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OPTIMIZATION OF ROUNDABOUT DESIGN ELEMENTS

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Preliminary notes
Analysis of roundabouts constructed in several Croatian cities has shown that the developed intersection areas, when reconstructing the classical intersections into roundabouts, have limited the outer radius of the intersection as a rule. Croatian guidelines for roundabout design and equipment, for capacity calculation of small and medium roundabouts suggest application of the Austrian method which takes into consideration the design conditions at intersections, which is why it has been applied in this paper for analyzing the correlation between the intersection design and capacity. Since urban locations do not always allow application of the optimal radius, this paper analyses the way of optimizing the radius and other elements of the intersection in relation to capacity. The results have shown that the roundabout entrance and exit parameters as well as the achieved distance between the conflict points have an impact on roundabout capacity and the optimization of its size as a function of the capacity can rationalize the area needed for the intersection.

Keywords: *capacity, design elements, radius, roundabouts, volume*

Optimizacija projektnih elemenata kružnog raskrižja

Prethodno priopćenje
Analiza izvedenih kružnih raskrižja u nekoliko hrvatskih gradova ukazuje na to da izgrađenost područja raskrižja pri rekonstrukciji klasičnih tipova raskrižja u kružna u pravilu limitira raspon vanjskog polumjera samoga raskrižja. Hrvatske smjernice za projektiranje i opremanje raskrižja kružnog oblika-rotora, za proračun kapaciteta malih i srednjih kružnih raskrižja sugeriraju uporabu Austrijske metode koja u proračunu respektira geometrijske uvjete na raskrižjima što je razlog njezine uporabe za analizu korelacije između geometrije i kapaciteta raskrižja u ovome radu. Kako urbane lokacije ne omogućavaju uvijek primjenu optimalnog polumjera u ovome radu se analizira način optimiranja polumjera i drugih geometrijskih elemenata raskrižja u ovisnosti o željenom kapacitetu raskrižja. Rezultati su pokazali da elementi oblikovanja ulaza i izlaza u kružno raskrižje kao i postignuta udaljenost konfliktnih točaka na samom privozu imaju utjecaj na kapacitet samog raskrižja te da se optimiranjem njihovih iznosa u funkciji kapaciteta može racionalizirati potreban prostor za raskrižje.

Ključne riječi: *kapacitet, projektni elementi, polumjer, kružno raskrižje, volumen*

1 Introduction

Roundabouts are constructed on locations with lower traffic safety and where their construction enables a better traffic capacity. The roundabout construction justifiability on lower traffic safety locations is based on number of traffic accidents in relation to their consequences, the vehicle speeds achieved after roundabout construction in relation to the period before reconstruction and other measures which ensure safety primarily to pedestrians and bicyclists in roundabouts [1, 2, 3].

Analysis of roundabouts in larger Croatian cities such as the cities of Osijek, Rijeka and Zagreb showed that the classical intersections were replaced with roundabouts very successfully with the aim of achieving higher intersection capacity and sufficient traffic safety [4, 5, 6].

A better traffic capacity is easily justified by comparing the level of service at the existing intersection and the planned roundabout taking into consideration the defined design period, that is, the estimated traffic growth rate in that period [5, 6, 7].

Both factors support the fact that during the past decade the roundabouts have found its place and application even outside the countries which have traditionally been constructing them from the 60-tees (e.g. Netherlands, Great Britain, Australia) and have a large experience in designing and applying this traffic solution [8, 9, 10].

Unsatisfactory level of service occur as a rule at intersections located in city centers or close to them where spatial conditions rarely allow construction of roundabouts with larger outer radii and capacity.

According to their location and size of the outer radius, roundabouts in urban areas are classified as follows [11]:

- mini roundabouts – with the outer radius from 7 to 12,50 m,
- small roundabouts – with the outer radius from 11 to 17,50 m,
- medium large roundabouts – with the outer radius from 15 to 20,00 m.

Presuming that the intersections have 4 equally loaded arms, the framework theoretical capacity of the afore-mentioned intersections is 10 000 AADT (Annual Average Daily Traffic) for mini roundabouts [7], 15 000 AADT for small roundabouts and 20 000 AADT for medium large roundabouts [11].

