average delays d were estimated using the 'indirect method' [54]. The received results showed that favourable traffic conditions (LOS A$\div$C, $d < 35$ s/veh) occurred when the traffic volume in the entire intersection was lower than 5000 veh/h with a typical traffic distribution and a length of traffic light cycle T = 120 s (Fig. 3).

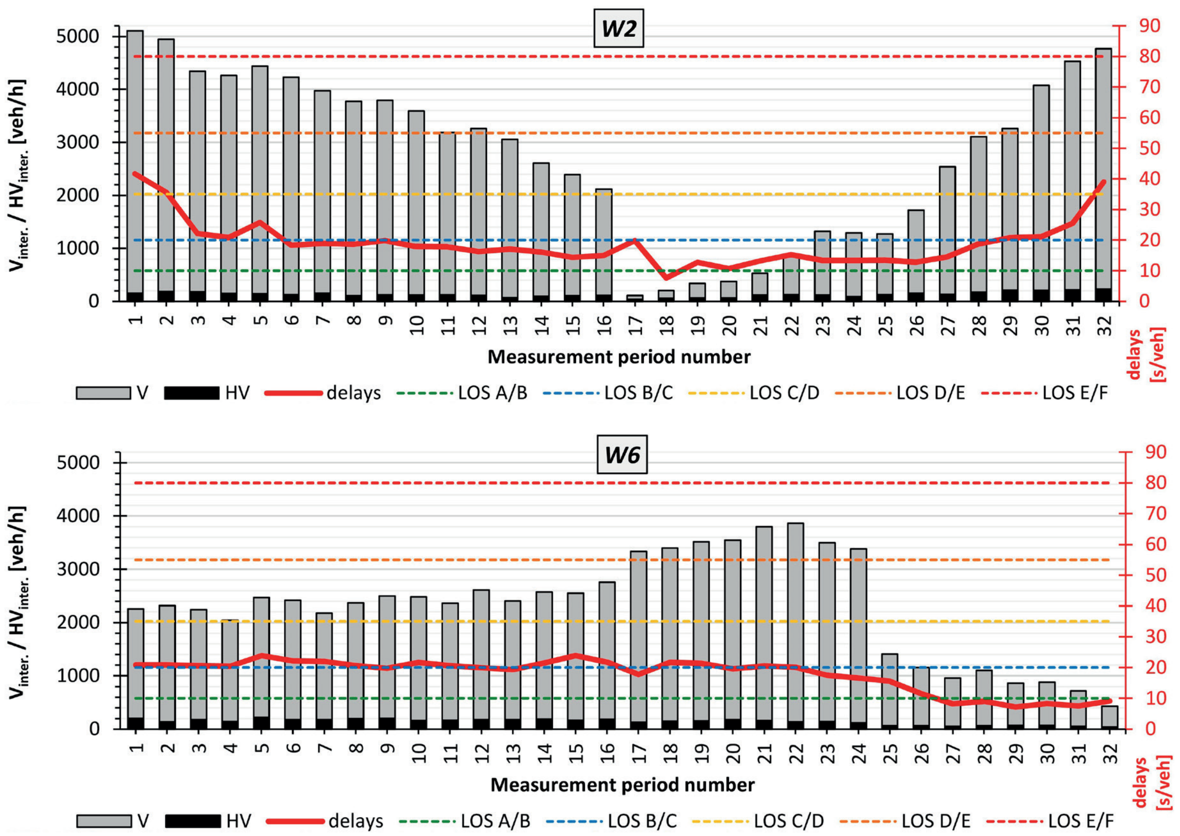

Fig. 3. Sample results of delays d at intersections W2 and W6 depending on the traffic volume of all vehicles ($V_{inter.}$) and heavy vehicles ($HV_{inter.}$)

It was also established that with traffic volume below 1000 veh/h in the entire intersection, large and significant differences occur in vehicle speeds as well as large fluctuations of the heavy vehicles' participation in traffic. This caused significant differences in the value of L_{Aeq}. Therefore, the noise levels determined in the intersection at the range of traffic volume from 1000 to 5000 veh/h were adopted for further analysis and calculations.

3. Results and analysis

The method of general multiple regression analysis was used to design the model. In accordance with the chosen approach the calculations of the regression model were based on the results of the L_{Aeq} measurements obtained for a traffic load of 1000 to 5000 veh/h in the analysed intersections (436 results connected to the $L_{Aeq,centr}$ at the midpoints of the central islands and 1387 – with L_{Aeq} measurements at points located in the vicinity of the intersections). The ranges of the obtained L_{Aeq} and $L_{Aeq,centr}$ results and the measurements of traffic parameters in the 4 analysed intersections are presented in Table 1.

