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Approach Alignment Impact on the Geometric Design of Urban Roundabouts

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Abstract

Nowadays existing three and four-leg intersections are frequently replaced by roundabouts. Compared to conventional intersections, the implementation of roundabouts on a road network offers several advantages, such as increased safety and intersection capacity, reduced maintenance costs and air pollution. However, in some cases, these are not realized because of the poor geometric design. One of the main prerequisites for the optimal roundabout design is that all the approach axes must intersect at the centre of a roundabout. The alignment of the approach axis relative to the centre of a roundabout plays an important role in the roundabout design. It affects the amount of deflection (the ability to control driving speed through roundabout), the swept path of a design vehicle and the sight distance. In practice, due to spatial constraints and increasing property development along the road, this precondition cannot always be satisfied. This comes to the fore particularly in urban environments, where the reconstruction of the approach axis is usually not possible. Considering the above, this paper will investigate the impact of the radial offset of approach axis (the axis does not pass through the roundabout centre) on the geometric design of urban roundabouts. The research is carried out through several theoretical examples of the small and medium-sized urban roundabouts with various external radii and for the design vehicle 12.0 m long bus.

Keywords: urban roundabouts; geometric design; approach centreline offset; swept path analysis, fastest path analysis

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1. Introduction

Single-lane roundabouts have many advantages over other types of intersections, including significant safety and operational benefits. Numerous studies (NCHRP (2007), Persaud et al. (2000), Cunningham (2007), Lenters (2005)) have shown that roundabouts, compared to conventional intersections, can significantly improve traffic safety. The geometric design of single-lane roundabouts reduces the number of conflicting points between vehicles as there are no conflicting points for crossing and weaving traffic, which are present at standard intersections. Extensive research conducted in the US showed a total reduction in all traffic accidents on roundabouts by 38%, as an alternative to signal and stop sign control at intersections, and a reduction in all accidents with physical injuries by 76% (Persaud et al. (2000)). Traffic accidents that cause severe physical injuries or result in fatalities are very rare. According to Persaud et al. (2000), the number of such traffic accidents on roundabouts was reduced by 89%, and according to the study Cunningham (2007) reduction of traffic accidents with deaths was reduced about 100%. It should also be emphasized that the cruising speed on roundabouts is low (25 - 40 km/h), which reduces the severity of injuries in case of collision between vehicle and pedestrian. Nevertheless, the advantages mentioned above can be reduced to a great extent because of the poor roundabout design. According to Montella (2011) one of the most frequent crashes contributing factor, present in almost 60% of all accidents, is the geometric design of roundabouts, which includes an excessively low entry angle and excessive entry radius.

The alignment of the approach axis, in relation to the centre of the roundabout, plays a significant role in the design of the roundabout. It effects on the central island deflection (the ability to control the pass-through speeds), swept path of a design vehicle and the sight distance. One of the prerequisites for the optimum roundabout design is that all approach axes intersect in the centre of the roundabout. In practice, due to spatial constraints this precondition cannot always be respected. This is particularly evident in urban areas, where it is usually impossible to reconstruct the approach/road axis. Due to the mentioned facts research was conducted in order to see the effect of the different alignment of the approach axis (axis do not pass through the roundabout centre) on the geometric design of urban roundabouts. The research was carried out on theoretical examples of small and medium-size single-lane roundabouts.

2. Background

According to the guidelines, regulations and recommendations from different countries (CROW (1998), FGSV (2006), FSV (2010), HC (2014), NCHRP (2007), NCHRP (2010), SETRA (1998), SRB (2012), TSC (2011) and Montella (2011)) it is preferable that all approach axes intersect at a right angle at the centre of the roundabout. That position normally allows an adequate roundabout geometric design resulting in low driving speed when entering or leaving a roundabout (Bastos Silva and Seco (2005)). The solution to move the approach axis to the left, relative to the central island, is preferable while moving to the right is not preferable because the desired results are not usually achieved (NCHRP (2010), FSV (2010)), i.e. such position of approach axis results in tangential entrance where vehicles can have high entry speed. Tangential entrance increases the chance of collision between the vehicles in the roundabout and those entering the roundabout. Moving the approach axis to the right is not considered as a mistake if the proper entry speed can be achieved and other roundabout elements can be formed.