The study analyzing 6 potential locations for roundabout construction in the city of Rijeka, Croatia [5] has shown that 4 out of 6 locations within the city area allow construction of the outer radius which is characteristic for medium large urban intersections (radius span from 15 to 20 m). Only one location spatially allows construction of an intersection with the outer radius of 22 m, which is classified as a medium large (single-lane) roundabout [11].

The justifiability of applying a specific roundabout diameter size within an urban area where space is of great importance because it is shared both by motorized and non-motorized traffic participants is an important design element in relation to the achieved capacity.

The methods which are usually applied for roundabout capacity calculation are based on linear regression or on gap acceptance model. The first group of methods, which is analyzed in this paper, consists of the Austrian method, the British linear regression method, the Swiss method and other [12]. The other group of methods, which are based on a gap acceptance model developed in Germany by W. Brilon and others, estimates the roundabout capacity by using the basic parameters of critical and follow-up time. This methodology is used in e.g. American Highway Capacity Manual - HCM 2000 and the Australian SIDRA - Signalized and Unsignalized Intersection Design and Research Aid [13].

More recently, when determining roundabout capacity, particularly through microsimulation, the influence of pedestrians, whose number on the urban roundabouts is not negligible, is taken into account [14].

Behavior of drivers at roundabouts has been subject to numerous studies in order to establish more accurate parameters for calculating the roundabout capacity so that application of roundabouts could efficiently increase critical point capacity of city road networks [15].

The vehicle speed at roundabout is relatively low; from 25 km/h at mini roundabouts to 40 km/h at medium large roundabouts. This was confirmed by the analysis of five roundabouts in Osijek, where drivers achieved speeds of 30 ÷ 40 km/h [4].

In practice, when at roundabouts, drivers do not keep the necessary distance between vehicles which would prevent bumping into other vehicles. When calculating the capacity, lower values of driver's reaction time can be adopted, which then results in higher actual traffic loads at roundabouts [16].

This paper analyzes the impact of radius size and other related intersection design elements on roundabout capacity through inverse design procedure so that the design elements are determined based on previously set arm saturation percentage and traffic load and its distribution. Since a dominant application of small (and, conditionally, mini) roundabouts is expected within urban areas, the analysis has been conducted for this roundabout group. The methodology was not tested for the new, so called, alternative types of roundabouts that have been designed and constructed lately [17, 18]. The analysis has been based on the Austrian method of calculating the roundabout capacity (which is also suggested by Croatian guidelines [11]) and which takes into consideration the impact of design elements on roundabout capacity. The aim is to optimize roundabouts design elements in order to achieve optimal traffic capacity by using minimal geometric elements.

2 Austrian method for calculating roundabout capacity

The Croatian roundabout design guidelines [11] recommend two methods for calculating the capacity: the Austrian and the Australian one.

The Austrian roundabout capacity calculation method is usually applied for small and medium size roundabouts (urban intersections) while the Australian non-linear method is applied for large roundabouts. Due to the calculation complexity, a computer program, e.g. SIDRA should be applied when calculating with the Australian method [11].

When starting the process of capacity assessment, the Austrian method suggests assessment of roundabout construction justifiability at a specific location and under specific traffic conditions (Fig. 1).

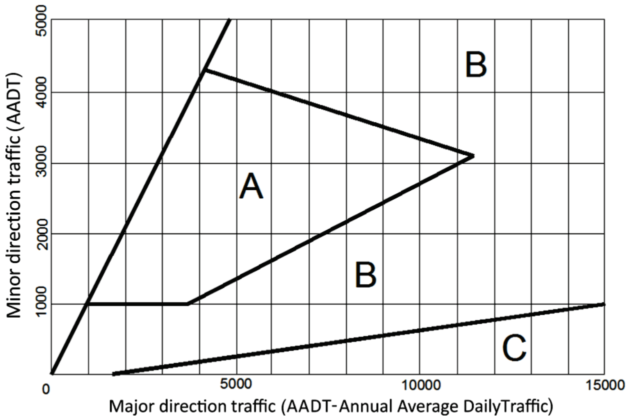

Figure 1 Justifiability of roundabout construction [7]

If the minor and major direction loads intersect in the A zone where the borderline relation between the minor and the major direction is about 3,6:1, construction of a roundabout is recommended. If they intersect in the B zone, the justifiability of constructing other types of intersections must be examined. If they intersect in the C zone, construction of a classic intersection is recommended.