It was assumed that the equivalent sound level in the vicinity of the signalised roundabout depends on the traffic at the entry which is closest to the given noise reception point and the traffic at the remaining three entries. The influence of three remaining entries is expressed using sound level at the midpoint of the central island ('X' in Figs. 4 and 5) and corrected by the distance of the noise reception point from the midpoint of the central island. This assumption was made because the midpoint can be considered as a reference point for this type of intersection.

Accordingly, in the first stage of analysis a model was designed which allowed to determine the noise level at the midpoint of the central island $(L_{Aeq,centr})$. During the second stage this model was used to calculate the noise levels at the midpoint of the central island $(L^*_{Aeq,centr})$ determined based on traffic data from the three further entries (it doesn't matter how many entries are used to calculate the noise level at the midpoint if it is at the same distance from all entries, so this point will reflect the impact of these entries). The obtained $L^*_{Aeq,centr}$ values in accordance to the established process were used to create the base model for predicting L_{Aeq} levels in the vicinity of the signalised roundabouts (at point 'Y' in Figs. 4 and 5).

3.1. Equivalent sound level at the midpoint of the central island ($L_{Aeq,centr}$). The base for the designing of the model was the data on traffic in the entire intersection and the corresponding results of equivalent sound level measurements at the midpoint of the central island $(L_{Aeq,centr})$ as well as the following geometric parameters:

- The diameter of the central island (D_w) calculated as the average of its width along the road axis.
- Average length of inner areas of accumulation (L_{acum}) and number of lanes around the central island (n_w).

The group of independent variables related to traffic in the intersection takes into account the variables relating to traffic volume as well as traffic distribution (percentage participation of each traffic movement in the intersection) and traffic composition (percentage of noisy vehicles in the intersection – heavy vehicles, buses and motor-cycles). The schematic of the chosen method of determining the $L_{Aeq,centr}$ noise level from traffic in the entire $V_{inter.}$ intersection is presented in Fig. 4.

Table 1
The ranges of the L_{Aeq} $(L_{Aeq,centr})$ and traffic parameters results

No.	Distance from the road [m]	Data results	L_{Aeq} $(L_{Aeq,centr})$ [dB]	$V_{inter.}$ [veh/h]	$\%HV_{inter.}$ [%]	V_{entry} [veh/h]	$\%HV_{entry}$ [%]
W2	10	97	65.2–71.2	1160–4944	3.7–20.1	164–1600	0.8–36.6
	20	286	60.0–66.7	1012–4986	3.4–20.1	104–1768	0.0–34.6
	30	21	59.4–63.4	1268–4532	4.3–14.0	268–1068	4.8–28.4
	40	66	56.2–61.4	1012–4922	3.8–19.6	184–1768	0.0–14.4
	midpoint of the central island	144	(59.5–64.0)	1012–4944	4.0–17.0	–	–
W3	10	87	62.3–67.3	1112–2780	1.8–5.9	144–1216	0.0–6.4
	20	41	58.8–64.5	1300–2696	1.8–5.9	256–1004	0.0–6.3
	midpoint of the central island	37	(60.3–63.1)	1112–2696	1.8–5.2	–	–
W5	10	168	62.0–69.7	1000–4612	1.8–10.7	196–1508	0.3–15.5
	20	265	57.4–65.8	1000–4636	0.6–10.5	196–1684	0.0–16.4
	30	23	58.0–61.0	1232–4636	2.7–6.2	228–1020	2.2–7.9
	midpoint of the central island	155	(60.9–66.5)	1000–4636	1.3–10.6	–	–
W6	10	167	63.6–68.7	1008–3652	2.7–14.8	124–1440	2.0–16.1
	20	166	59.8–65.1	1008–3652	2.7–13.5	124–1440	2.0–18.0
	midpoint of the central island	100	(61.6–66.1)	1008–3652	3.3–12.5	–	–

