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Article

Speed Analyses of Intersections Converted to Roundabouts – Case Study from Croatia

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Abstract: The reconstruction of standard at-grade intersection into roundabout is very often motivated by the need to improve the safety of a part of the road network. To assure the effect of the reconstruction before-after analyses based on traffic accidents or some other indirect traffic safety parameter is needed. This paper presents a detailed analysis of four roundabouts reconstructed from the at-grade intersection according to the Croatian Guidelines for Roundabout Design. The analysis included a comparison of speeds at the location - a standard intersection-before and a roundabout - after reconstruction, time distribution of operational speed and applied design elements as well as their correlations. Experimentally gathered data on operational speed showed that the expected effect of speed reduction was not achieved in most of the analyzed cases. The conclusion is that given that the Croatian Guidelines set a very wide range for roundabout elements, the designer has a great influence on the selection and, consequently, on the effects of the roundabout implementation. The revision of the Guidelines is suggested.

Keywords: roundabout design; traffic parameters; geometry parameters; operational speed.

1. Introduction

Road intersections are the most hazardous points of the road network due to a series of decisions that the driver needs to make in a short period of time. This is why intersections should be designed with all their elements in an understandable and simple manner that ensures easy navigation but also forces drivers to decrease speed to have more time to observe the situation and decide.

Reconstruction of at-grade signalized or non-signalized intersections in roundabouts is often motivated to increase traffic safety of the existing intersection because, due to the way of moving and reduced number of potential conflict points, they are precepted as safer solutions. The curved path of passage through the intersection also increases safety, as the speed of movement inside and in the wider zone of the intersection (delivery and departure) is reduced [1,2].

Around the world, roundabouts have the same basic elements, but regulations and guidelines for roundabout design can differ a lot between countries and European countries. Depending on the overall traffic culture and habits, some countries and this is the case Croatia [3] also tried to adopt more conventional elements – e.g., smaller entry and exit radii, preferably orthogonal entrance and all that to ensure maximum effect of the above-mentioned advantages of roundabouts related to traffic safety. Except for traffic safety improvement, roundabouts are, especially in the cases of reconstruction of existing intersections in urban areas, efficient solutions for capacity improvement [4,5].

Many countries have developed a set of criteria for comparing different designs to ensure the positive effects of intersection reconstruction. These criteria test different aspects of roundabout performance and compare them during the design phase with possible standard intersection solutions [6].

After roundabouts are implemented, it is common practice to monitor their performance to improve the solution and achieve the best possible effects—by increasing capacity, reducing the number of traffic accidents and/or speed, etc. The results of several relevant studies are presented in Chapter 2 of this paper.

In Croatia, the last guidelines for designing roundabouts were issued in 2015 [3], referring primarily to state roads. Still, since there is no other technical regulation, the Guidelines are widely applied to all categories of roads outside and in urban areas where pedestrians are regularly present. It has to be pointed out that Croatian guidelines for roundabouts have a lot of similarities with those of surrounding countries (e.g., Slovenia, Serbia, and Bosnia and Herzegovina). Croatian Guidelines give designers lots of freedom to choose and optimize design elements. To ensure the functionality of the design, three checks are suggested - visibility, swept path, and operating speed [3].

The available traffic safety statistics at the national level for Croatia [7] show that since the implementation of new guidelines for the design of roundabouts in 2015, the number of traffic accidents at roundabouts has been increasing in the period 2016-2022 by 35%. The number of fatally injured in the same period is almost constant, and it varies from 0 to a maximum of 3 deaths per year. The increasing number of accidents in the period 2016 - 2022 can be connected with the increasing number of this type of intersection (there are no reliable figures on the number of reconstructed intersections in the Republic of Croatia) and their implementation in areas where they represent a novelty and a certain period of user adaptation to a specific way of moving through the intersection is needed. Even so, it is important to check if the implementation of roundabouts has influenced expected positive changes in traffic flow.

Although there have been years in which there was not a single fatality at roundabouts, data show [7] that in some of the analyzed years, the proportion of fatalities at roundabouts is the same as at standard at-grade intersections even if they are applied with the presumption that they are the safer solution.

The analysis of existing research shows that collecting and analyzing data related to traffic safety at roundabouts is an extremely important step in defining traffic and infrastructural elements that affect safety [8]. Analysis of the functionality of the roundabout - safety and capacity, and a comparison with the previous solution at the exact location, when it comes to reconstructions, are the basis for improving the theory and practice of designing this type of intersection. In several European countries (mainly Scandinavian), design standards were analyzed and improved in the early 2000s [9]. According to the author, such research has not been systematically conducted in Croatia.