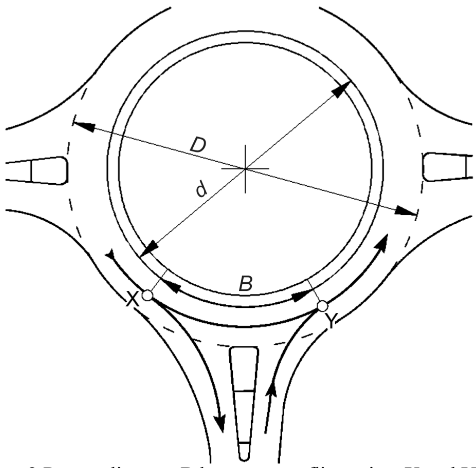

Figure 2 Proper distance B between conflict points X and Y [11]

The roundabout capacity depends on the capacity of the roundabout entrance Q_E which is determined with the following equation:

$$Q_E = 1500 - \left[\frac{8}{9} \cdot \left(b \cdot M_K + a \cdot M_A \right) \right], \tag{1}$$

where:
Q_E – entrance capacity, PC/h
M_K – circulating traffic load, PC/h
M_A – exit traffic load, PC/h
a – geometry coefficient (determined in Fig. 3)
b – coefficient of number of lanes in a roundabout.

Coefficient a depends on the distance B between conflict points of entry and exit (Fig. 2).

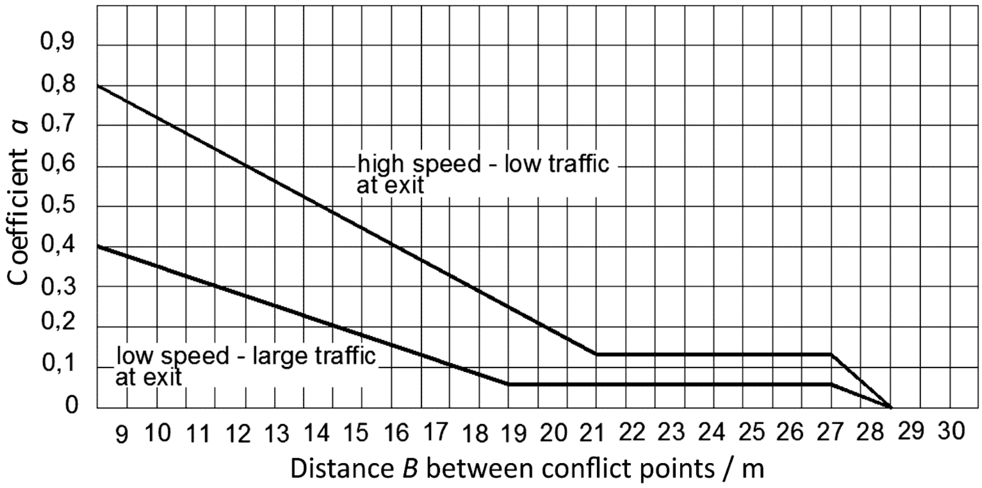

Figure 3 Diagram for determining coefficient *a* based on proper distance *B* between conflict points X and Y [11]

The distance *B* is calculated according to the equation for single-lane roundabout entrance (Fig. 4) [10]:

$$B = \frac{(D - FB) \cdot \pi \cdot \varphi}{180}, \tag{2}$$

where:
D – outer diameter of roundabout, m
FB – circulatory roadway width, m
φ – half of the central angle between the conflict points, °.

Central angle φ depends on the roundabout geometry:

$$\sin\varphi = \frac{B'}{2 \cdot (D - FB)}, \tag{3}$$

while B' is:

$$B' = \frac{(T + FB/2 + Z/2 \cdot \sin\alpha) \cdot W}{T}, \tag{4}$$

where:
T – splitter island length, m
W – splitter island width, m
Z – approach width, m
α – half of the acute angle of splitter island, °.

and:

$$\tan\alpha = \frac{W}{2T}. \tag{5}$$

The coefficient *b* expresses the influence of roundabout lane number (the brackets contain values of the same coefficient which are used in Switzerland and Austria):

- single-lane $b = 0{,}90 \div 1{,}00$ $(0{,}90 \div 1{,}00)$
- two-lane $b = 0{,}80 \div 0{,}84$ $(0{,}60 \div 0{,}80)$.