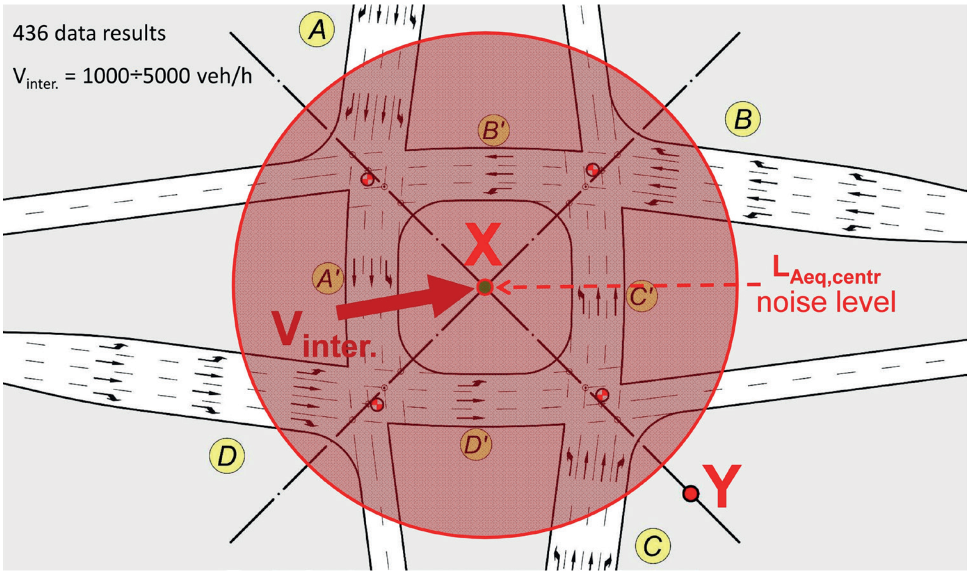

Fig. 4. A schematic of the chosen method of determining the $L_{Aeq,centr}$ noise level: X – $L_{Aeq,centr}$ measurement; Y – L_{Aeq} measurement point in the vicinity of the intersection; $V_{inter.}$ – total of traffic volume in the intersection (total from 4 entries)

Based on the calculated Pearson linear correlation coefficients, independent variables that were related to each other were excluded from further analysis. After conducting a multiple regression analysis the following model was obtained which explains 78% of variability of the dependent variable $L_{Aeq,centr}$ with a standard estimation error of $S_e = 0.73$ dB:

$$\begin{aligned} L_{Aeq,centr} &= 44.991 + 7.139 \cdot \log(V_{inter.}) + \\ &+ 0.259 \cdot \%HV_{inter.} - 0.109 \cdot \%V_{inter.(RT)} + \\ &- 8.921 \cdot \log(D_w) + 2.699 \cdot n_w \end{aligned} \tag{1}$$

$(n = 436;\ R^2 = 0.78;\ S_e = 0.73\ \text{dB};\ V_{inter.} = 1000 \div 5000\ \text{veh/h})$

where: $L_{Aeq,centr}$ – equivalent sound level at the midpoint of island [dB]; $V_{inter.}$ – intersection traffic volume [veh/h]; $\%HV_{inter.}$ - percentage of noisy vehicles at intersection [%]; $\%V_{inter.(RT)}$ - percentage of right-turn movements on the intersection [%]; D_w – diameter of central island [m].

The values of the Fisher-Snedecor test (5, 430, 0.05) = 307.875 and the level of test probability $p < 0.05$ confirmed the statistical significance of the designed model. Moreover, the values of the t statistic showed that the assessment of all regression coefficients is significantly different from zero. Other results of the statistical analysis can be found in [55].

3.2. Equivalent sound level in the vicinity of an intersection.

According to the chosen assumptions, the goal of the next step of the analyses was to relate the equivalent sound level in the vicinity of an intersection to:

- Traffic at nearest entry to the L_{Aeq} reception point 'Y' (red colour in Fig. 5).
- Traffic at three remaining entries (blue colour in Fig. 5), which is expressed using sound level ($L^*_{Aeq,centr}$) at the midpoint of the central island 'X' and corrected by the distance $dist_{centr}$ between noise reception point 'Y' and midpoint of the central island 'X'.

A schematic of the chosen method of determining noise level L_{Aeq} in the vicinity of an intersection is presented in Fig. 5.

The base for designing the model were the data listed below:

- Noise levels L_{Aeq} in the vicinity of the intersection (point 'Y').
- Traffic data at the closest entry including traffic volume of all vehicles (red V_{entry} in Fig. 5), noisy vehicles (HV_{entry}) in every traffic stream (left, right and through movements).
- Distance measured according to Fig. 5 between the sound reception point and:
  - The central point of the nearest sub-intersection: $dist_{sub}$ (point where the axes of the entry and the inner area of accumulation intersect).
  - The midpoint of the central island: $dist_{centr}$.
- Noise levels at the midpoint of the central island ($L^*_{Aeq,centr}$) calculated using the model (1) including traffic data from three further intersection entries (e.g. if L_{Aeq} is calculated at point 'Y' near entry D, then for calculations $L^*_{Aeq,centr}$ in point 'X' data from entries A, B and C should be used; when point 'Y' is near entry A, then for calculations $L^*_{Aeq,centr}$ in point 'X' data from entries B, C and D should be used, etc.):

