CETRA 2016

4th International Conference on Road and Rail Infrastructure
23-25 May 2016, Šibenik, Croatia

Road and Rail Infrastructure IV

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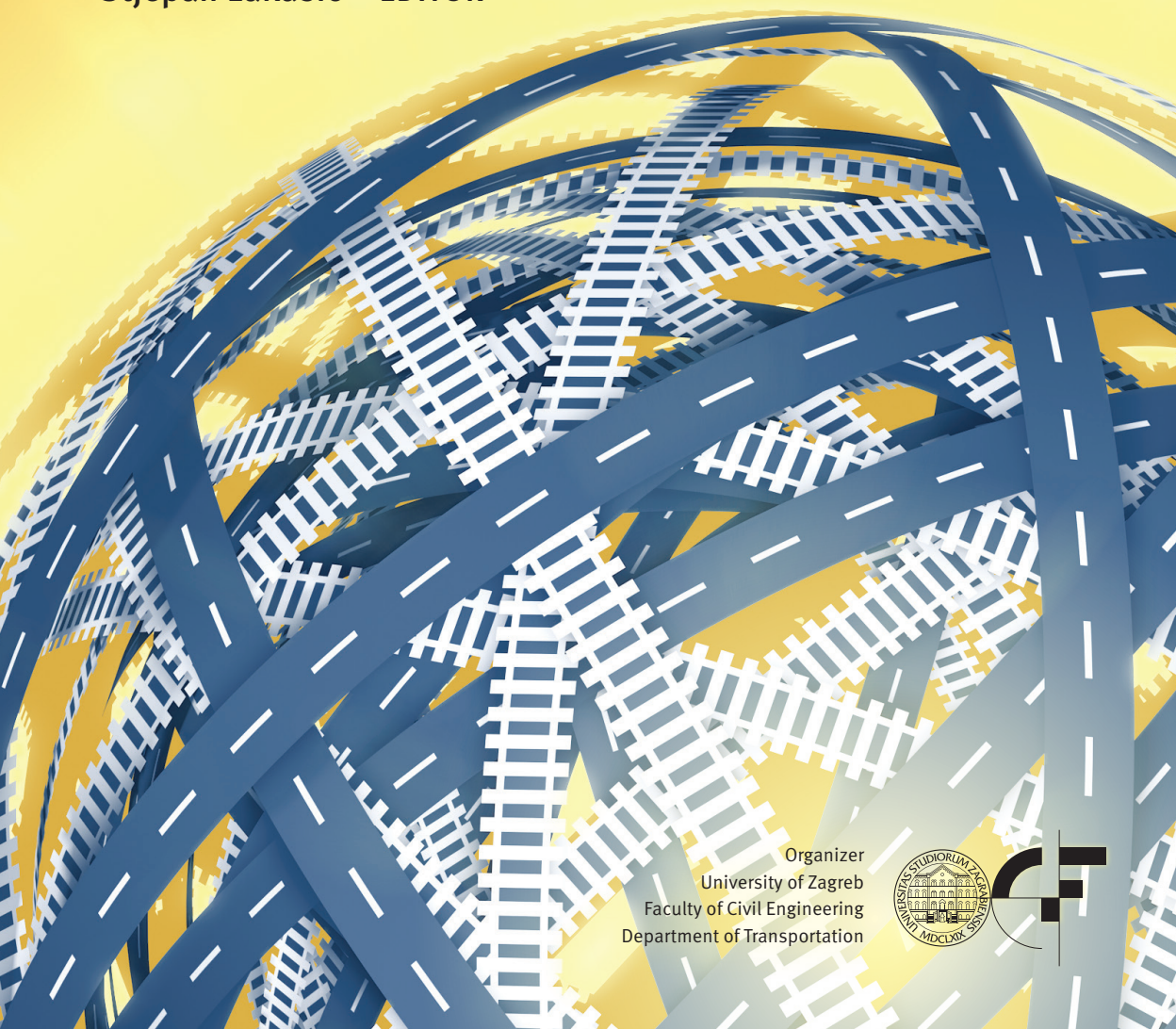

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SWEPT PATH ANALYSIS ON ROUNDABOUTS FOR THREE-AXLE BUSES – REVIEW OF THE CROATIAN DESIGN GUIDELINES