In this study, analyses are done for four roundabouts situated in Rijeka City and the surrounding region. The chosen roundabouts were reconstructed from at-grade intersections and designed according to Croatian Guidelines [3]—further in the text Guidelines—with elements suggested in the document. Elements pointed out in the Guidelines are not strictly defined. There are wide suggestions on the values of the elements to be applied, so the final roundabout design is greatly influenced by traffic needs, location characteristics, and environment, but it also depends on the designers' choices.

At all four locations, traffic volumes, structure, and speed were measured 24 hours on the site before the reconstruction - at standard intersections and after reconstruction - at the roundabouts. Measured speeds at the standard intersections represent one of the reasons for the reconstruction of the intersection from a classic to a roundabout. Detailed analyses of measured speed were done to define possible parameters influencing that speed – traffic and design parameters. The limitation of the study is that traffic accident data were not included as the number of reported accidents is very small and, therefore, not valid for the purpose of safety analyses.

The main goal of this research is to analyze the operational speeds at the entrance and exit of roundabouts and their correlation with the selected traffic and parameters to establish if the effect of traffic calming in the area of the reconstructed roundabout is achieved. As previous research analysis confirmed (in detail in Chapter 2), real-speed data from standard intersections before reconstruction and roundabouts after reconstruction can serve as a valuable measure for estimating the impact of the roundabout implementation on traffic safety.

The research results provide a basis for a clearer definition of recommendations for selecting elements that directly or indirectly affect the speeds in roundabouts. This can serve as a basis for improvement in Croatian and overall roundabout design theory and practice.

2. Roundabout Efficiency Analyses – An Overview

Different approaches are used to analyze the effects of roundabout implementation efficiency at locations where standard intersections were converted into roundabouts.

Two main types of procedures can be distinguished:

- procedures for analyzing and comparing solutions in advance, during the planning or design phase, to determine whether the roundabout is an optimal solution compared to other types of at-grade intersections concerning the reason for the reconstruction of the intersection and
- research that is carried out after the construction of roundabouts when, based on the performance data, the impact of the roundabout implementation on the safety, capacity, environment, etc., is analyzed and estimated.

2.1. Analyses of Possible Effects of Roundabout Implementation before Implementation- Planning Stage

The analysis of roundabout applicability to select the optimal solution for a particular intersection usually includes applying multi-criteria analyses (MCA) and/or creating and testing traffic microsimulation models for different types of solutions.

To evaluate the appropriateness of the use of roundabouts in relation to some other type of intersection, procedures are defined in many countries through the criteria based on which the comparison is made. The criteria include various aspects of the analyzed solutions - traffic functioning, impact on traffic safety and the environment, economic justification, etc. [6]. In this way, it is possible to choose the optimal solution by analyzing its potential effects through multi-criteria analysis (MCA) [10,11].

Traffic microsimulation models are used to analyze the future traffic function of the intersection within the MCA [12] or alone. Models created in one of the traffic microsimulation solutions (VISSIM; AIMSUN, etc.) enable the analysis of several variants of the infrastructure solution for different variants and scenarios of traffic demand. Alternatives compared and evaluated through microsimulation outputs (e.g., travel time, vehicle delay, queue length, or other) can give very valuable answers regarding which type of intersection will have the best traffic performance [4,5] or how the number of roundabouts on the corridor affects the traffic flow [13]. Results of microsimulation models can also give an idea of the environmental impact of different types of intersections analyzed [14,15], and traffic microsimulations are also efficient tools for the analyses of traffic safety in advance [16].

2.2. Analyses of Traffic Safety after the Implementation of the Roundabout

To improve the design and performance of roundabouts, the results of studies that analyze the effects of the implementation of roundabouts through the so-called before-after analysis are usually used. Such research includes the analysis of certain selected indicators of the functionality of roundabouts expressed through safety/capacity/impact on the environment by comparing the values of the indicators before and after the roundabout was implemented. The analysis of the improvement of traffic safety is mainly based on the analysis of the number of traffic accidents that occurred at the location before and after the roundabout was built [9] or the impact of a roundabout on reducing speed [2].

The second research group relates to developing a model for predicting traffic accidents at roundabouts by analyzing a larger number of roundabouts [17,18].

Below are presented the results of before-after analyses conducted for roundabouts in several European countries: Flanders, Sweden, Lithuania, the Czech Republic, and the USA.

The goal of the extensive before-after study conducted in the USA [18] was to analyze the number of traffic accidents that would have occurred at the intersection if it had not been reconstructed into a roundabout with the number of traffic accidents that actually occurred at the

roundabout. The analyzed comparison data for 24 intersections of different types and control methods show that the application of roundabouts reduces the number of traffic accidents, depending on the type of roundabout, by 58-61% and the reduction of accidents with injured persons by 77-82%. The other systematic before-after study in the USA was done to establish safety effects when signalized intersections are reconstructed in roundabouts [19]. The study included 28 converted roundabouts, and the conclusion was that roundabouts influenced reductions in both total and injury crashes with a larger benefit for injury crashes. Important was the conclusion that the positive effect of the roundabout decreases with the increase of traffic volume at the spot.