If it isn't possible that approach axes intersect at right angle, the rotation of the approach axis is allowed, around the roundabout centre, at an angle of 5 to 10°, according to Serbian guidelines (SRB (2012)) and Slovenian regulations (TSC (2011)), or around the intersection point between the approach axis and the outer circular roadway edge, at an angle less than 10°, according to Croatian guidelines (HR (2014)). Dutch (CROW (1998)) and German guidelines (FGSVa (2006), FGSVb (2006)) have no recommendations regarding the rotation or moving of the approach axis relative to the roundabout centre. It is mandatory for German designers to control the deflection of the central island (FGSVa 2006)) and for Dutch designers, it is mandatory to test the fastest path through the roundabout (CROW (1998)).

The influence of the alignment of approach axis on roundabout safety performance can be evaluated by defining the radius of the deflection (trajectory of a vehicle travelling along the so-called fastest path through the roundabout) and then calculating the vehicle speed (Galleli et al. (2014)). This theoretical fastest path is representative of most used trajectory by drivers under free-flow conditions when minimizing their driving discomfort (Bastos Silva and Seco (2005)). At first glance, this roundabout performance check seems straightforward: firstly, the fastest path is defined, then the path radii are measured or calculated, and at the end, the vehicle speed is estimated based on speed-radius relationship. However, inconsistencies in design standards and practices concerning procedures for the definition of the deflection, construction of the fastest path, vehicle speed estimation and the speed profile requirements can be observed (Ahac et al. (2016)). As mentioned above, speed analysis on roundabouts can be conducted using different approaches:

- by measuring the roundabout's geometry features and checking the achieved deflection (as described in German guidelines (FGSVa (2006)),
- by measuring the roundabout's geometry features and calculating the path radii and vehicle speed (as described in Croatian guidelines (HR (2014)), Dutch (CROW (1998)) and Slovenian guidelines (TSC (2011)),
- by constructing the fastest paths through the roundabout, measuring the path radii and then calculating the vehicle speed (as described in American (TRB (2010)) and Serbian guidelines (RS (2011)).

According to Lenters (2005), Kennedy et al. (2005), SETRA (1998) fastest path for vehicles travelling through the roundabout should not have a radius greater than 100 m, while radius less than 70 m is preferable (FHWA (2000)).

3. Research procedure

The study on the impact of approach axis alignment on the geometric design of roundabout was conducted on theoretical examples of single-lane urban roundabouts. Theoretical examples of roundabouts were designed with these parameters (Fig. 1. (a)):

- different radii of outer edge of circular roadway were selected, Rv = 15.0, 17.5 and 20.0 m,
- triangular splitter islands were 29.5 m long, with a 1:15 side slope,
- the pedestrian crossing within the splitter island was 4.0 m long and the minimum width is 2.0 m,
- the width of the traffic lanes on the entrances was 3.5 m,
- one approach axis rotated around the point on the outer circular roadway edge, angles of rotation (α) were between -40 and 40°, with the step of 5°,
- design vehicle was 12.0 m long bus.