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Abstract

Latest edition of Croatian design guidelines for roundabouts was published in 2014, and its usage is mandatory for intersections on the state roads. This paper offers a review of aforementioned guidelines, with the emphasis on the roundabout geometric design, which are presented through several theoretical examples of suburban roundabouts with various external radii. On these roundabouts swept path analysis for tri-axle bus is conducted, and results of this analysis are commented on. This long passenger vehicle was chosen for the analysis even though it is not defined as a design vehicle in guidelines, due to the following facts: (1) Croatia is a popular tourist destination, with numerous guests arriving from distant locations, and tri-axle buses are a common mean of their transport; (2) swept path analyses have shown that the space needed by the vehicle body during the turning movements is larger for this type of vehicle, compared to design vehicles from the guidelines. Because of that, this paper presents the impact of aforementioned long passenger vehicles on the geometric design of roundabouts.

Keywords: Croatian guidelines, roundabouts, design vehicle, three-axle buses

1 Introduction

Today the existing three-leg and a four-leg cross intersections are often replaced by roundabouts. Compared to conventional intersections, application of roundabouts in the road network has many positive effects, such as increased safety and intersection capacity, reduced maintenance costs and air pollution [1, 2]. However, in some cases these benefits may be annulled due to the poor geometric design, which can be result of wrong selection of the design vehicle or even lack of critical performance check: the swept path analysis [3].
Croatian guidelines for roundabout design were published in June 2014 [4]. They define two design vehicles for swept path analysis, semitrailer truck and truck with trailer. Unlike for example Austrian [5] and German guidelines [6], Croatian guidelines do not define buses as design vehicles, even though buses play an important role in the transport of passengers in long-distance lines in Croatia (such as the transport of tourists to popular destinations on the Croatian coast). Tourism is one of the key drivers of the Croatian economy: the increase in the number of tourists is recorded each year, and the total income from these activities in 2014 accounted for 17.2% of GDP [7]. Because of the cost effectiveness (lower costs) these passengers are increasingly transported with three-axle buses with maximum permissible length up to 15.0 m [8]. Previous research [9] showed that three-axle buses occupy larger area when turning compared to heavy goods vehicles (semitrailer truck). Because of that, swept path analysis for six three-axle buses from different manufacturers [10 – 13] has been conducted on a few examples of roundabouts designed according to Croatian guidelines [4]. The main goal for this research was to define the impact that these vehicles have on the operating ca-

pabilities and geometric design of roundabouts. All bus movement trajectories were drawn by Vehicle Tracking software [14].

2 Geometric design of roundabouts according to the Croatian guidelines

Geometric design of suburban roundabouts according to the Croatian guidelines is carried out in nine major steps [4]:

1) selection of the external radius (Rv),
2) selection of the two-axle design vehicle and determination of the circulatory roadway width (u) by using vehicle movement trajectory while driving in a full circle (Fig. 1a, chapter 2.1),
3) selection of the heavy goods design vehicle and determination of the central island truck apron width (u') by using vehicle movement trajectory while driving in a full circle (Fig. 1b, chapter 2.1),
4) selection of the approach roadway lane width (v) and splitter island form and length (m) (Fig. 2),
5) designing the outer roadway edge on entry: selection of the entrance width (eul) and the outer edge radius (Rul) (Fig. 2),
6) designing the outer roadway edge on exit: selection of the exit width (eiz) and the outer edge radius (Riz),
7) control of the entry angle (Φ) and roadway widening severity (S),
8) swept path analysis on the roundabout for the design vehicle and for all movement directions,
9) determination of the fastest path through the roundabout.

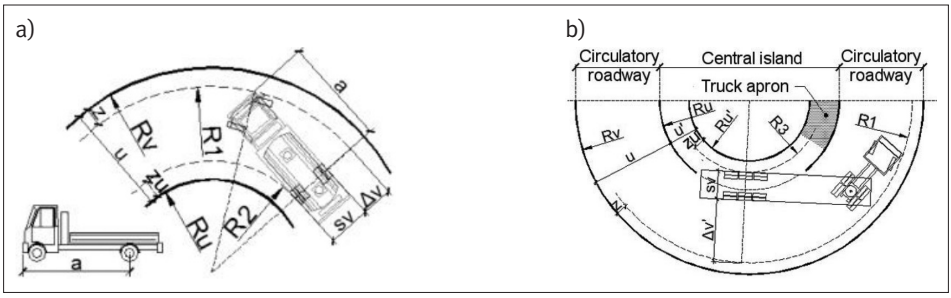


Figure 1 Determination of the circulatory roadway and truck apron width [4]

If the swept path analysis shows that the entry and exit lane widths (eul/iz) are insufficient for unobstructed movement of the design vehicle, steps 5 to 9 have to be repeated. Roundabout design process is an iterative one.