A very detailed comparative study [9] was carried out in Flanders on 95 roundabouts and 119 standard-level intersections to analyze the impact of roundabouts on traffic safety. Traffic accidents were analyzed three years before and one year after the construction of roundabouts on roads where allowed speeds in the main and secondary directions are from 50 to 90 km/h. It was found that the number of traffic accidents with injuries was reduced by 34%, and greater improvements were observed on roads with higher permitted speeds (highest for crossing the main and secondary directions at speeds of 90 and 70 km/h, respectively). In general, it was determined that the number of traffic accidents of each injury level decreased at all types of roundabouts.

Published results [8] related to the before-after analysis of small roundabouts in Sweden show that this type of roundabout significantly reduces speeds in the intersection zone and on corridors between roundabouts without causing any side effects. A correlation was established between the reduction of approaching speed and injury accident risk. It was also shown that the reconstruction of traffic-lighted intersections with roundabouts had a greater impact on waiting times and the reduction of emissions (CO and NOx) than was the case with the reconstruction of non-signalized intersections. An important conclusion of the study is that details in the design are of decisive importance for road safety on roundabouts.

The study conducted in Lithuania [2] covered 11 roundabouts with a diameter of 11 to 85 meters to determine the speed of vehicles passing through the intersections. Based on previous international studies, the basic premise of this study was that reducing vehicle speed at roundabouts is correlated with accident numbers. It has been shown that passenger vehicles develop significantly higher speeds at large roundabouts, and the size of the radius is an important element for speed and accident reduction.

Paper [17] describes the process of developing a traffic accident prediction model at a roundabout based on data collected in four Central European countries: the Czech Republic, Hungary, Poland, and Slovakia. Those related to geometry and roundabout traffic conditions were analyzed as independent variables. According to the finally adopted model, based on the combined sample from all countries, injury accident frequency positively correlates with traffic volume and apron width while negatively correlates with deflection (at the entrance and inside the roundabout).

The study conducted in the Czech Republic aimed to analyze how entry design parameters influence safety at roundabouts and use these findings to update current Czech guidelines [20]. Analysis of data on geometry, traffic load, and speed in the area of roundabouts resulted in the conclusion that both crash frequency and severity are influenced by entry geometry, as the geometry also influences driving speed. The final conclusion was that safety performance is dictated by both geometry and speed.

Very detailed research that included 33 parameters considering the geometry design of roundabouts, markings, signs, road environment, and pavement conditions was conducted in Italy [21] to establish a safety index for evaluating urban roundabouts. The developed procedure aims to provide a proactive approach to road safety assessment of urban roundabouts based on their design characteristics and risk factors. It was tested on a sample of 50 urban roundabouts in Rome, Italy. The findings were that road users' improper behavior was mainly affected by a combination of roundabout geometry design, markings, and signs.

The analysis of existing research points to the conclusion that there are two main groups of parameters that affect traffic safety at roundabouts:

Traffic parameters – speed, amount, and structure of traffic flow in the narrower and broader zone of the intersection,

Design parameters – the size of the outer radius, the radius of the central island, etc.

Before-after studies are usually done based on an extensive number of intersections and traffic accident data. This was not possible in this case as there is no systematic monitoring of the roundabouts' safety performance. This is why the research presented in this paper is based on the analyses of four roundabouts based on detailed analyses of speed before and after the roundabout was implemented.

3. Materials and Methods

For the purposes of this study, four roundabouts on the county road network of the City of Rijeka, Croatia, and its surroundings were selected. In the last eight years, all selected intersections have been reconstructed from classic intersections (non-signalized intersections) to roundabouts to improve both capacity and safety in expected changed traffic conditions.

Functional analysis and comparison of non-signalized at-grade intersections with roundabout solutions at the same locations in the same or partly changed conditions were carried out for selected roundabouts. The selected roundabouts differ in size—defined by the size of the outer radii as well as by the other design elements—while they all have in common the fact that pedestrian traffic is present.

The collected data on traffic conditions at the intersection were analyzed, including operational speed, traffic load, design elements, and, depending on availability, traffic accidents in the wider intersection area, both before and after the reconstruction into roundabouts.

3.1. Selected Parameters

The locations of the selected roundabouts were analyzed using parameters that previous research (Chapter 2) proved to be essential for their functioning from the aspect of traffic safety.

Two groups of parameters were analyzed at the selected intersections:

- Traffic parameters and
- Design parameters.

3.1.1. Traffic Parameters

Traffic parameters include data related to the characteristics of traffic flow at the intersection:

- operational speed
- time distribution of traffic volume and speed.

