SIMULATION OF CAPACITY OF ROUNDBOUTS APPLYING PRINCIPLES OF SUSTAINABLE URBAN DEVELOPMENT

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Abstract. Standards (STR) valid in Lithuania do not contain methodologies for assessment designing and functioning quality of roundabouts. Normative documents neither of EU nor of other parts of the world contain methodologies for calculation of the capacity of exits from roundabouts. The article analyses the methodology for calculation of the capacity of entrances to exits from roundabouts, transport time losses and line length, taking the principles of urban sustainable development into consideration.

Keywords: roundabouts, capacity of entrance/exit, transport time losses, vehicle line length, flow movement quality.

1. Introduction

Designing or reconstructing roundabouts special emphasis is laid on the safety of roundabouts: a small number of conflict points between different direction flows, lower speed of movement, milder outcomes of traffic incidents. However, researches on functioning of roundabouts in the towns of Lithuania revealed that in roundabouts with over-saturated transport flows (flow saturation rate of $g_{sat}>0.85$) and with passenger flows ($P>200$ pedestrians/hour) going in both directions the capacity of an intersection is reduced, transport entering into the intersection suffers time losses, long lines of vehicles ($N_{el}>20$ veh.) get formed, and only level of service (LOS) D and E is achieved under HBS/HCM recommendations \cite{1,2}. Besides, comparing with classical traffic-light regulated intersections, on the roundabout transport movement time is longer; large land plots are necessary for their construction ($F_{tank}= 5000 – 7200$ m$^2$), which increases the price of construction as land is very expensive in the central parts of the town (~ LTL200,000/are).

2. Problem formulation and objectives

Although roundabouts are quite popular in the towns of Lithuania, there are no normative documents \cite{3} or a recommended methodology for designing of such intersections. The article proposes the methodology for calculation of the capacity and efficiency of roundabouts based on modern principles of sustainable urban development, taking account of the impact of pedestrian flows on the time of transport spent on the roundabout as well as on the number of traffic incidents, the number of conflict points depending on the roundabout diameter and on “intermingling” of flows moving on the roundabout.

Research object is the capacity of roundabouts with over-saturated transport flows on roundabouts when additional transport interferences are impacted by pedestrian flows.

Research goal is:

– to devise the methodology for calculation of the capacity of roundabouts with over-saturated flows on the roundabout and on its entrances;
– to devise the methodology of calculation of the capacity of entrances and exits of roundabouts, taking priority pedestrian flows P21, P22 that conflict with transport flows into consideration;
– to assess indiscipline of drivers entering and exiting the roundabout and the impact of infringements of Traffic Rules on the capacity of the roundabout.

Research methods

Researches on transport and pedestrian flows employ a telecamera. Individual flows of transport and their trajectories are being shot, and later information on flows is processed with the help of a computer. This allows analysis of the slow-motion view of trajectories of vehicles entering the roundabout (changing of traffic lanes) and distribution between individual exit directions (to the right, straight, to the left). With the help of a telecamera researches may be carried out both on small ($D_r < 25$ m) and on large ($D_r = 300$ m) roundabouts. During researches and when processing the flow data it was assumed that arrival of individual vehicles at the roundabout is close to the Poisson distribution \cite{4}. 

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3. **Calculation of the capacity of entrances into the roundabout**

In the towns of Lithuania roundabouts were designed in 1970-1974 keeping to standards that recommended two traffic lanes on entrances and three traffic lanes on exits. Functioning of such intersections was sufficient when automobilization level was 160-180 veh./1000 population. At present, when automobilization level reaches 460-480 veh./1000 population, it is necessary to assess whether the existing intersections are able to satisfy the desired LOS C [1,2] and whether new traffic regulation methods should be applied according to the principles of sustainable urban development. Analysing the capacity of roundabouts depending on the diameter of the roundabout researches were carried out at Bochum University [4], Vilnius Gediminas Technical University, Department of Urban Engineering [5], and Dresden University [6], and research results are summarised in designing standards and capacity calculation programmes [7,8,1,5]. The diameter of roundabouts analysed during the researches were from 12 to 99 meters in the central parts and up to 300 meters in the suburban zone. Schemes of transport and pedestrian flows on roundabouts are given in Figure 1.