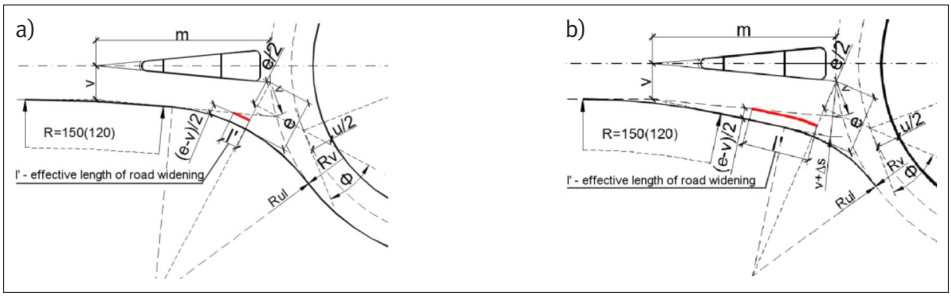


Figure 2 Outer roadway edge design and entry angle determination [4]

2.1 Recommended dimensions of the roundabout design elements

On small and medium sized rural and suburban roundabouts (Rv = 11.0 – 25.0 m) splitter islands usually have triangular form (Fig. 2). Their recommended length (m) ranges from 15.0 to 50.0 m. Conditions for unobstructed vehicle movement on roundabout entry and exit are achieved by proper selection of the entry (Rul) and exit (Riz) radii, the entrance and exit widths (eul/iz), the circulatory roadway width (u), and by the proper design of the outer roadway edge on entry and exit. The outer roadway edge can be formed in two different ways:

a) with shorter effective roadway widening length (l') – the outer roadway edge is composed of circular arc and straight line which is parallel to the side of the triangular splitter island (Fig. 2a),
b) with longer effective roadway widening length (l') – the outer roadway edge is composed of circular arc and straight line which isn't parallel to the side of the triangular splitter island (Fig. 2b).

The designer has to choose the way which ensures unobstructed vehicle movement. Decision must be based on the design vehicle swept path analysis. Recommended and limit values of roundabout design elements are given in Table 1.

Table 1 Recommended and limit values of roundabout design elements [4]

Element	Recommended values	Limit values
eul/iz [m]	4.0 – 7.0	3.6 – 10.0
v [m]	3.0 – 3.5	2.5 – 7.0
Rul [m]	8.0 – 20.0	6.0 – 25.0
Riz [m]	10.0 – 25.0	8.0 – 50.0

Circulatory roadway width (u) is determined on the basis of the drawn two-axle vehicle movement trajectory, while driving in a full circle (Fig. 1a). Values (u) are given in guidelines [4] only for specific (a) and (R1) values, and they range from 2.0 to 8.3 m. The minimum central island truck apron width (u') is 1.0 m. At the end of roundabout design process specific parameters have to be controlled: effective roadway widening length (l'), entry angle (Φ) and roadway widening severity (S) (Fig. 2). Entry angle (Φ) limit values range from 0 to 77 °, while the recommended values range from 20 to 40 °. Dimensionless roadway widening severity (S) is calculated according to the following formula:

$$S = 1.6 \cdot (e - v) / l' \tag{1}$$

where e [m] is the entrance width, v [m] is the approach lane width, and l' [m] is the roadway widening length.

Limit and recommended (S) values ranges from 0 to 2.9. If the (S) value is greater than 1.0, roadway widening is short and sharp (Fig. 2a). Longer roadway widenings (Fig. 2b) on entrance are more effective and desirable especially when vehicles with higher approaching speeds are expected. Usually longer roadway widening meet boundary condition: S < 2.9.

2.2 Design vehicles and swept path analysis

Roundabout swept path analysis can be performed with two design vehicles [4]: semitrailer truck (l = 16.5 m) and truck with trailer (l = 18.75 m). Dimensions of those vehicles (Fig. 3) are in compliance with EU Directive [8]. Complete dimensions of two-axle vehicles are not given in guidelines [4]: only (a) values are given and they ranges from 3.0 to 9.7 m. These two-axle

vehicles are only used for the determination of the circulatory roadway width (u) (Fig. 1a). Their choice should be harmonized with the needs of users at the proposed roundabout location and with the consent of the road administration.