$$\begin{aligned} L^*_{Aeq,centr} &= 44.991 + 7.139 \cdot \log(V^*_{inter.}) + \\ &+ 0.259 \cdot \%HV^*_{inter.} - 0.109 \cdot \%V^*_{inter.(RT)} + \\ &- 8.921 \cdot \log(D_w) + 2.699 \cdot n_w \end{aligned} \tag{1*}$$

where: $V^*_{inter.}$ – traffic volume at three further entries [veh/h]; $\%HV^*_{inter.}$ – percentage of noisy vehicles in traffic at three further entries [%]; $\%V^*_{inter.(RT)}$ – percentage of left-turn traffic movement at three further entries [%]; D_w – diameter of central island [m]; n_w – average number of lanes around the central island [–].

Based on the calculated Pearson linear correlation coefficients, independent variables that were related to each other

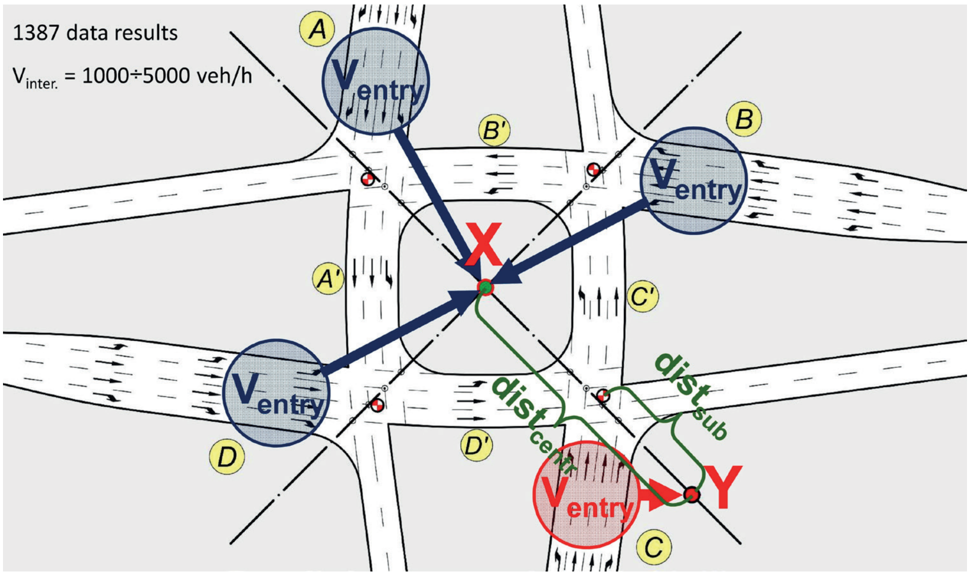

Fig. 5. A schematic of the chosen method of determining the noise level L_{Aeq} in the vicinity of an intersection (V_{entry}: traffic volume at the closest entry – red or at the further entries – blue)

were excluded from further analysis. After conducting a multiple regression analysis, the final model was obtained explaining 85% of the variability of the dependent variable L_{Aeq} with a standard estimation error of $S_e = 1.02$ dB:

$$\begin{aligned} L_{Aeq} = 9.734 + 0.618 \cdot L^{*}_{Aeq,centr} + 36.586 \cdot \log(dist_{centr}) + \\ + 3.081 \cdot \log(V_{entry}) - 0.057 \cdot \%V_{entry(RT)} + \\ + 0.261 \cdot \%HV_{entry(RT)} - 0.091 \cdot \%HV_{entry(LT)} + \\ + 0.027 \cdot \%HV_{entry(Th)} - 39.628 \cdot \log(dist_{sub}) \end{aligned} \tag{2}$$

(n=1387; R^2=0.85; S_e=1.02 dB; $V_{inter.}$=1000÷5000 veh/h) where: $L^{*}_{Aeq,centr}$ – noise level at the mipoint of the central island calculated from (1) based on traffic data for the three further entries of the intersection [dB]; $dist_{centr}$ – distance to the midpoint of the central island [m]; V_{entry} – traffic volume at the nearest entry [veh/h]; $\%V_{entry(RT)}$ – percentage of right-turn traffic movement at the nearest entry [%]; $\%HV_{entry(RT)}$, $\%HV_{entry(LT)}$ and $\%HV_{entry(Th)}$ – percentage of noisy vehicles according to turn movement: right-turn, left-turn, through at the nearest entry accordingly [%]; $dist_{sub}$ – distance to the central point of the nearest sub-intersection [m].

