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ORIGINAL SCIENTIFIC PAPER

Influence of geometric elements of roundabouts on circulating lane speed (roundabout)

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Abstract: Research conducted in recent decades has shown that there are significant variations in speed at roundabouts depending on the geometric elements. Due to the characteristics of roundabouts and the way vehicles move, there is a reduction in speed, not only in the roundabout zone, but also in circulation (roundabout). This paper analyzes the influence of different types of roundabouts as one of the elements of the street system, on speed as one of the basic parameters of traffic flow that defines the functionality and quality of traffic conditions.

Keywords: roundabout, speed, circulation, geometric elements.

INTRODUCTION

Roundabouts are increasingly being part of the city's arteries, and their impact on traffic conditions is specific compared to other types of intersections. Compared to other types of intersections, roundabouts, due to their specific geometry, significantly affect the speed of traffic flow for all movements and maneuvers, on all part of raoundabout. Ever since the first scientific and professional papers, the functional connection between the geometric and constructive characteristics of the functional parts of the road and street network and the speed of traffic flow (HCM, 1950), and thus the conditions of traffic, has been established (Bogdanović, V., 2005).

Many papers have investigated the relationships between certain geometric characteristics of roundabouts and average speed, which they defined as the average value of input speed, speed at the roundabout (circulation) and output speed (Chen, Y., Persaud, B., Lyon, C., 2011), (Akçelik, R., 2011), (Almoarawi M., D. E., 2018), (Bezina, Š., Dragičević, V., Stančerić I.,, 2019)

The connection between the geometric characteristics of roundabouts, speed and capacity, traffic flow parameters and traffic conditions has been confirmed in many studies (Davidović S., Bogdanović V., Garunović N., Papić Z., Pamučar D., 2021) (Vincenzo, G., Rosolino, V., Teresa, I., 2014), (Rodegerdts, L., Bansen, J., Tiesler, C., Knudsen, J., Myers, E., Johnson, M., & O'Brien, A., 2010). The combination of the influence of geometric elements, traffic flow parameters and driver behavior makes the conditions of traffic at roundabouts very complex with significant variations in speed and other traffic flow parameters.

Speed is one of the basic parameters defined in simulation models in order to describe as much as possible the real conditions of traffic at roundabouts (Nikolic, G, Pringle, R., Bragg, K., 2010), (Gallelli, V., Vaiana, R., Iuele, T.,, 2014)

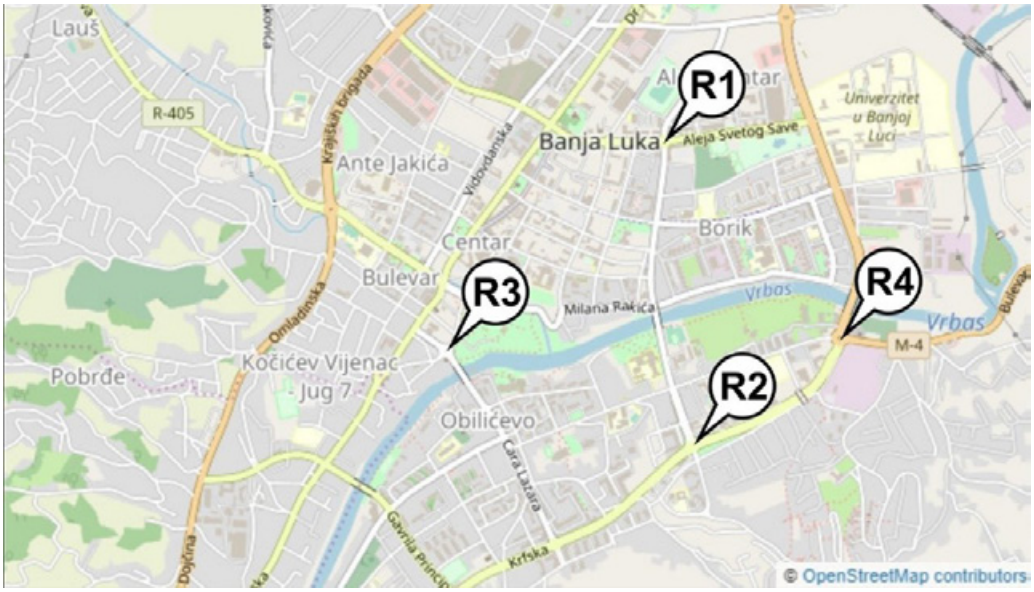
There is no methodology for calculating traffic flow parameters, capacity and service levels related to the part of the street network where the conditions of uninterrupted traffic flows prevail (Highway Capacity Manual, 2010) in which the influence of the geometric elements of the road is not included and valorized through various parameters.