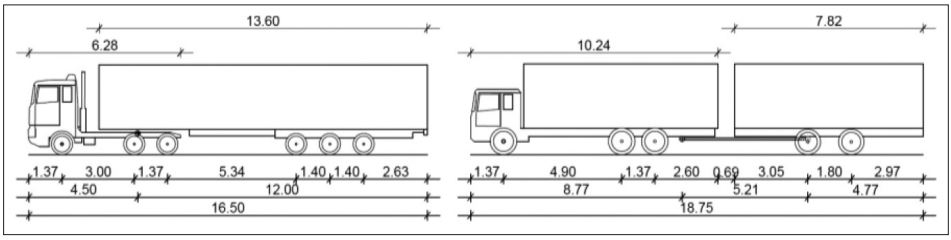


Figure 3 Design vehicles [4]

Swept path analysis is conducted by drawing the design vehicle (body) movement trajectories in all possible directions on roundabout blueprint. It ensures that conditions for unobstructed vehicle movement on roundabout entry and exit are achieved. The minimum protective lateral width along the trajectories (zu) is 0.5 m (exceptionally 0.3 m) on all segments, except on the outside edge of the circulatory roadway where the minimum lateral width (z) is 1.0 m (Fig. 1).

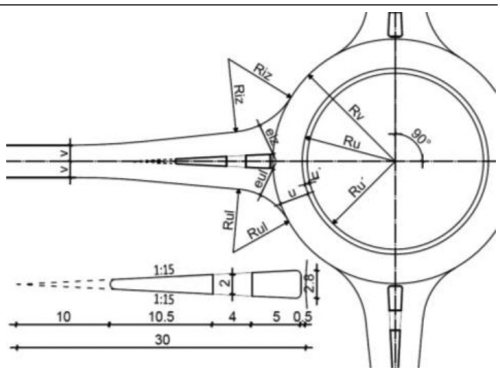
3 Research

Research presented in this paper was conducted on five roundabouts that were designed on the basis of the following input data (Table 2):

- approach road axis intersect at a right angle (90°);
- roundabouts outer radii (Rv) range from 15.0 to 25.0 m (step 2.5 m);
- splitter islands are triangular, 30.0 m long, with side slope 1:15;
- approach roadway lanes are 3.3 m wide.

Table 2 Applied design elements dimensions

Dimensions	RO 1	RO 2	RO 3	RO 4	RO 5
Rv [m]	15.0	17.5	20.0	22.5	25.0
R1 [m]	14.0	16.5	19.0	21.5	24.0
sv+Δv [m]	5.70	5.14	4.75	4.48	4.24
u [m]	7.25	6.75	6.25	6.00	5.75
u' [m]	1.0	1.0	1.0	1.0	1.0
eul [m]	5.0	5.0	6.0	6.0	6.0
eiz [m]	6.0	6.0	6.0	6.5	6.5
Rul [m]	13.0	13.0	13.0	13.0	13.0
Riz [m]	15.0	15.0	15.0	15.0	15.0
Φ [°]	37.5	42.8	46.4	46.8	46.8
S	0.48	0.39	0.58	1.16	1.10

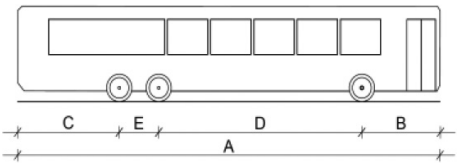


Radii (R1) were determined on the basis of the roundabout outer radii (Rv), in a way that values (Rv) were reduced by the protective lateral width z = 1.0 m (Fig. 1b, Table 2). Circulatory roadway widths (u) were defined as the sum of the widths z = 1.0 m, zu = 0.5 m and sv+Δv, rounded to 0.25 m (Table 2). Widths sv+Δv were determined on the basis of the drawn two-axle vehicle (EvoBus, Setra S 415 H, l = 12.2 m [10]) movement trajectory, while driving in a full circle of radii (R1). Circulatory roadway widths were defined in that way because they are not specified in the guidelines [4] for the selected two-axle bus (a = 8.9 m) and all selected radii