Formula (1) was derived without considering pedestrian flows P1 and P2 conflicting with the flows on the entrance and the exit. To avoid transport jams on the roundabout in case of an incident, most roundabouts designed in 1970-1988 were designed applying the following principle: the number of traffic lanes on the roundabout, \( n_r \), is bigger than the number of traffic lanes on entrances \( n_i \) and could be defined applying the following formula:

\[
n_r = n_i + 1.
\]

Parameters of vehicle movement depend on the flow composition [4], roundabout diameter, \( D_r \) [9], state of roundabout pavement (especially in winter). Time values determined during the researches are given below.

Minimal time between vehicles on the roundabout \( t_{\text{min}} = 1.2 \) s (in winter), 1.0 s (in summer).
The average time between vehicles on the roundabout $t_g = 4.1$ s. The average time between vehicles on the entrance $t_f = 2.9$ s.

The vehicle flow moving on the roundabout, $Q_r$, which interferes with the entering flow $Q_i$, depends on the distribution between individual exits and flow reformation when moving on the roundabout (Figure 1) and can be estimated applying the following formula:

$$Q_r = q_{12} + q_{13} + q_{14} + q_{32} + q_{42} + q_{43}. \quad (3)$$

If transport flow in the roundabout (with three traffic lanes) is $Q_r = 2000$ veh./h, then two traffic lanes can uptake the flow of $Q_i = 360-370$ veh./h (see Figure 2).

![Fig. 2. Dependence of the entrance flow size on transport on the roundabout [7].](image)

On roundabouts the actual capacity of entrances depends on the fact whether priority pedestrian crossings (“zebras”) are installed and on indiscipline of drivers. The actual capacity of an individual entrance $G_z$ is calculated applying the following formula:

$$G_z = G \cdot f_f \cdot k_d. \quad (4)$$

$G_z$ – actual capacity of entrance, veh./h; $G$ – theoretical capacity of entrance, veh./h; $f_f$ – coefficient estimating decrease in roundabout capacity because of priority pedestrian crossings ($0.72 – 0.99$) calculated according to the diagram in Figure 3.

![Fig. 3. Dependence of coefficient, $f_g$, of reduction of transport flow entering the roundabout on the size of pedestrian flow, $P_1$ and $P_2$.](image)
$k_d$ – coefficient increasing capacity of entrance into / exit from the roundabout because of undisciplined drivers; it depends on the rate of flow over-saturation, $g_{sat}$, and according to the research results in Lithuania it fluctuates in a wide interval (1.0-1.4) [6].

Where a sign of “priority pedestrian crossing” is installed before the roundabout, then the flow of pedestrians becomes uncontrollable. Where priority pedestrian flows, $P_{21}+P_{22}$, exceed 200 pedestrians/hour, and the exiting transport flow is $q_{o}>400$ veh./h, then a conflict situation arises: the exiting transport flow is held back in the roundabout to let pedestrians first. Then the vehicle line on the roundabout exceeds ¼ of it and blocks the vehicles that want to enter the roundabout on entrance 1. Besides, the vehicle flow on entrance 1 is also delayed by the priority pedestrian flow $P_1$. Then drivers penetrate through the pedestrian flow without observing Traffic Rules, which results in an increased actual capacity of entrances and exits, $G_z$, and also it results in $2.4-2.7$ times increased number of non-recordable traffic incidents that involve pedestrians (compared to the traffic-light regulated intersection). Where a sign of “priority pedestrian crossing” is installed before the roundabout, then when calculating the capacity the pedestrian flow $P = P_{21}+P_{22}$ must be estimated; and where no such sign exists, then the pedestrian flow is $P = 0.22*P_{21} + P_{22}$.

Where during a working day (8 hours) such situation is brought about at least for two hours when the exiting transport flow is $q_{o}>400$ veh./h, then a conflict situation arises: the exiting transport flow is held back in the roundabout to let pedestrians first. Then the vehicle line on the roundabout exceeds ¼ of it and blocks the vehicles that want to enter the roundabout on entrance 1. Besides, the vehicle flow on entrance 1 is also delayed by the priority pedestrian flow $P_1$. Then drivers penetrate through the pedestrian flow without observing Traffic Rules, which results in an increased actual capacity of entrances and exits, $G_z$, and also it results in $2.4-2.7$ times increased number of non-recordable traffic incidents that involve pedestrians (compared to the traffic-light regulated intersection). Where a sign of “priority pedestrian crossing” is installed before the roundabout, then when calculating the capacity the pedestrian flow $P = P_{21}+P_{22}$ must be estimated; and where no such sign exists, then the pedestrian flow is $P = 0.22*P_{21} + P_{22}$.