The values of the Fisher-Snedecor test (8, 1378, 0.05) = 1001.320 and the level of the test probability $p < 0.05$ confirmed the statistical significance of the designed model. Moreover the values of the t statistic showed that the assessment of all regression coefficients also significantly varies from zero. Other results of the statistical analysis can be found in [55].

3.3. Verification of the designed models. In order to verify the designed models – the basic model (2) and the model for the midpoint of the island (1) – additional measurements of the equivalent sound level and the traffic parameters were performed in intersections W2, W3, W5 and W6. Based on the traffic data obtained from field measurements, the predicted L_{Aeq} values were calculated using the designed models (1) and (2) and then compared to the L_{Aeq} values from field measurements. The identified differences ΔL_{Aeq} (Table 2) were within the range of -1.4 dB to $+1.2$ dB at measurement points located 10 m from the road edge and -1.1 dB to $+1.1$ dB at point located 20 m from the edge. Similar values were also obtained for distances of 30 m and 40 m. The ΔL_{Aeq} differences at the midpoint of the central island were from -0.9 dB to $+1.2$ dB. The identified differences confirmed the good compatibility of the designed models (1) and (2) with the results of field measurements.

The L_{Aeq} values, obtained from additional field measurements and calculations according to the designed models (1) and (2), were additionally compared to the results of noise level predictions conducted in the SoundPLAN computer software according to the French 'NMPB-Routes-2008' method [56] and German 'RLS-90' method [57]. The calculations in the SoundPLAN software were conducted on the example of the W2 intersection. The prediction of the L_{Aeq} value was conducted at points in which the additional noise field measurements were conducted. The traffic data required for the calculations were the result of the additional field measurements in the W2 intersection, and the geometric data were imported from a digital primary topographic map. Sound reception points were defined at the noise measurement points at a height of 1.5 m above street level. Each relation was modelled as a separate sound emission bandwidth, assigning to each of its sections real data on the volume and characteristics of traffic, as well as values of speed and traffic dynamics (Fig. 6).

Figure 7 shows an example of the obtained maps of the predicted L_{Aeq} values and the resulting differences between the calculations according to the 'NMPB-Routes-2008' and 'RLS-90' methods.

Table 2

ΔL_{Aeq} differences between noise levels according to the designed models (1) and (2) and the noise levels from field measurements

Intersection	No.	ΔL_{Aeq} [dB] at points											
		A-10	B-10	C-10	D-10	A-20	B-20	C-20	D-20	B-30	A-40	C-40	centr.
W2	1	–	–	–	–	+0.6	–	−0.7	–	–	+0.7	−0.1	+0.4
	2	–	–	–	–	+0.5	+1.0	–	+0.7	–	–	–	+0.4
	3	–	–	–	–	−0.1	+0.2	–	−0.4	–	–	–	+0.2
	4	–	–	–	–	+0.5	–	−1.0	–	–	+1.0	+0.1	−0.6
	5	–	–	–	–	+0.3	−0.8	–	–	–	+0.4	-1.2	−0.9
	6	−0.3	–	–	−0.3	+1.0	–	–	–	–	–	–	+0.1
	7	–	−0.3	–	–	–	−0.2	–	–	+0.2	–	–	−0.9
	8	–	–	+0.1	–	–	–	+0.1	–	–	–	–	+0.8
	9	–	–	–	–	−0.4	−0.5	–	−0.5	–	–	–	−0.8
	10	–	–	–	–	+0.4	–	−0.1	–	–	+0.7	+1.0	−0.4
	11	–	−1.1	–	–	–	−0.9	–	–	−0.4	–	–	−0.3
	12	−0.6	–	–	−0.9	+0.4	–	–	–	–	–	–	−0.5
	13	–	–	–	–	+0.5	−1.0	–	–	–	+1.0	+0.2	−0.4
	14	–	–	+0.1	–	–	–	+0.3	–	–	–	–	+1.2
W3	15	+0.8	+1.0	–	–	–	-0.4	–	–	–	–	–	0.0
	16	+1.1	–	+0.6	–	–	–	+0.6	–	–	–	–	−0.1
	17	+0.5	+0.9	–	–	–	-0.5	–	–	–	–	–	+0.2
	18	+0.8	+1.2	–	–	–	-0.4	–	–	–	–	–	+0.4
	19	+0.2	+1.2	–	–	–	-0.6	–	–	–	–	–	+0.2
W5	20	–	–	–	–	-0.6	+0.9	+0.9	–	–	–	–	+0.1
	21	–	–	–	–	+0.3	+0.5	−0.1	–	–	–	–	0.0
	22	–	–	–	–	−1.1	–	+0.1	–	+0.5	–	–	−0.7
	23	–	–	–	–	−0.7	+1.1	−0.1	–	–	–	–	−0.4
	24	+0.5	–	–	−1.0	+0.3	–	–	–	–	–	–	+0.1
	25	–	–	–	–	−0.8	+1.0	−0.7	–	–	–	–	−0.6
	26	–	–	–	–	−0.5	+0.5	−0.3	–	–	–	–	−0.6
	27	–	–	–	–	−0.9	–	−0.9	–	+0.9	–	–	−0.5
	28	+0.3	–	–	−0.7	+0.1	–	–	–	–	–	–	−0.1
W6	29	–	−0.1	+0.2	–	–	−0.1	–	–	–	–	–	+0.4
	30	−1.1	–	–	+0.6	–	–	–	+1.0	–	–	–	+0.6
	31	–	−0.6	−0.7	–	–	−0.7	–	–	–	–	–	−0.5
	32	–	−1.0	−0.7	–	–	−0.9	–	–	–	–	–	−0.2
	33	–	−0.5	−1.1	–	–	−0.4	–	–	–	–	–	−0.4
	34	–	−0.5	–	−0.2	–	+0.1	–	–	–	–	–	+0.3
	35	–	−0.6	–	−0.2	–	−0.2	–	–	–	–	–	+0.1
	36	–	−1.4	–	−0.2	–	−0.7	–	–	–	–	–	0.0