After determining the entrance capacity, the load level of each entrance is determined according to the equation:

$$\overline{M}_\mathrm{E} = \frac{c \cdot M_\mathrm{E}}{Q_\mathrm{E}} \cdot 100, \tag{6}$$

where:
$\overline{M}_\mathrm{E}$ – entrance traffic load level, %
M_E – entry flow, PC/h
Q_E – entrance capacity, PC/h
c – coefficient of number of lanes on entry to the roundabout.

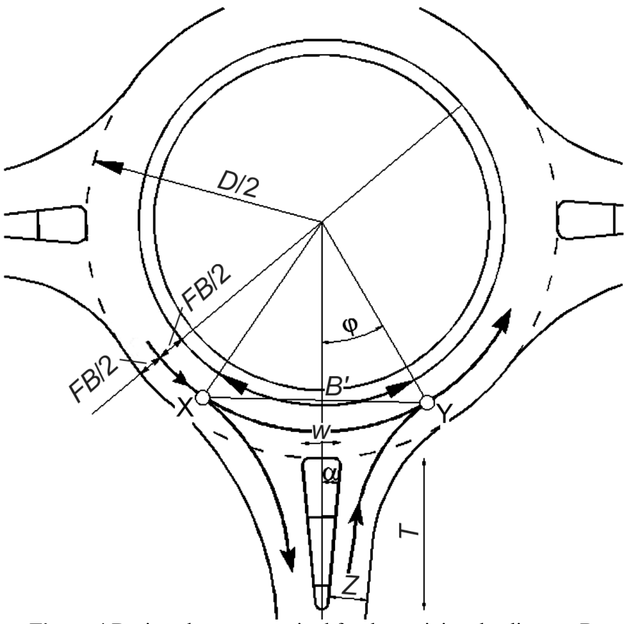

Figure 4 Design elements required for determining the distance B between the conflict points [11]

Coefficient *c* depends on the number of traffic lanes on the roundabout entrance (the brackets contain values of the same coefficient which are used in Switzerland and Austria).

The level of entrance load must not exceed 90 % of the maximum traffic load per hour [11].

3 Impact of design elements on roundabout capacity

Roundabout arm design elements are defined with marginal radius boundary values. This paper applies design parameter values defined by Guidelines for

Roundabout Design and Equipment, 2002 [13]. The roundabout capacity calculation is made by applying the Austrian method which has been described in this paper.

3.1 Impact of outer radius size of roundabout on its capacity

The entrance capacity Q_E is determined by equation (1). The empirically determined diagram (Fig. 3) of coefficient a depends on distance B between conflict points X and Y, is applied for determining the entrance design coefficient a. According to Fig. 3, the geometry coefficient a can be from a = 0,08 for low vehicle speeds and large traffic at exit point to a = 0,8 for higher vehicle speeds and low traffic at exit point. Under the same traffic load M_K and M_A, the entrance capacity Q_E will be higher with a lesser value of coefficient a. According to Fig. 3, the coefficient a value from 0,08 to 0,13 consequently corresponds to the distance B between conflict points when longer than 21 m. Fig. 5 shows vehicle paths at the roundabout with conflict points X and Y.

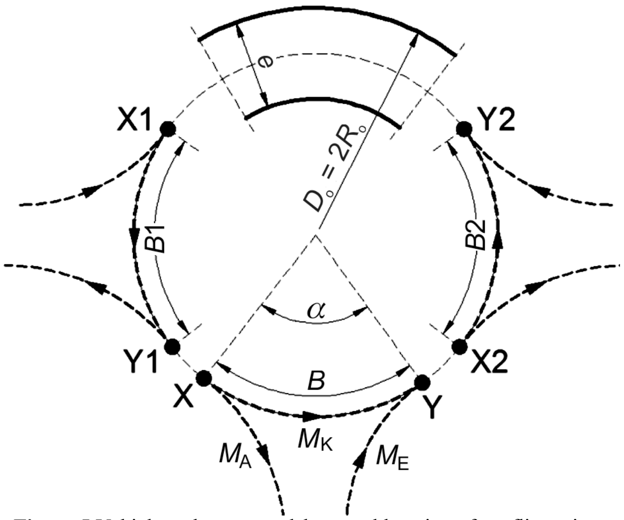

Figure 5 Vehicle path at a roundabout and location of conflict points

The maximum distance B of conflict points is achieved by correspondence of the exit point X and the entrance point Y1 of the previous arm and entrance point Y with the exit point X2 of the next arm. The interlacing area of entrance, exit and roundabout traffic lanes has been ignored in the process because, according to the afore-mentioned calculation method, it has no influence on arm capacity. The distance B between conflict points on the roundabout vehicle path is:

$$B = \frac{(D_o - e)\cdot \pi}{N}, \mathrm{m} \quad (7)$$

where :
N – number of arms of roundabout, –
e – circulatory roadway width, m
$D_o = 2R_o$ – outer diameter of roundabout, m.

Diameter of roundabout is:

$$D_o = e + \frac{B\cdot N}{\pi}, \mathrm{m}. \quad (8)$$

Under given conditions and with the adopted value for single-lane roundabout (e = 6,0 m), the desired outer radius of roundabout, that is, the radius which enables the desired distance B > 21 m between conflict points would be:

- for a three-arm roundabout: R_o > 13,0 m
- for a four-arm roundabout: R_o > 16,40 m.

It can be concluded that the desired conflict point distance value of B > 21 m can be achieved at medium large roundabouts by favorable entrance and exit construction and by applying the minimum recommended values of outer roundabout radius.

3.2 Arm construction and outer roundabout radius

Arm construction elements of a roundabout loaded with heavy trucks are defined by boundary values of marginal radii according to references of Guidelines for Roundabout Design and Equipment, 2002 [11], as shown in Tab. 1.

The paper has analyzed intersections with outer radii from R_o = 15,0 to R_o = 20,0 m. According to radius size, such intersections are classified as medium large single-lane roundabouts. For such roundabouts, referential values of entrance and exit radii range from 10,0 m to 14,0 m for the entrance radius construction (R_{en}), that is, from 12,0 m to 16,0 m for exit radius construction (R_{ex}). The roundabout circulatory roadway width meets traffic load requirements and ranges from 5,75 to 8,00 m.

Based on selected boundary values of roundabout construction elements, values for elements required for roundabout vehicle path construction were obtained (Fig. 6) and shown in Tab. 2.

Table 1 Roundabout design elements according to Guidelines for Roundabout Design and Equipment, 2002 [11]

Outer radius R_o / m	Circulatory roadway width e / m	Conditions			
		Approach width / m	Departure width / m	Entry radius R_{en} / m	Exit radius R_{ex} / m
13,00 ÷ 17,50	6,50 ÷ 8,00	3,25 ÷ 3,50	3,50 ÷ 3,75	10,00 ÷ 12,00	12,00 ÷ 14,00
17,50 ÷ 22,50	5,75 ÷ 6,50	3,50 ÷ 4,00	3,50 ÷ 4,25	12,00 ÷ 14,00	14,00 ÷ 16,00

Table 2 Values for elements required for roundabout vehicle path construction

Design elements	Outer radius R_o / m	Entry radius R_{en} / m	Exit radius R_{ex} / m	Circulatory roadway width e / m	Vehicle path radius (on circulatory roadway) R' / m	Vehicle path entry radius R'_{en} / m	Vehicle path exit radius R'_{ex} / m
minimum	15,00	10,00	12,00	8,00	11,00	11,75	13,75
maximum	20,00	12,00	14,00	6,50	16,75	13,75	15,75