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Where during a working day (8 hours) such situation is brought about at least for two hours when the flow on the roundabout is $Q$, $P = 200$ veh./h, and the pedestrian flow is $P = P_{200}$ ped/h, then it is advisable to introduce traffic-light regulation. This would enable regulation of pedestrian flows and, at the same time, increase the capacity of entrances. The pay-back of such a project is 16 months (estimating the prise of transport time losses and taking account of other factors sticking to the principles of sustainable urban development). Where long vehicle lines are formed in two sections of the roundabout, then it is advisable to “rip up” the roundabout in the direction of the main flow. Another reason for ripping up the roundabout is routes of trolleybuses in the direction of the main direction of the roundabout.

4. Assessment of quality of transport flow movement on roundabouts

Traffic quality on the roundabout is assessed by two indicators with strong inter-correlation: capacity reserve, $R_i$, of individual critical entrance into the roundabout and the average waiting time of one vehicle (time losses), $t_{wi}$. Capacity reserve of entrance into the roundabout, $R_i$ (veh/h), is calculated applying the following formula [5]:

$$R_i = Gi – Qi.$$  \hspace{1cm} (5)

The average waiting time of vehicles, $t_{wi}$ (s), is the main indicator that defines the quality of flow movement (LOS) [1,2]. The level of service quality and the value of waiting time, $t_{wi}$, with different capacity reserve values, $R_i$, is taken from Table 1.

<table>
<thead>
<tr>
<th>Table 1. Assessment of flow movement quality depending on the average waiting time of a vehicle.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theoretical capacity, $Ci$, veh./h</td>
</tr>
<tr>
<td>1000</td>
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<tr>
<td>1000</td>
</tr>
<tr>
<td>1000</td>
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<td>800</td>
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<td>200</td>
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<tr>
<td>200</td>
</tr>
</tbody>
</table>

*$the roundabout have to be reconstructed.

5. Calculation of the average length of the line of a vehicle

The length of the vehicle line, g.b., waiting to enter into the roundabout is expressed in meters or in the number of vehicles (assuming that 1 vehicle takes the length $l_v = 6.0$ metres). Where a line of vehicles forms in the roundabout because of the insufficient capacity of exit, and the line length exceeds ¼ of the roundabout, then the preceding entrance is blocked. On roundabouts with large priority flows of pedestrians ($P>200$ ped/h) the length of vehicle line on the roundabout, $N_v$, may be more significant than the line length, $N_i$, on the entrance. This is observed when flows are over-saturate, $g_{sat}>0.85$. The flow saturation rate, $g_{sat}$, for entrance flows is calculated as the ratio of the actual flow, $Q_i$, and the potential theoretical capacity, $C_i$:

$$g_{sat} = Q_i / Ci.$$  \hspace{1cm} (6)

Researches of the theoretical capacity of exits have been insignificant [1,5]. In accordance with the researches of roundabouts carried out in Lithuania, estimating the size of priority pedestrian flow, $P_0$, it was determined that the capacity of exit on roundabouts could be calculated applying the following formula:

$$C_o = a_o – b_o * P_o.$$  \hspace{1cm} (7)

Where the roundabout has three traffic lanes, and the exit has two traffic lanes, the regression equation coefficients are $a_o = 1180$, $b_o = 0.418$. The line of vehicles on the roundabout, $N_v$, depending on the rate of flow saturation and on the probabilistic line length reliability percent ($p = 95\%$) could be taken from Table 2. Researches showed that when the roundabout diameter is $Dr = 99.0$ metres, then the length of ¼ of the roundabout, $l_v = 77.75$ m, is shorter than the vehicle line, $N_v = 79$, and then the vehicle flow on entrance 1 is blocked.
Table 2. Dependence of the vehicle line length on the rate of saturation of entrance/exit flow.