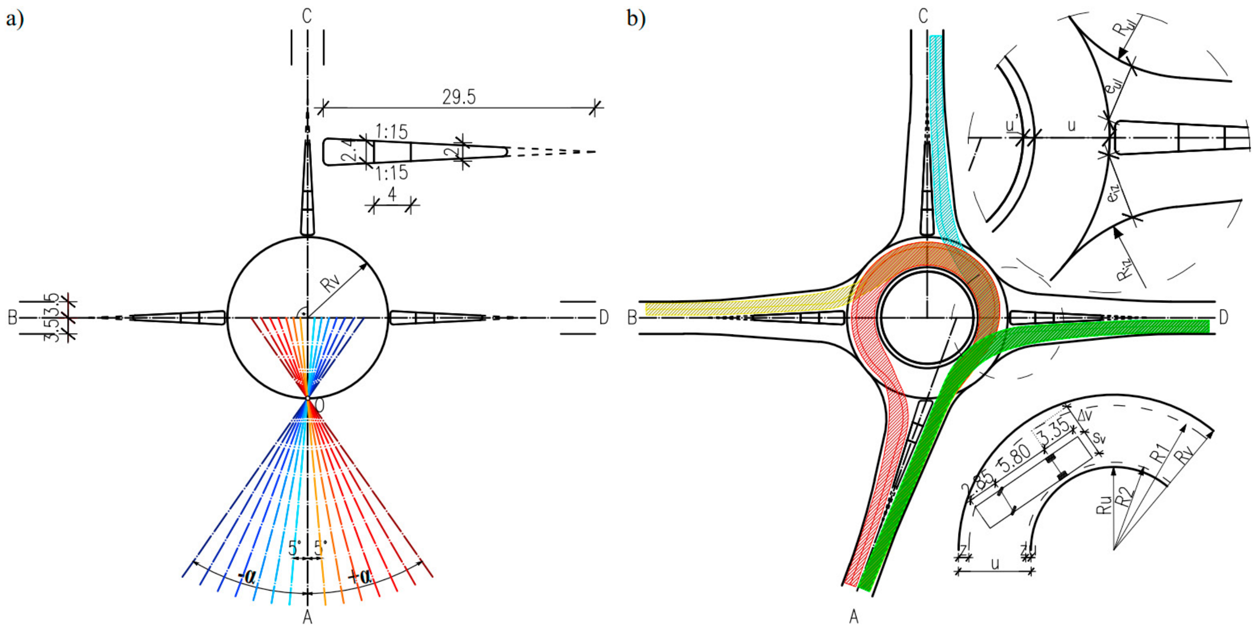

Fig. 1. (a) initial roundabout scheme; (b) swept path analysis for the design vehicle

Dimensions of a bus were taken from the German guidelines (FGSV (2001)) because this type of vehicle is common on urban and suburban roads in Europe. After the selection of the external radii (Rv), traffic lane widths and shape and length of the splitter islands, circulatory roadway widths (u) were defined as the sum of the lateral protective widths (z = 1.0 m, zu = 0.5 m) and width ($s_v + \Delta v$), and rounded to 0.1 m (Tab. 1., Fig. 1. (b)). Widths ($s_v + \Delta v$) were determined on the design vehicle movement trajectories while driving in a full circle of radii R1 (Tab. 1).

The selected width of the truck apron (u') was 1.0 m. The dimensions of the remaining roundabout design elements: the entry radius (R_{ul}), the exit radius (R_{iz}), the entry width (e_{ul}) and the exit width (e_{iz}) were determined by the swept path analysis for the design vehicle (Fig. 1. (b)), with the addition of protective lateral widths of 0.5 m. All trajectories on roundabouts were drawn by Autodesk software (Vehicle Tracking 2017) for all movement directions: straight, right, left, U-turn and circular.

Only (A) approach axis was rotated (Fig. 1.). By rotating that axis, it has been accomplished that this axis does not pass through the centre of the roundabout. The point (O) around which the rotation was made is defined as the intersection point between the extension of approach axis and the outer edge of the circular roadway (Fig. 1. (a)). The aim of this research was to determine the maximum angle of rotation of an axis, to the left and right side, at which it is possible to geometrically design all the elements (islands and roadway edges) of the roundabout.

After the geometric design of roundabouts examples was done, they were used for the fastest path (determination of pass-through speed) analysis according to TRB (2010) because other approaches could not be applied due to the non-standard position of road axis. The aim of that research was to determine in what way the rotation of approach axis to the left and right affects the results of speed analyses. Speed analysis according to TRB (2010) procedure is composed of the following steps:

- construction of the fastest path on the designed roundabout with the prescribed clearance to the geometric feature: (a) painted edge line of the splitter island, (b) a right curb on the entrance and exit of the roundabout, and (c) a curb of the central island, as shown in Fig. 2.,
- measurements of path radii (Ri),
- estimations of vehicle speed based on speed-radius relationship:

$$V_i = \sqrt{127 \cdot R_i \cdot (f \pm e)} \tag{1}$$

where (Vi) is predicted design speed (km/h), (Ri) is a radius of the curve (m), (f) is side friction factor and (e) is superelevation.