**A-10/C-20* – means measurement points located between intersection arms at the distance of 10/20 m from the edge of the road, near to entry A/C*

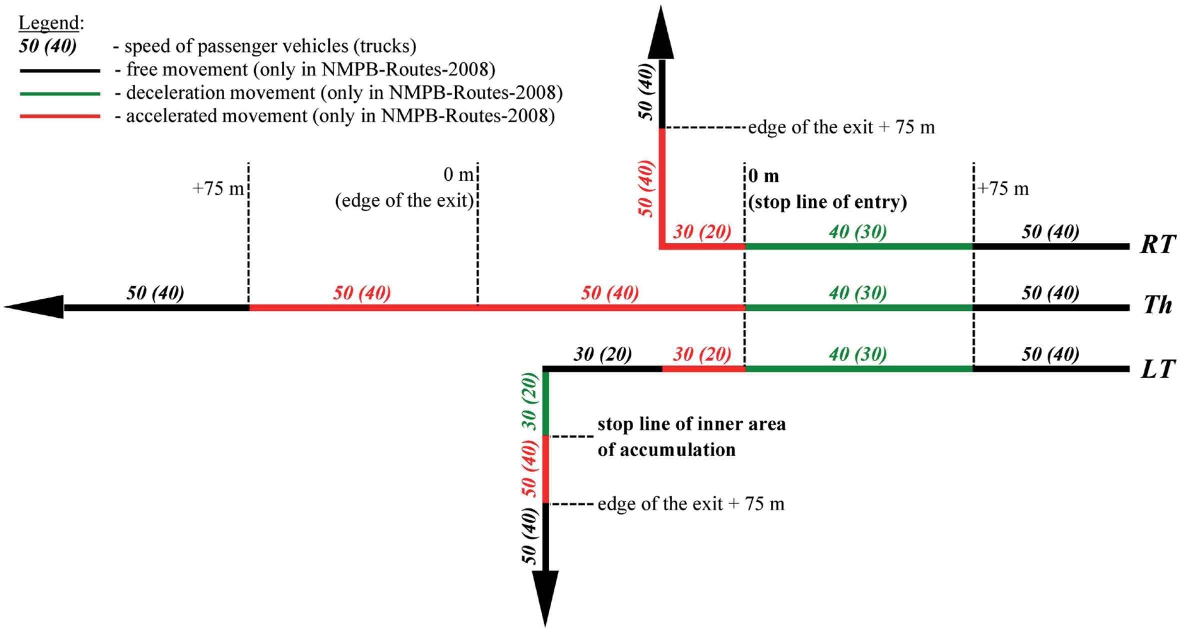

Fig. 6. The assumed dynamic states of movement and speed of left (LT) and right-turn (RT) traffic streams as well as driving through (Th) at the entry