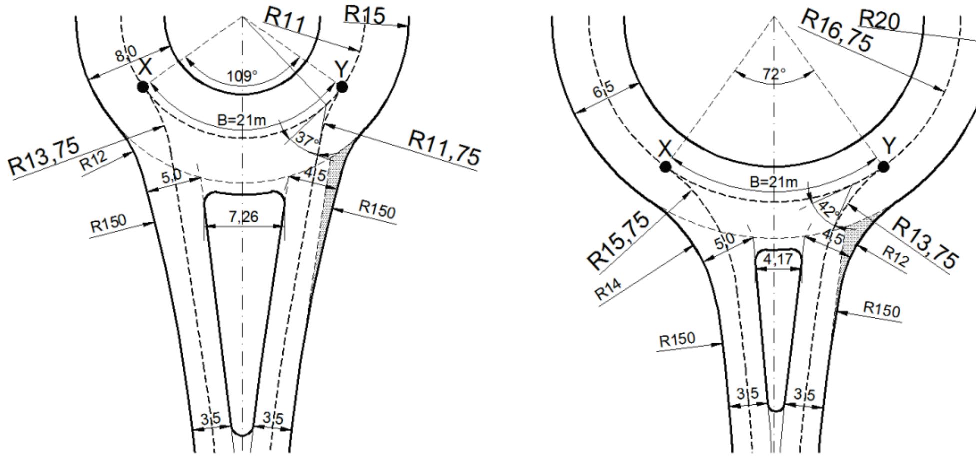

Figure 6 Approach constructions according to adopted boundary values

Arm construction according to stated values and respecting the desired conflict point distance B > 21 m is shown in Fig. 6. Arm construction base are vehicle paths which are principally defined as central axes of traffic lanes.

By applying the minimum radius (R = 15 m), the desired entrance and exit point distance (B = 21 m) can be achieved at three-arm intersections. By applying the maximum radius (R = 21 m), a five-arm intersection can be constructed.

Traditionally, when designing roundabouts, an even design ratio of arm axes should be achieved (120° at three-arm and 90° at four-arm intersections). The outer roundabout radius should be the largest possible radius under the limited location conditions in urban area.

A more proper selection of basic construction elements can be achieved if the required values of entrance and exit conflict point distances, which ensure an even entrance and exit load for the expected traffic, are pre-selected by arm load calculation.

The sum of thus obtained distances provides the minimum vehicle path length at the roundabout, which enables determination of minimum outer roundabout radius. Fig. 6 shows that such approach ensures application of the recommended design elements even in case of more demanding traffic load conditions. That, in turn, has positive impact on roundabout capacity.

The entrance traffic load level is defined by equation (6). Presuming that the acceptable solution has the entrance load grade of $\overline{M}_\mathrm{E}$ = 80 %, by applying the equation (6) the required entrance capacity Q_E can be determined as:

$$Q_{\mathrm{E\ req}} = \frac{c \cdot M_\mathrm{E}}{80} \cdot 100 = 1{,}25 \cdot c \cdot M_\mathrm{E}, \ \ \text{PC/h}. \tag{9}$$

By applying the obtained $Q_{\mathrm{E\ req}}$ from equation (1), the required coefficient value can be determined as:

$$a = \frac{9}{8} \cdot \frac{1500 - Q_{\mathrm{E\ req}} - \frac{8}{9} \cdot b \cdot M_\mathrm{K}}{M_\mathrm{A}}. \tag{10}$$

Furthermore, Fig. 3 enables determination of the required exit Y and entrance X conflict point distance B. By repeating the procedure for all roundabout arms, the minimum vehicle path radius at the roundabout is determined ($R'_{\min}$) as:

$$R'_{\min} = \frac{\sum B_i}{2\pi}, \ \text{m}. \tag{11}$$

Table 3 Examples of determining basic design elements when constructing a roundabout