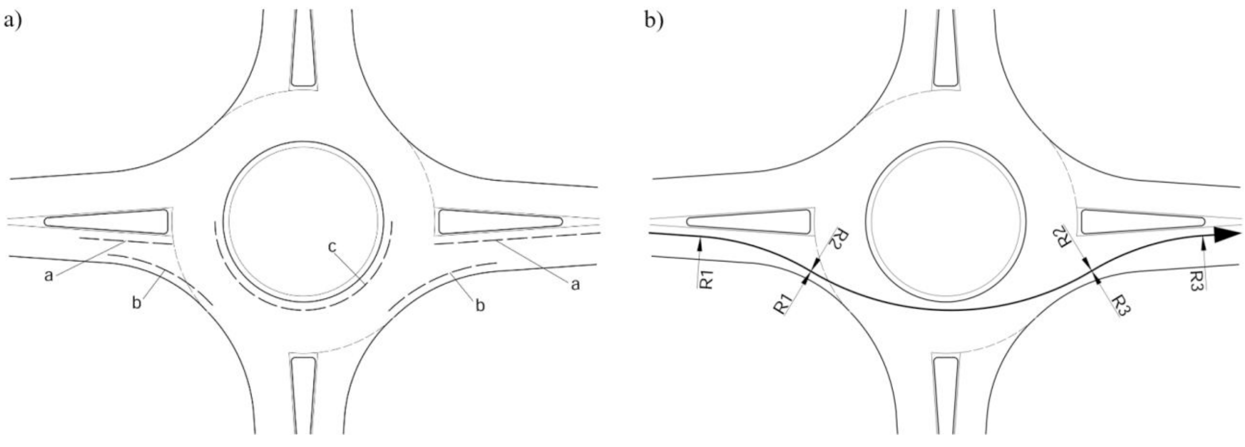

Fig. 2. (a) lateral clearances for the fastest path construction; (b) fastest path radii according to TRB (2010)

American guidelines (TRB (2010)) define lateral clearance as (a) = 1.0 m, (b) = (c) = 1.5 m. Distance (a) of 1.0 m is too small for unobstructed passage of personal vehicles and it was replaced with a distance of 1.5 m. Superelevation values were +0.025 for entry and exit curves, and -0.025 for curves around the central island. Side friction factor varies with vehicle speed and was determined in accordance with AASHTO (2011).

4. Research results

Research results (Tab. 1) showed that the maximum angle of rotation (α) of an approach axis of designed roundabouts is mostly influenced by the size of the outer circular roadway radius (Rv). The larger the radius of circular roadway (Rv) is the greater the angle of rotation of approach axis is possible. At roundabouts with the radius Rv = 15.0 m it is possible to rotate approach axis from -10 to 15°, and at the roundabouts with the radius Rv = 17.5 m it is possible to rotate approach axis from -25 to 30°. The largest angle of rotation of approach axis is possible at roundabouts with the radius Rv = 20.0 m and it ranges from -40 to 40°. The maximum values of rotation angles of approach axis were determined only by the criteria if it is possible to geometrically design all roundabouts elements for unobstructed passage of the design vehicle, with the addition that the outer roadway edges on entrance and exit of adjacent approaches are not overlapping. Entry and exit widths weren't relevant for the determination of the maximum angle of axis rotation.

Table 1. Dimensions of all design elements of roundabouts

α (°)	-40	-35	-30	-25	-20	-15	-10	-5	0	5	10	15	20	25	30	35	40
Rv = 15.0 m																	
s_v+Δv (*m*)	-	-	-	-	-	-	5.6	5.6	5.6	5.6	5.6	5.6	-	-	-	-	-
u (*m*)	-	-	-	-	-	-	7.1	7.1	7.1	7.1	7.1	7.1	-	-	-	-	-
R_{ul} (*m*)	-	-	-	-	-	-	13.0	13.0	13.0	13.0	13.0	13.0	-	-	-	-	-
R_{iz} (*m*)	-	-	-	-	-	-	15.0	15.0	15.0	15.0	15.0	15.0	-	-	-	-	-
e_{ul} (*m*)	-	-	-	-	-	-	4.2	4.5	4.8	5.1	5.5	6.0	-	-	-	-	-
e_{iz} (*m*)	-	-	-	-	-	-	6.5	6.0	5.6	5.4	5.1	4.9	-	-	-	-	-
Rv = 17.5 m																	
s_v+Δv (*m*)	-	-	-	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	-	-
u (*m*)	-	-	-	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	-	-
R_{ul} (*m*)	-	-	-	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	-	-
R_{iz} (*m*)	-	-	-	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	-	-
e_{ul} (*m*)	-	-	-	3.8	4.0	4.1	4.4	4.7	5.1	5.5	6.0	6.4	6.9	7.5	8.1	-	-
e_{iz} (*m*)	-	-	-	8.4	7.8	7.3	6.7	6.2	5.8	5.4	5.0	4.8	4.4	4.3	4.2	-	-
Rv = 20.0 m																	
s_v+Δv (*m*)	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7
u (*m*)	6.2	6.2	6.2	6.2	6.2	6.2	6.2	6.2	6.2	6.2	6.2	6.2	6.2	6.2	6.2	6.2	6.2
R_{ul} (*m*)	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0
R_{iz} (*m*)	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0
e_{ul} (*m*)	3.5	3.8	3.9	3.9	4.1	4.3	4.6	5.0	5.4	5.8	6.3	6.8	7.3	7.9	8.6	9.3	10.1
e_{iz} (*m*)	11.2	10.4	9.6	8.9	8.3	7.7	7.4	6.6	6.2	5.6	5.3	4.9	4.6	4.2	4.0	3.7	3.5