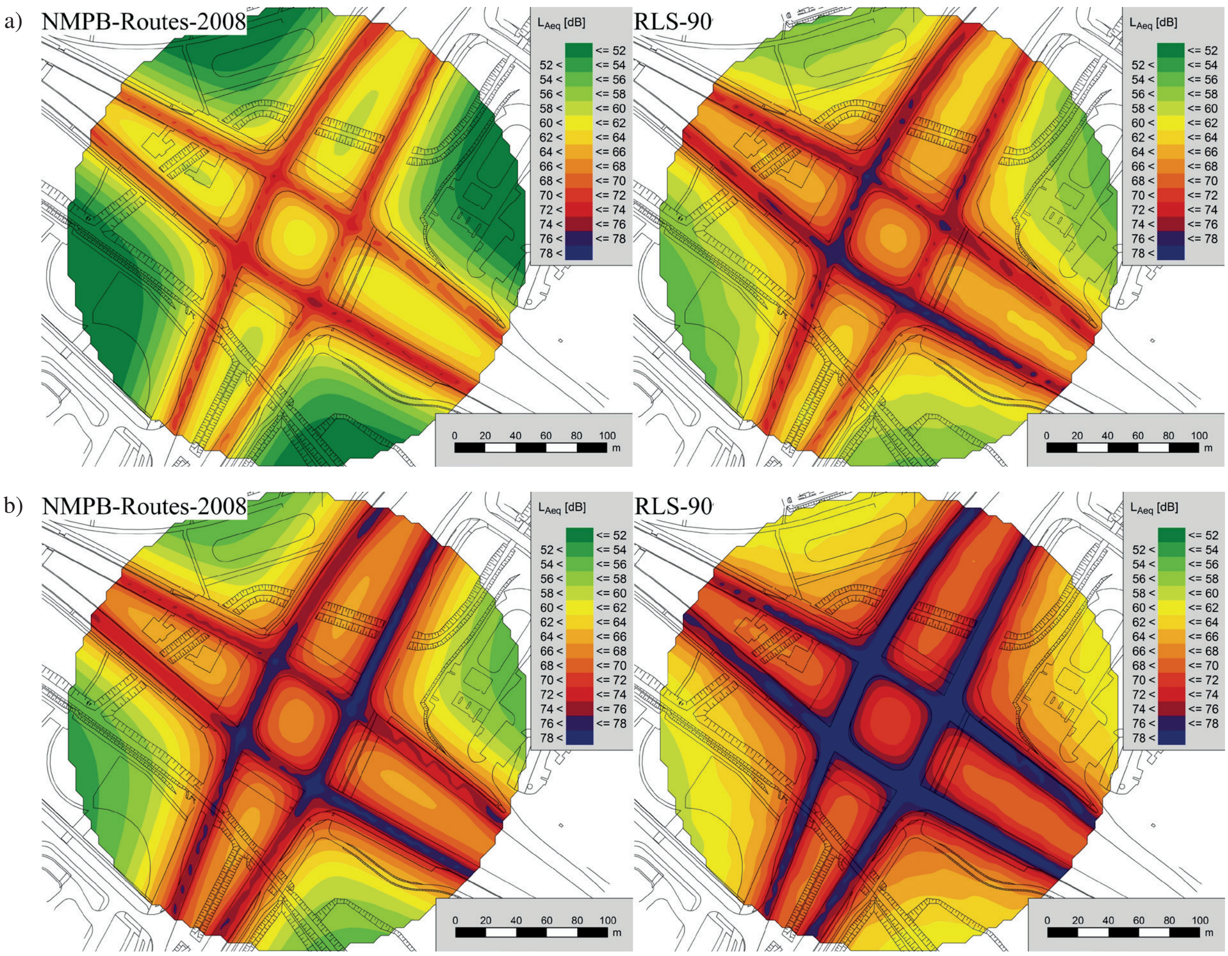

Fig. 7. Maps of the predicted L_{Aeq} levels for traffic load in the W2 intersection $V_{inter.}$: a) 1052 veh/h, b) 4668 veh/h depending on the prediction method

Based on the comparison of the differences between the L_{Aeq} calculated for the W2 intersection using models (1) and (2) as well as the SoundPLAN software using the 'NMPB-Routes-2008' and 'RLS-90' methods and the L_{Aeq} values determined in additional field measurements it was determined that:

- Model (2) is characterised by a accuracy of L_{Aeq} prediction at a distance of 10 m to 40 m from the road within the range: -1.2 dB ÷ $+1.0$ dB, while the 'NMPB-Routes-2008' method: -2.8 dB ÷ $+1.3$ dB, and the 'RLS-90' method: $+0.8$ dB ÷ $+5.2$ dB.
- Model (1) is characterised by a accuracy of $L_{Aeq,\,centr}$ predictions at the midpoint of the central island within a range: -0.9 dB ÷ $+1.2$ dB, while the 'NMPB-Routes-2008' method: $+1.1$ dB ÷ $+4.9$ dB, and the 'RLS-90' method: $+5.1$ dB ÷ $+8.6$ dB.