<table>
<tr><td></td><td colspan="6">Case A</td><td colspan="6">Case B</td><td colspan="6">Case C</td></tr>
<tr><td>Arm of roundabout:</td><td colspan="2">1</td><td colspan="2">2</td><td colspan="2">3</td><td colspan="2">1</td><td colspan="2">2</td><td colspan="2">3</td><td colspan="2">1</td><td colspan="2">2</td><td colspan="2">3</td></tr>
<tr><td>M_E – entry traffic load / PC/h</td><td colspan="2">720</td><td colspan="2">840</td><td colspan="2">810</td><td colspan="2">720</td><td colspan="2">840</td><td colspan="2">810</td><td colspan="2">720</td><td colspan="2">840</td><td colspan="2">810</td></tr>
<tr><td>M_A – exit traffic load / PC/h</td><td colspan="2">820</td><td colspan="2">750</td><td colspan="2">800</td><td colspan="2">825</td><td colspan="2">765</td><td colspan="2">780</td><td colspan="2">828</td><td colspan="2">774</td><td colspan="2">768</td></tr>
<tr><td>M_K – circulatory traffic load / PC/h</td><td colspan="2">270</td><td colspan="2">240</td><td colspan="2">280</td><td colspan="2">405</td><td colspan="2">360</td><td colspan="2">420</td><td colspan="2">486</td><td colspan="2">432</td><td colspan="2">504</td></tr>
<tr><td>$\overline{M}_\mathrm{E}$ – entrance load level / %</td><td colspan="2">80</td><td colspan="2">80</td><td colspan="2">80</td><td colspan="2">80</td><td colspan="2">80</td><td colspan="2">80</td><td colspan="2">80</td><td colspan="2">80</td><td colspan="2">80</td></tr>
<tr><td rowspan="2">Distribution of entry traffic load M_E from one arm to another / PC/h</td><td>1÷2</td><td>1÷3</td><td>2÷3</td><td>2÷1</td><td>3÷1</td><td>3÷2</td><td>1÷2</td><td>1÷3</td><td>2÷3</td><td>2÷1</td><td>3÷1</td><td>3÷2</td><td>1÷2</td><td>1÷3</td><td>2÷3</td><td>2÷1</td><td>3÷1</td><td>3÷2</td></tr>
<tr><td>480</td><td>240</td><td>560</td><td>280</td><td>540</td><td>270</td><td>360</td><td>360</td><td>420</td><td>420</td><td>405</td><td>405</td><td>288</td><td>432</td><td>336</td><td>504</td><td>324</td><td>486</td></tr>
<tr><td>a – geometry coefficient</td><td colspan="2">0,49</td><td colspan="2">0,36</td><td colspan="2">0,34</td><td colspan="2">0,33</td><td colspan="2">0,19</td><td colspan="2">0,16</td><td colspan="2">0,23</td><td colspan="2">0,10</td><td colspan="2">0,06</td></tr>
<tr><td>B – adopted distance between conflict points / m</td><td colspan="2">8</td><td colspan="2">10</td><td colspan="2">10,5</td><td colspan="2">10,5</td><td colspan="2">14,5</td><td colspan="2">16</td><td colspan="2">14,3</td><td colspan="2">17,5</td><td colspan="2">27,5</td></tr>
<tr><td>ΣB_i / m</td><td colspan="6">28,5</td><td colspan="6">41</td><td colspan="6">59,3</td></tr>
<tr><td>2φ – central angle between conflict points / °</td><td colspan="2">101,1</td><td colspan="2">126,3</td><td colspan="2">132,6</td><td colspan="2">92,2</td><td colspan="2">127,3</td><td colspan="2">140,5</td><td colspan="2">86,8</td><td colspan="2">106,2</td><td colspan="2">166,9</td></tr>
<tr><td>e – circulatory roadway width / m</td><td colspan="6">8,0</td><td colspan="6">8,0</td><td colspan="6">8,0</td></tr>
<tr><td>$R_{\min}$ – minimal outer radius / m</td><td colspan="6">8,5</td><td colspan="6">10,5</td><td colspan="6">13,4</td></tr>
<tr><td rowspan="2">δ – angle between arm axes /°</td><td colspan="2">1÷2</td><td colspan="2">2÷3</td><td colspan="2">3÷1</td><td colspan="2">1÷2</td><td colspan="2">2÷3</td><td colspan="2">3÷1</td><td colspan="2">1÷2</td><td colspan="2">2÷3</td><td colspan="2">3÷1</td></tr>
<tr><td colspan="2">113,7</td><td colspan="2">129,5</td><td colspan="2">116,8</td><td colspan="2">109,8</td><td colspan="2">133,9</td><td colspan="2">116,3</td><td colspan="2">96,5</td><td colspan="2">136,6</td><td colspan="2">126,9</td></tr>
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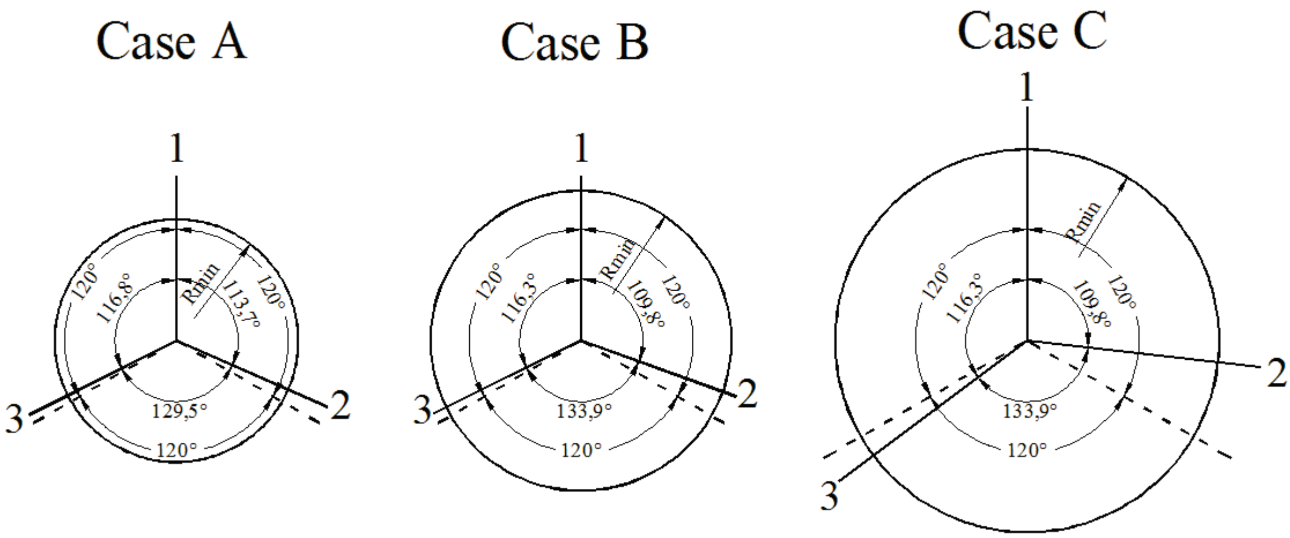