The main goal of this research is to define and model the influence of geometric characteristics of roundabouts on the speed of vehicle circulating lane speed (roundabout).

In order to realize the goal, research was conducted in the real conditions of traffic, and the dependence between the geometric characteristics of roundabouts and the speed of traffic flow in circulation (roundabout) was analyzed and defined.

Data collection was done by recording the real traffic flow at four roundabouts (picture 1) in the urban area of the city of Banja Luka (Republika Srpska - Bosnia and Herzegovina). The roundabouts where the research was done belong to the roundabouts of medium size and large city roundabouts.

4 roundabouts with different geometric characteristics were selected: R1 Aleja svetog Save – Gundulićeva (picture 2); R2 Majke Jugovića – Bulevar Desanke Maksimović (picture 3), R3 Patre – Isaije Mitrović (picture 4) i R4 Bulevar Stepe Stepanovića – Bulevar Petra Bojovića (picture 5). During the research, it was sunny weather with a temperature of 15-35 ^{o}C, without fog, rain, strong wind and other unfavorable climatic conditions, the road was dry and without damage, without situations that would affect the flow of traffic.



Picture 1. Positions of analyzed roundabouts on the street network of the city of Banja Luka

Picture 2. R1 Aleja svetog Save – Gundulićeva

Picture 3. R2 Majke Jugovića – Bulevar Desanke Maksimović

Pisture 4. R3 Patre – Isaije Mitrović

Pisture 5. R4 Bulevar Stepe Stepanovića – Bulevar Petra Bojovića

Table 1 shows data on the GPS position of roundabouts.

Table 1. data on GPS position of roundabouts

Position of roundabouts in WGS-84 coordinate system	R1	R2	R3	R4
Latitude	44.773963	44.762172	44.765897	44.766366
Longitude	17.199593	17.201245	17.187834	17.209049

Traffic recording was done by the "DJI Mavic 2 Pro" drone. The created video material has a frequency of 24 fps and is processed by the software "Data From Sky" which enables marking of reference lines, analysis of the movement of objects (vehicles) on the image and review of the image by sequences with an accuracy of approximately 0.042 seconds.

By viewing the videos, two categories of vehicles were formed: vehicles that were obstructed and those that were not obstructed. Obstructed vehicles are those that had to stop at the approach to the roundabout (significantly reduce speed, below 10 km / h) for the following reasons:

- In front of the pedestrian crossing due to pedestrians,
- Before the entrance due to the traffic situation in the circulation zone.

Vehicles were also considered obstructed if they stopped at the exit from the roundabout due to pedestrians or other reasons (for example due to another vehicle that stopped due to pedestrians).

Tables 2 and 3 show the vehicle speed in circulation (roundabout) - S_crc, for unobstructed (CON) and obstructed vehicles (DIS).

Table 2. Characteristics of the vehicle speed in circulation (roundabout)- S_crc, unobstructed vehicles (CON)