4. Conclusions

The conducted analyses allowed to design two models for calculating noise levels in signalised roundabouts. The designed model (1) allows to estimate noise levels at the midpoint of the central island and is used to calculate noise levels in the vicinity of an intersection according to model (2). Figure 8 shows the algorithm of the developed methodology of predicting traffic noise levels in the vicinity of signalised roundabouts for traffic volumes on the entire intersection in range: $V_{inter.} = 1000 \div 5000$ veh/h.

The designed models are characterised by higher accuracy of noise level calculations in signalised roundabouts in comparison to the two noise prediction methods – the French 'NM-BRoutes-2008' and the German 'RLS-90'. In the case of the 'RLS-90' method, significant differences were noted between the noise levels predicted using this method and the ones determined during measurements. The reasons for this could be the method of conducting noise emissions for the 'RLS-90' model and the lack of consideration of the impact of traffic conditions (interrupted traffic), as well as the way of taking into account the influence of the traffic lights on noise level, based on the addition of the so-called 'K' adjustment. In the case of the French method 'NMPB-Routes-2008', as well as the German 'RLS-90', the largest differences between the predicted results and the field measurement values were related to the midpoint of the central island. The reason for that was that none of the two methods took into account the mutual shielding of vehicles, which move on a multi-lane road around the island (vehicles moving along the left-turn lanes adjacent to the island are shielding the vehicles on other traffic lanes). This is especially significant for measurement points located at lower heights.

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1. Determining the data on:

1.1. The geometric solution: diameter of the central island, number of lanes around the island, distance between sound reception point and the center of the island and the center of the nearest sub-intersection.

1.2. Traffic: traffic volume of light vehicles (passenger + delivery) and noisy vehicles (HGV + buses + motorcycles) on individual streams (right-turn, left-turn, through) at each entry of the intersection.

↓

2. Calculating the $L_{Aeq,centr}^*$ noise level at the midpoint of the central island based on the geometric solution data of intersection and traffic data on the three further entries (*) according to the model ($V_{inter.} = 1000 \div 5000$ veh/h):

$$L_{Aeq,centr}^* = 7.139 \cdot \log(V_{inter.}^*) + 0.259 \cdot \%HV_{inter.}^* - 0.109 \cdot \%V_{inter.(RT)}^* - 8.921 \cdot \log(D_w) + 2.699 \cdot n_w + 44.991 \quad (S_e = 0.73\ dB)$$

↓

3. Calculating the L_{Aeq} noise level in the vicinity of the intersection based on data on the distance of the sound reception point from the nearest sub-intersection ($dist_{sub}$) and the midpoint of the central island ($dist_{centr}$), as well as the $L_{Aeq,centr}^*$ value and the data on the traffic at the nearest entry according to the model ($V_{inter.} = 1000 \div 5000$ veh/h):

$$L_{Aeq} = 0.618 \cdot L_{Aeq,centr}^* + 36.586 \cdot \log(dist_{centr}) + 3.081 \cdot \log(V_{entry}) - 0.057 \cdot \%V_{entry(RT)} + 0.261 \cdot \%HV_{entry(RT)} - 0.091 \cdot \%HV_{entry(LT)} + 0.027 \cdot \%HV_{entry(Th)} - 39.628 \cdot \log(dist_{sub}) + 9.734 \quad (S_e = 1.02\ dB)$$

Fig. 8. The algorithm for calculating traffic noise levels in the vicinity of signalised roundabouts

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Glossary

- V – total traffic volume (all vehicles) [veh/h];
- HV – number of noisy vehicles (the category included: multiple axle heavy vehicles, trucks, buses and motorcycles since their noise emissions are close to each other) [veh/h];
- $\%V$ – percentage of all vehicles [%];
- $\%HV$ – percentage of noisy vehicles [%];
- subscript *inter.* it is meaning 'whole intersection';
- subscript *entry* it is meaning 'only on the closest entry to the noise reception point';
- subscripts RT, LT, Th are meaning 'right-turn', 'left-turn' and 'through movement';
- L_{Aeq} – A-weighted equivalent sound level in the vicinity of intersection [dB];
- $L_{Aeq,centr}$ – A-weighted equivalent sound level in the midpoint of the central island [dB].