Figure 7 Different angles between arms for cases A, B and C

The relation among lengths B_i is at the same time the desired relation among arm axes angles determined according to roundabout traffic load. The final selection of outer roundabout radius in urban areas depends on the available space at the location. However, if the roundabout design elements are defined in the aforementioned way, their impact on capacity within the same available space can be optimized in the case of maximum entrance load grade (of 85 %) as well as in the cases of lower loads levels.

3.2 Example of roundabout radius and arm angle calculation in the function of roundabout capacity

Hereafter, a three-arm roundabout was theoretically analyzed. Three cases were discussed (A, B and C). The same value was taken for the entry traffic load (M_E), while the distribution of entry traffic load on other arms (exits) varied so that the relation between the number of vehicles using the first and the second exit is 2:1 in case A, 1:1 in case B and 1:2 in case C. This resulted in a different traffic load at exits (M_A) and at the roundabout (M_K). The calculation was made for a very unfavorable entrance load level of boundary $\overline{M}_E$ = 80 %, which ensures meeting the requirements at other, lesser entrance load levels, that is, a backup for this theoretical model. The result analysis of these three cases is shown in Tab. 3.

The result analysis has shown that the minimum outer roundabout radius and the desirable arm relation (different from the usual "proper" one) can be defined by the "inverse" design process. The "inverse" procedure starts from the assumed entrance saturation level and by the calculation of the theoretically required conflict point distance for small (and, conditionally, mini) roundabouts.

This procedure optimizes the radius and the arm location because, depending on the load distribution within the intersection, different angle values are obtained between conflict points, that is, between the adjacent arms. It can also be concluded that the stated design values are significantly in function of intensity and load distribution at the roundabouts.

4 Conclusion

The aim of implementing roundabouts at locations of the existing classical intersections is to increase traffic safety and/or intersection capacity within the city road network. Application of larger roundabout radii results in larger traffic capacity of the intersection. However, the problem with urban intersections is lack of space for constructing a roundabout so that radius optimization with the aim to retain desired traffic capacity is an imperative. By applying the Austrian method for calculating the intersection level of service, the possibility of defining certain intersection design elements in function of previously set entrance saturation level was analyzed in this paper. The analysis has shown that the minimum conflict point distance and the optimal arm angle can be defined by applying the inverse procedure. The procedure implies that on the basis of the defined entrance saturation level, which can be up to 85 % according to the Austrian method, design elements can be calculated. This enables optimization of spatial requirements as far as level of service is concerned. In the paper results of the application of the procedure on the three-arm roundabout are presented, the same methodology can be applied on the four- armed roundabouts too. The suggested methodology can be considered as the first phase of roundabout design procedure. Besides the aforementioned steps, a review of intersection traffic capacity for a specific vehicle and influence of pedestrian/bicycle traffic on the traffic capacity of the roundabout need to be analyzed too.

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