INT	DEP	N	Mean	SE Mean	StDev	Min	Q1	Med	Q3	Max
R1	A	2	24,88	4,64	6,56	20,24	*	24,88	*	29,52
	B	8	22,59	0,98	2,76	19,68	20,49	21,69	24,27	28,06
	C	2	19,84	1,73	2,44	18,11	*	19,84	*	21,57
	D	1	23,20	*	*	23,20	*	23,20	*	23,20
R2	A/1	-	-	-	-	-	-	-	-	-
	A/2	-	-	-	-	-	-	-	-	-
	B/1	21	27,82	1,05	4,79	21,18	24,67	25,93	32,04	40,14
	B/2	54	28,77	0,77	5,68	18,91	25,06	28,54	30,87	51,85
	C/1	22	23,00	0,47	2,22	19,08	21,39	22,92	24,48	27,48
	C/2	14	23,31	0,49	1,84	19,50	22,39	23,13	25,06	25,79
	D/1	5	21,19	0,50	1,12	20,38	20,38	20,98	22,11	23,10
	D/2	-	-	-	-	-	-	-	-	-
R3	A	15	24,57	0,94	3,62	20,49	20,93	24,01	27,08	31,85
	B	35	25,12	0,35	2,05	19,77	24,03	25,14	24,46	29,11
	C	12	23,69	0,55	1,89	20,82	21,80	23,85	24,92	26,83
	D	2	25,73	0,63	0,89	25,10	*	25,73	*	26,36
R4	A/0	3	25,54	3,31	5,73	20,29	20,29	24,67	31,65	31,65
	A/1	1	22,40	*	*	22,40	*	22,40	*	22,40
	A/2	39	28,82	0,70	4,36	20,16	26,06	27,97	31,32	38,19
	B/0	13	26,70	0,50	1,79	23,53	25,70	26,71	28,00	30,05
	B/1	22	27,44	0,53	2,48	23,07	25,51	27,24	29,43	32,65
	B/2	24	29,69	0,59	2,90	25,08	27,31	29,67	32,51	34,89
	C/0	7	26,68	0,74	1,95	22,66	25,96	26,48	28,41	28,49
	C/1	20	26,87	0,50	2,25	22,86	24,48	27,143	28,86	30,77
	C/2	5	29,01	0,87	1,95	26,21	27,25	28,83	30,85	30,87
	D/0	-	-	-	-	-	-	-	-	-
	D/1	1	26,76	*	*	26,76	*	26,76	*	26,76
	D/2	-	-	-	-	-	-	-	-	-

Table 3. Characteristics of the vehicle speed in circulation (roundabout)- S_crc, obstructed vehicles (DIS)

INT	DEP	N	Mean	SE Mean	StDev	Min	Q1	Med	Q3	Max
R1	A	18	22,56	0,97	2,76	19,68	20,50	21,69	14,27	28,06
	B	40	20,70	0,36	2,27	19,82	18,59	2064	22,46	26,13
	C	12	19,99	0,48	1,67	17,83	18,26	20,03	21,18	22,98
	D	-	-	-	-	-	-	-	-	-
R2	A/1	-	-	-	-	-	-	-	-	-
	A/2	1	16,02	*	*	16,02	*	16,02	*	16,02
	B/1	21	21,57	0,73	3,36	15,71	19,07	21,93	24,16	26,89
	B/2	63	22,32	0,46	3,68	15,39	20,30	22,15	24,70	32,13
	C/1	46	20,19	0,36	2,42	15,42	18,53	19,95	21,59	27,95
	C/2	12	20,41	0,42	1,45	18,42	18,85	20,74	21,58	22,60
	D/1	15	19,95	0,33	1,29	17,80	18,99	20,16	21,09	22,58
	D/2	6	20,52	0,57	1,40	18,16	19,56	20,64	21,78	21,91
R3	A	32	21,21	0,81	4,81	10,08	19,09	21,34	24,77	29,98
	B	57	21,57	0,34	2,55	15,56	19,86	21,30	23,32	27,36
	C	23	21,54	0,44	2,10	16,95	20,40	21,39	23,37	24,80
	D	1	19,50	*	*	19,50	*	19,50	*	19,50
R4	A/0	1	25,96	*	*	25,96	*	25,96	*	25,96
	A/1	-	-	-	-	-	-	-	-	-
	A/2	27	20,34	0,64	3,35	13,35	18,02	21,06	22,04	27,72
	B/0	16	25,066	0,90	3,61	21,00	22,20	25,08	26,32	35,55
	B/1	19	24,90	0,55	2,40	20,80	23,14	24,78	27,20	29,28
	B/2	30	24,25	0,41	2,23	19,63	22,83	24,22	25,81	28,46
	C/0	12	24,21	0,76	2,63	20,31	22,28	24,02	26,53	29,06
	C/1	22	24,16	0,34	1,59	22,05	22,68	23,73	25,47	25,88
	C/2	4	23,63	1,46	2,92	21,08	21,43	22,82	26,66	27,82
	D/0	1	32,58	*	*	32,58	*	32,58	*	32,58
	D/1	3	25,02	0,50	0,87	24,44	24,44	24,59	26,02	26,02
	D/2	1	18,47	*	*	18,47	*	18,47	*	18,47