(-) - not applicable because entrance and exit roadway edges on adjacent approaches are overlapping

After the determination of maximum rotation angles according to geometric design for the design vehicle safety performance of roundabouts was tested (pass-through speed test). The pass-through speeds were tested for the most critical directions, movement of the vehicle through the roundabout: the straight passage - the AC and CA directions and the right turn - BA and AD directions (Fig. 1.). Regarding certain pass-through speeds, the roundabouts with different radius (Rv) and angles of rotation of approach axis are divided into three categories:

- optimal ($25 \leq V \leq 40$ km/h),
- acceptable ($15 \leq V < 25$ km/h and $40 < V \leq 50$ km/h),
- unacceptable ($V < 15$ km/h and $V > 50$ km/h).

Table 2. Speed analysis for passing straight through the roundabouts

α (°)	-40	-35	-30	-25	-20	-15	-10	-5	0	5	10	15	20	25	30	35	40
Rv = 15.0 m																	
$V1_{A-C}$ (*km/h*)	-	-	-	-	-	-	53	42	38	35	34	33	-	-	-	-	-
$V2_{A-C}$ (*km/h*)	-	-	-	-	-	-	25	25	25	26	26	26	-	-	-	-	-
$V3_{A-C}$ (*km/h*)	-	-	-	-	-	-	47	49	47	47	49	47	-	-	-	-	-
$V1_{C-A}$ (*km/h*)	-	-	-	-	-	-	36	37	38	38	38	39	-	-	-	-	-
$V2_{C-A}$ (*km/h*)	-	-	-	-	-	-	26	26	25	25	25	26	-	-	-	-	-
$V3_{C-A}$ (*km/h*)	-	-	-	-	-	-	42	45	47	62	105	112	-	-	-	-	-
Rv = 17.5 m																	
$V1_{A-C}$ (*km/h*)	-	-	-	119	62	45	43	41	38	34	34	30	29	29	28	-	-
$V2_{A-C}$ (*km/h*)	-	-	-	23	23	22	23	23	23	23	24	24	24	24	25	-	-
$V3_{A-C}$ (*km/h*)	-	-	-	41	42	38	40	41	41	42	43	43	42	41	38	-	-
$V1_{C-A}$ (*km/h*)	-	-	-	37	35	34	38	35	38	35	36	38	37	36	33	-	-
$V2_{C-A}$ (*km/h*)	-	-	-	24	24	24	24	23	23	22	23	23	23	23	23	-	-
$V3_{C-A}$ (*km/h*)	-	-	-	33	34	34	35	38	41	45	46	53	76	85	na	-	-
Rv = 20.0 m																	
$V1_{A-C}$ (*km/h*)	na	na	na	61	49	44	39	37	35	32	31	30	28	28	28	28	27
$V2_{A-C}$ (*km/h*)	24	23	23	22	22	22	22	22	23	22	23	23	22	24	23	24	24
$V3_{A-C}$ (*km/h*)	39	38	38	39	39	38	40	40	39	39	40	40	41	40	39	39	39
$V1_{C-A}$ (*km/h*)	35	34	34	34	34	35	34	35	34	36	34	35	34	34	35	34	34
$V2_{C-A}$ (*km/h*)	24	25	24	24	23	23	22	22	23	22	22	22	22	23	23	22	23
$V3_{C-A}$ (*km/h*)	29	31	31	32	32	34	34	36	40	41	44	48	61	85	105	na	na