<table>
<thead>
<tr>
<th>Theoretical capacity, $G_i$, veh./h</th>
<th>Flow saturation level, $g_{sat}$</th>
<th>Length of vehicle line on roundabout, $N_c$, veh.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>0.8</td>
<td>11</td>
</tr>
<tr>
<td>1000</td>
<td>1.0</td>
<td>36</td>
</tr>
<tr>
<td>1000</td>
<td>1.2</td>
<td>79</td>
</tr>
<tr>
<td>600</td>
<td>0.8</td>
<td>9</td>
</tr>
<tr>
<td>600</td>
<td>1.0</td>
<td>29</td>
</tr>
<tr>
<td>600</td>
<td>1.2</td>
<td>51</td>
</tr>
<tr>
<td>200</td>
<td>0.8</td>
<td>8</td>
</tr>
<tr>
<td>200</td>
<td>1.0</td>
<td>17</td>
</tr>
<tr>
<td>200</td>
<td>1.2</td>
<td>30</td>
</tr>
</tbody>
</table>

The number of conflict points on roundabouts that in literature is given without estimating intermingling of transport flow trajectories on the roundabout depends in the following factors:

- traffic organisation on the traffic lanes of the roundabout;
- internal diameter, $D_r$, of the roundabout
- size of all entrance flows of the roundabout, $S_{Q_i}$;
- distribution of flows on each entrance to the roundabout into individual exits, $q_r$, $q_d$, $q_l$;
- number of traffic lanes on the roundabout, $n_c$;
- number of traffic lanes on the entrance to the roundabout, $n_i$.

Fig. 4. Conflict points and transport flow trajectories on the roundabout during reformation of transport flows.

According to researches of transport flow trajectories on roundabouts carried out in Lithuania, the following regression equation was obtained for calculation of the number of conflict points, $N_{cr}$, on the roundabout:

$$n_{cr} = (\sum (a_i \cdot q_{kd} + a_d \cdot q_{kd} + a_r \cdot q_{kd})) \cdot (n_r \cdot b_l + n_i \cdot b_l) \cdot 0.25 \cdot D_r \cdot Q_i.$$  \hspace{1cm} (7)

Where the roundabout has three traffic lanes, and the entrances have two traffic lanes, the regression coefficient values are the following:

$$a_i = 2.12, a_d = 1.68, a_r = 1.42, b_r = 0.27, b_i = 0.18.$$  

The probable annual number of recordable and non-recordable traffic incidents, $N_{acr}$, on the roundabout depends on the size of the flow of all vehicles that enter the roundabout, $S_{Q_i}$, roundabout diameter, $D_r$, and on discipline of drivers, and it could be calculated applying the following regression equation:

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N_{si} = 0,0000514 \cdot \Sigma Q_i \cdot D_i . \quad (8)

6. Conclusions and remarks

1. Calculating the capacity, G, of the whole roundabout or an individual entrance to the roundabout and the reserve of the existing capacity, C_{rez}, on urban intersections, it is necessary to take account of pedestrian flows conflicting with transport flows on entrances and exits, P1 and P2.

2. It is recommended that when designing new or reconstructing the existing roundabouts the number of traffic lanes on the roundabout, n_r, is bigger that the number of traffic lanes on the entrance n_i (n_r = n_i + 1).

3. It is not recommended that both urban and suburban roundabouts have only one traffic lane, as in case of a traffic accident the roundabout is paralysed for 40-60 minutes.

4. The average idle time losses of a vehicle, t_w, when the flows are over-saturated satisfy only traffic movement LOS E and B.

5. The average length of vehicles, n_{wi}, on the entrance to the roundabout with over-sature flows is 88-92 vehicles at rush hours and blocks the neighbouring intersections.

6. The possible average vehicle line length, n_{wr}, on the roundabout (roundabout blockage) depends on the size of pedestrian flow, P_2, on the exit from the roundabout, Q_r, and the length of ¼ of the roundabout.

7. The number of conflict points on roundabouts depends on the flow size and flow distribution between individual exits and the diameter of the roundabout; and at the roundabout of 99.0 m diameter that number is 72.

8. Analysis of statistical data of traffic incidents on roundabouts in Vilnius and Klaipédéa in 2004 -2006 shows that when the capacity of entrances to roundabouts is exhausted (traffic saturation rate g_{sat} > 0.85) the number of recordable and non-recordable traffic incidents that involve pedestrians is ~2.4 times higher than that on roundabouts similar by their flow size (2+2 traffic lanes) where flows are regulated by traffic-lights.

References