Based on the results of previous research and field observations, fourteen geometric parameters have been identified that could potentially affect vehicle speed:

En_lane	Parameter that defines the movement of the vehicle on the approach, entrance to the circle, roundabout and exit;
N_lne	Number of traffic lanes on the approach;
W_lne	Width of the traffic lane at the approach (m);
W_en	Entrance width (m);
R_en	Radius of entrance (m);
D1	External diameter of the roundabout (m);
D2	Diameter of the central island (m);

N_cr	Number of traffic lanes in the roundabout;
W_lnc	Width of the traffic lane in the roundabout (m);
W_cr	Road width in a circle (m);
N_lnx	Number of traffic lanes on the exit branch to which the observed vehicle flow exits;
W_lnx	Width of the traffic lane on the exit branch to which the observed vehicle flow exits (m);
W_ex	Width of the exit at which the observed flow of the vehicle exits (m);
R_ex	Exit radius at the exit branch where the observed vehicle flow exits (m);

In tables 4., 5., 6. i 7., the geometric elements of roundabouts are shown.

Table 4. Geometric parameters of the roundabout R1: Gundulićeva – Aleja svetog Save

R1 – Gundulićeva – Aleja svetog Save					
General geometric characteristics	External diameter of the roundabout (m)			33,6	
	Diameter of the central island (m)			22,0	
	Road width in a circle (m)			5,8	
	Number of traffic lanes in the roundabout			1	
	Width of the traffic lane in the roundabout (m)			5,8	
Geometric characteristics of the approach		**Approach**			
		1	**2**	**3**	**4**
Number of traffic lanes on the approach		1	1	1	1
Approach	Width of the approach (m)	3,6	3,6	5,0	3,6
	Width of the traffic lane at the approach (m)	3,6	3,6	5,0	3,6
Entrance	Entrance width (m)	5,0	5,2	5,3	5,0
	Width of the traffic lane at the entrance (m)	5,0	5,2	5,3	5,0
Radius of entrance (m)		14,0	21,2	15,0	20,0
Entrance angle (0)		26,9	20,9	28,7	25,3
Exit	Exit width (m)	5,3	4,6	5,5	5,0
	Number of traffic lanes on the exit	1	1	1	1
Width of the traffic lane at the exit (m)		4,0	3,6	4,5	3,6
Radius of exit (m)		16,9	17,4	23,3	22,1
Dividing island width (m)		1,8	2,9	3,0	2,6

Table 5. Geometric parameters of the roundabout R2: Majke Jugovića – Bulevar Desanke Maksimović

R2 – Majke Jugovića – Bulevar Desanke Maksimović					
General geometric characteristics	External diameter of the roundabout (m)			33,0	
	Diameter of the central island (m)			16,0	
	Road width in a circle (m)			8,0	
	Number of traffic lanes in the roundabout			2	
	Width of the traffic lane in the roundabout (m)			4,0	
Geometric characteristics of the approach		**Approach**			
		1	**2**	**3**	**4**
Number of traffic lanes on the approach		2	3	2	2
Approach	Width of the approach (m)	7,0	9,8	6,4	7,5
	Width of the traffic lane at the approach (m)	3,5*	3,4+3,4+3	3,2*	3,75*
Entrance	Entrance width (m)	7,4	13,0	7,6	7,6
	Width of the traffic lane at the entrance (m)	3,7*	3,7+3,7+5,6	3,8*	3,8*
Radius of entrance (m)		12,6	15,8	15,9	12,3
Entrance angle (0)		23,8	21,8	50,7	42,2
Exit	Exit width (m)	7,6	8,2	9,2	7,2
	Number of traffic lanes on the exit	2	2	2	2
Width of the traffic lane at the exit (m)		3,5*	3,6*	3,2*	3,4*
Radius of exit (m)		12,0	14,2	14,0	18,2
Dividing island width (m)		1,2	3,1	1,1	4,6

* traffic lanes of the same width

Table 6. Geometric parameters of the roundabout R3: Patre, Cara Lazara – Teodora Kolokotronisa, Isaije Mitrovića