V1 - entry speed; V2 - speed along the circular island; V3 - exit speed
na - speed analysis according to TRB (2010) is not applicable because of tangential entrance or exit from roundabout

Test results (Tab. 2. and 3.) have shown that:

- at roundabouts with the radius Rv = 15.0 m there are no optimum angles of rotation of approach axis, while acceptable angles of rotation range from -5 to 0° (Tab. 2),
- at roundabouts with the radius Rv = 17.5 m there are no optimum angles of rotation of approach axis, while acceptable angles of rotation range from -15 to 10°,
- at roundabouts with the radius Rv = 20.0 m there are no optimum angles of rotation of approach axis, while acceptable angles of rotation range from -20 to 15°,
- right turn speed values are not relevant for the determination of maximum rotation angle of the approach axis.

Table 3. Speed analysis for right turn on roundabouts

α (°)	-40	-35	-30	-25	-20	-15	-10	-5	0	5	10	15	20	25	30	35	40
Rv = 15.0 m																	
V_{A-D} (*km/h*)	-	-	-	-	-	-	30	30	28	28	27	26	-	-	-	-	-
V_{B-A} (*km/h*)	-	-	-	-	-	-	27	28	28	30	30	32	-	-	-	-	-
Rv = 17.5 m																	
V_{A-D} (*km/h*)	-	-	-	36	35	34	34	32	31	31	30	30	30	28	27	-	-
V_{B-A} (*km/h*)	-	-	-	27	28	30	30	30	31	33	33	34	35	38	38	-	-
Rv = 20.0 m																	
V_{A-D} (*km/h*)	44	42	40	39	37	36	35	35	34	33	33	32	32	31	30	30	29
V_{B-A} (*km/h*)	27	28	29	30	30	31	32	32	34	35	35	37	38	40	41	44	47

Based on the results shown in Tables 1 and 2 it is apparent that outer radius (Rv) and angle of rotation (±α) of approach axis affects the design of roundabout geometric elements and values of the pass-through speed. By increasing the angle of rotation of approach axis to the left (- α):

- the required entry width (e_{ul}) decreases, while the speeds ($V1_{A-C}$) increases as the path radius (R1) increases,
- the required exit width (e_{iz}) increases, while the speeds ($V3_{C-A}$) decreases as the path radius (R3) decreases.

By increasing the angle of rotation of approach axis to the right (+ α):

- the required entry width (e_{ul}) increases, while the speeds ($V1_{A-C}$) decreases as the path radius (R1) decreases,
- the required exit width (e_{iz}) decreases, while the speeds ($V3_{C-A}$) increases as the path radius (R3) increases.

The passing-through speed (V2) around the central island varies slightly with the change of the outer radius (Rv), the width of the circulatory roadway and the angle of rotation (α) of approach axis.

5. Conclusions

On the urban road network, there is often a need for the construction of roundabouts with approach axes which don't pass through the roundabout centre and they don't intersect with other approach axes at a right angle. The aim of this study was to determine the impact of approach axis rotation on the geometric design of roundabouts. The research was carried out on theoretical examples of roundabouts with different radii (Rv = 15.0, 17.5 and 20.0 m) and the 12.0 m long two-axle bus was chosen as a design vehicle. The research results showed that the rotation of an approach axis has an impact on the geometric design of roundabouts. By rotating the approach axis to the left, the required entry width decreases while the required exit width increases. By rotating the approach axis to the right required entry width increases and the required exit width decreases. The maximum rotation angle value depends on the size of the radius (Rv), the greater the radius (Rv) is the greater is the possible angle of rotation of the approach axis.

In addition to the geometric design and the unobstructed passage of a design vehicle, it is also necessary to check the safety performance of designed roundabouts. Results from speed analysis even further limited the rotation angles of approach axis. The values of a rotation angle of approach axis, determined in this study, are considerably higher than the values prescribed by the guidelines and recommendations. The results obtained in this study should be compared to the results obtained on real examples of roundabouts with rotated approach axis to bring the final conclusions.

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