(R1) (Table 2). Initial entrance widths (eul), exit widths (eiz), outer edge radii and outer edge radii (Rul and Riz) were also selected.
After all the roundabout elements were selected and initial roundabouts design was finished, swept path analyses were conducted. Swept path analyses were conducted on all five roundabouts (Table 2), for all directions and for selected design vehicle (Fig. 3). Semitrailer truck was selected as a design vehicle because it occupies greater turning width than truck with trailer [9]. All trajectories were drawn by Vehicle Tracking software [14]. After swept path analyses were finished, following elements were defined: truck apron widths (u'), entrance widths (eul), exit widths (eiz), outer edge radii (Rul) and outer edge radii (Riz) (Table 2). Entry and exit roadways were formed with longer effective widening (l') to ensure unobstructed design vehicle movement. Entry angles (Φ) and widening severity (S) were also controlled. Obtained values of (Φ) angle are within limit range, while (S) values are within the recommended range (Table 2).
Swept path analyses were then conducted again on all five roundabouts, but this time for three-axle buses with the length up to 15.0 m (Table 3). Their dimensions were obtained from the web pages [10- 13] of renowned European bus manufacturers, because they are not defined in the guidelines [4]. Selected buses are designed for international passenger transport (Setra ComfortClass S 519 HD, Scania OmniExpress, and Irizar i6), and for intercity passenger transport (MB Citaro LU, Setra MultiClass S 419 UL, and Volvo 8900) (Table 3).

Table 3 Three-axle buses dimensions [10 – 13]

Vehicle	Dimensions [m]				
	A	B	C	D	E
Setra CC S519 HD	14.945	2.890	3.315	7.140	1.600
Scania Om.Ex.	14.890	2.795	3.395	7.200	1.500
Irizar i6	14.980	2.690	3.510	7.280	1.500
MB Citaro LU	14.995	2.705	3.400	7.290	1.600
Setra MC S419 UL	14.980	3.160	3.300	6.920	1.600
Volvo 8900	14.960	2.769	3.597	7.194	1.400



A: total length
B: front overhang
C: rear overhang
D: wheel base: front axle – rear axle
E: wheel base: rear axle – trailing axle
Vehicles width: 2.550 m

4 Research results

Results of the swept path analyses showed that all six three-axle buses, regardless of the type and manufacturer, can pass through all five designed roundabouts, but with certain problems that can slow down their movement. Most common problems that occurred are that buses had to use protective lateral widths (at the entrance and exit) and the truck apron (Table 4). In both cases minimum prescribed [4] protective lateral widths of 0.5 (0.3) m, or 1.0 m were not provided. Research showed that there is also an additional problem: when buses were entering the circulatory roadway their rear overhangs swung and used protective lateral width along the splitter island near the pedestrian crossing (Fig. 4). This can cause discomfort and reduced security of pedestrians.

Table 4 Results of the swept path analysis on roundabouts for three-axle buses

Vehicle	RO 1				RO 2				RO 3				RO 4				RO 5			
	→	↑	←	∩	→	↑	←	∩	→	↑	←	∩	→	↑	←	∩	→	↑	←	∩
Setra CC S 519 HD	■	●	●▲	●▲	✓	✓	▲	▲	✓	✓	▲	▲	●	●▲	●	●	●	●▲	●▲	●▲
Scania OmniEx.	■	●	●▲	●▲	✓	✓	▲	▲	✓	✓	▲	▲	●	●▲	●▲	●	●	●▲	●▲	●▲
Irizar i6	■	●	●▲	●▲	✓	✓	▲	▲	✓	✓	●▲	●▲	●	●▲	●▲	●▲	●	●▲	●▲	●▲
MB Citaro LU	■	●	●▲	●▲	✓	✓	▲	▲	✓	✓	●▲	●▲	●	●▲	●▲	●▲	●	●▲	●▲	●▲
Setra MC S 419 UL	■	●	●▲	●▲	✓	✓	▲	▲	✓	▲	●▲	●▲	●	●▲	●▲	●▲	●	●▲	●▲	●▲
Volvo 8900	■	●	●▲	●▲	✓	✓	▲	▲	✓	✓	●▲	●▲	●	●▲	●▲	●▲	●	●▲	●▲	●▲

Legend:
→ – right; ↑ – straight; ← – left; ∩ – U-turn; ● – uses lateral protective width on entrance;
■ – uses lateral protective width on exit; ▲ – uses truck apron on exit; ✓ – no problem