R3 – Patre, Cara Lazara – Teodora Kolokotronisa, Isaije Mitrovića					
General geometric characteristics	External diameter of the roundabout (m)			43,0	
	Diameter of the central island (m)			31,0	
	Road width in a circle (m)			6,0	
	Number of traffic lanes in the roundabout			1	
	Width of the traffic lane in the roundabout (m)			6	
Geometric characteristics of the approach		**Approach**			
		1	**2**	**3**	**4**
Number of traffic lanes on the approach		1	1	1	1
Approach	Width of the approach (m)	4,6	4,6	4,1	4,3
	Width of the traffic lane at the approach (m)	4,6	4,6	4,1	4,3
Entrance	Entrance width (m)	5,1	4,7	5,9	5,1
	Width of the traffic lane at the entrance (m)	5,1	4,7	5,9	5,1
Radius of entrance (m)		15,4	13,4	21,6	15,2
Entrance angle (0)		35,3	25,8	31,0	33,8

Exit	Exit width (m)	5,4	4,7	5,5	4,7
	Number of traffic lanes on the exit	1	1	1	1
Width of the traffic lane at the exit (m)		4,3	4,5	4,1	4,3
Radius of exit (m)		18,4	22,5	15,0	62,2
Dividing island width (m)		3,4	11,5	3,9	8,4

Table 7. Geometric parameters of the roundabout R4: Bul. Desanke Maksimović – Bul. VojvodeStepe Stepanovića

R4 – Bul. Desanke Maksimović – Bul. Vojvode Stepe Stepanovića					
General geometric characteristics	External diameter of the roundabout (m)			57,2	
	Diameter of the central island (m)			34,8	
	Road width in a circle (m)			9,4	
	Number of traffic lanes in the roundabout			2	
	Width of the traffic lane in the roundabout (m)			4,7	
Geometric characteristics of the approach		**Approach**			
		1	**2**	**3**	**4**
Number of traffic lanes on the approach		2	1	2	2
Approach	Width of the approach (m)	7,2	4,3	7,4	7,6
	Width of the traffic lane at the approach (m)	3,6*	4,3	3,7*	3,8*
Entrance	Entrance width (m)	8	4,2	8,4	9,2
	Width of the traffic lane at the entrance (m)	*	4,2	4,2*	4,6*
Radius of entrance (m)		23	17,9	20	23,7
Entrance angle (0)		43,4	31,9	35,9	28,0
Exit	Exit width (m)	9,4	4,7	9,4	5,8
	Number of traffic lanes on the exit	2	1	2	1
Width of the traffic lane at the exit (m)		3,6	4	3,7*	3,8
Radius of exit (m)		26,9	20,2	26,2	20,2
Dividing island width (m)		2,6	6	3,6	4,1

*traffic lanes of the same width

FORMATION OF THE MODEL OF THE AVERAGE FLOW SPEED IN CIRCULATION (ROUNDABOUT) - S_CRC

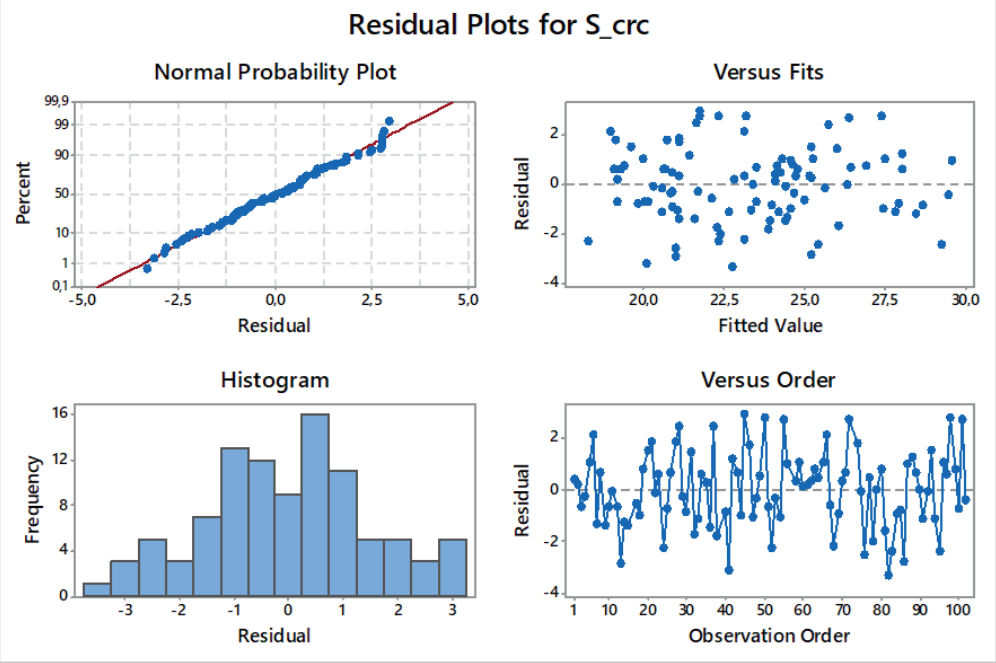
In accordance with the analysis that was done, the model of speed S_crc was formed:

$$S_{crc}^{A} = 9{,}396 + 0{,}3040\, S_{ent} + 0{,}1287\, D1 + 0{,}609\, N_{cr}$$
$$S_{crc}^{B} = 11{,}554 + 0{,}3040\, S_{ent} + 0{,}1287\, D1 + 0{,}609\, N_{cr}$$
$$S_{crc}^{C} = 10{,}250 + 0{,}3040\, S_{ent} + 0{,}1287\, D1 + 0{,}609\, N_{cr}$$
$$S_{crc}^{D} = 9{,}354 + 0{,}3040\, S_{ent} + 0{,}1287\, D1 + 0{,}609\, N_{cr}$$

$S_{crc}^{A;B;C;D}$ - Average flow speed in circulation (roundabout) (km/h), depending on the type of movement (A – right/first exit; B – right/second exit; C – left/third exit; D – u-turn / fourth exit);
S_{ent} - Average flow speed at the entry into the circle (km/h);
$D1$ - External diameter of the roundabout (m);
N_{cr} - Number of traffic lanes in circulation (roundabout);

The obtained regression has a derivation coefficient R2 = 77.85%. The corrected coefficient of determination R2 (adj) = 76.39%, while the predictive coefficient of determination is R2 (pred) = 73.94%. The standard regression error of the speed model S_crc is S = 1.54 (km / h). Based on the summary parameters of the model, it can be concluded that the determined equation very well describes the dependence of the speed S_crc and the selected predictors.

The analysis of the residues determined that they were randomly distributed around the line representing the regression curve. Residuals agree with the normal distribution (AD = 0.252; P-value = 0.731). The mean residual value is very close to zero and is 2,53765E-16. The following figure shows a graphical representation of the residuals of the velocity model S_app.



Picture 6. Residual from the speed model S_crc

CONCLUSION

At the beginning, roundabouts were mainly used on the secondary street network, but due to the positive effects of use, they quickly began to be used on the main city arteries. For the needs of traffic planning and regulation, as well as in operational and planning analysis, the effects of roundabouts are analyzed using classical methods, without taking into account the specific traffic conditions generated by geometric elements of roundabouts. Many studies since the end of the last century have shown in an objective way that roundabouts affect the speed of traffic flow.

The research in this paper was focused on the analysis of the influence of roundabouts and its basic geometric elements on the change of circulating lane speed (roundabout). The research was done in real traffic flow at four roundabouts with different geometric elements. The influence of the geometry of roundabout elements has been the subject of various studies, but in this paper, in addition to geometric elements, the influence of traffic flow, ie interaction with other vehicles at the roundabout, ie interference resulting from interaction. After the formation of the database of characteristic velocities, 14 geometric parameters of the roundabout were defined, which could potentially have an impact on the speed on the segments of the roundabout, as well as the mutual influence of speed.

With multiple regression analysis, a model was formed for calculating the average speed of traffic flow in circulation (roundabout) - S_crc, which shows depending on the type of movement (right/first exit; right/second exit; left/third exit; u-turn fourth exit), average flow speed at the entry into the circle (km/h), external diameter of the roundabout (m), number of traffic lanes in circulation (roundabout). Further research should focus on a wider area of roundabout approaches than the one covered by the analysis in this paper.

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