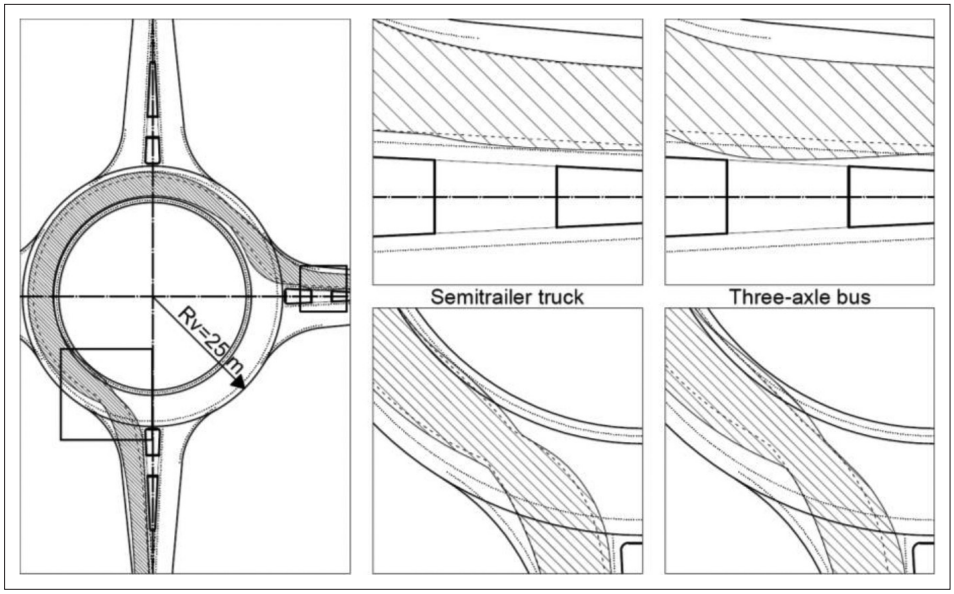


Figure 4 Semitrailer truck and three-axle bus movement trajectories

The main reason for these problems are that three-axle buses occupy greater widths while turning than semitrailer truck or two-axle bus (Table 5). Additional research showed (Table 5) that three-axle buses occupy from 0.21 to 0.34 m greater width than semitrailer truck, and from 0.47 to 0.89 m greater width than two-axle bus, while driving in full circle of radii (R1). Most suitable for the movement of three-axle buses have proved to be roundabouts RO 2 (Rv = 17.5 m) and RO 3 (Rv = 20.0 m). Most unfavourable has proved to be roundabout RO 5 (Rv = 25.0 m), due to the usage of the protective area with rear overhang at the entrance and exit.

Table 5 Width (u) which vehicles occupy while driving in a full circle of radii (R1)

Vehicle	u [m]				
	R1 = 14.0 m	R1 = 16.5 m	R1 = 19.0 m	R1 = 21.5 m	R1 = 24.0 m
Setra MC S 415 H, l = 12.2 m	5.70	5.14	4.75	4.48	4.25
Semitrailer truck, l = 16.5 m	6.25	5.71	5.20	4.83	4.51
Setra CC S 519 HD	6.65	5.91	5.40	5.03	4.75
Scania OmniExpress	6.61	5.88	5.38	5.01	4.73
Irizar i6	6.59	5.86	5.36	5.00	4.72
Mercedes Benz Citaro LU	6.62	5.88	5.38	5.01	4.73
Setra MC S 419 UL	6.69	5.94	5.43	5.06	4.77
Volvo 8900	6.59	5.86	5.36	4.99	4.72

5 Conclusions

Research presented in this paper has shown that analysed three-axle buses can physically pass through roundabouts designed according to Croatian guidelines, but with certain restrictions, which may slow down their movement and passenger comfort. Namely, while negotiating the intersection, these vehicles used the truck apron and lateral protective width along the movement trajectories. That happens because those vehicles occupy greater swept path width then the semitrailer truck while entering and exiting the roundabout. The reason for that are the vehicle dimensions, i.e. the sum of the length of the front overhang and wheel base, which range from 9.963 to 10.08 m for the selected vehicles. Based on the research results summarized above, the following recommendations for the design of roundabouts, on which an increased numbers of three-axle buses are present, can be made:

- outer roundabout radius (Rv) should be between 17.5 and 22.5 m,
- entrance and exit widths should be greater than the ones defined for the semitrailer truck,
- circulatory roadway width should accommodate buses in order to achieve greater passenger comfort (avoiding the use of truck apron),
- all swept path analyses should be conducted for three-axle bus,
- the splitter island should be wider than minimum prescribed (1.6 (2.0) m) in order for pedestrians and cyclists to feel safe.

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