To ensure the integrity and quality of the database, field measurements were conducted utilizing Datacollect SRD radar traffic counters, ensuring minimal disruption to the traffic flow. The traffic counters were strategically placed on either a streetlight pole or a traffic sign pole at a height of 2.20 meters.

Measurements with traffic counters were carried out in two phases: the first phase at non-signalized intersections (before reconstruction) and the second phase after their reconstruction into roundabouts.

In the first phase, data was collected with counters placed 40-70 m from the entrance to the intersection. This method determined the traffic load of each leg and the approach and departure speed on the corresponding intersection leg.

In the second phase, after the reconstruction into a roundabout, measurements were repeated at approximately the same positions as in the first phase (40-70 m from the entrance/exit to the roundabout to establish approach/departure speed), and additional counters were placed at the positions of the immediate entrance/exit from the roundabout (0-40 m from the entrance/exit to the roundabout) (Figure 1 and 2).



Figure 1. The position of traffic counters: at the entrance/exit from the roundabout (left) and at a distance of 40-70 m from the entrance/exit (right).

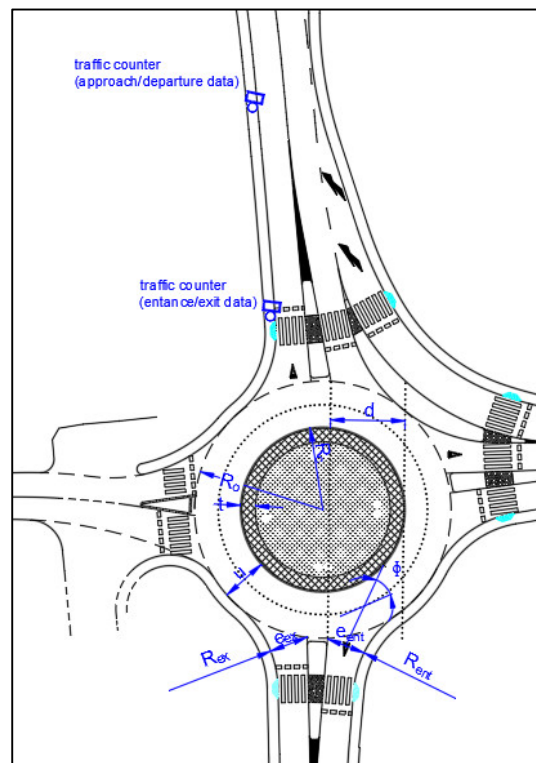


Figure 2. Traffic counter positions and design elements of the roundabout selected for analysis.

The positions and labels of the traffic counters are shown in Figure 2.

Speed data were systematically recorded over a 24-hour period, capturing both daytime speeds (6 a.m. to 10 p.m.) and nighttime speeds (10 p.m. to 6 a.m.), as well as speeds in the morning peak hour (7-8 a.m.). All measurements were done under stable weather conditions exclusively on working days (Monday – Friday). This approach aimed to guarantee the accuracy and reliability of the collected data as they were collected in standard traffic conditions.

3.1.2. Geometry Parameters

Detailed design drawings of each roundabout were used to collect data on the applied design elements. The following design elements (Figure 2) for which there are specific recommendations and limit values in the Croatian Guidelines [3] are determined:

- outer radius of the roundabout - R_o [m]
- width of the circulatory road - u [m]

- entry width - e_{ent} [m]
- entry radius - R_{ent} [m]
- exit width - e_{ex} [m]
- exit radius - R_{ex} [m]
- entrance angle - ϕ [°]
- radius of the central island (including traversable apron) - R_c [m]
- width of traversable apron – t [m]
- deflection – d [m].

In addition to the applied design elements mentioned, deflection and entry angle were additionally taken into analysis (parameters “ ϕ ” and “ d ” in Figure 2). The method of defining deflection and entry angle is shown in Figure 2.

3.2. Sample – Selected Roundabouts

For all four analyzed roundabouts, all of the selected parameters were available—detailed geometry and traffic characteristics before and after the reconstruction.

Table 1 presents the values recommended in the Croatian Guidelines and the main values adopted in the design of selected roundabouts. The limit values for individual design elements are set in a very wide range, which leaves the designer a great deal of freedom when choosing elements and can result in very different solutions.

Table 1. Applied design elements of selected roundabouts and recommended values.

	Intersection A			Intersection B				Intersection C			Intersection D				Croatian Guidelines (range of applied values)
	A1	A2	A3	B1	B2	B3	B4	C1	C2	C3	D1	D2	D3	D4	
R_o		19			16				17.5			15			11 - 25
u		7			7				6.5			6.5			4 - 9
e_{ent}	5.8	5.6	6.4	5.8	5.2	4.5	5.4	5.6	6.2	5.5	5.2	5.6	5.6	4.7	3.6 - 10
R_{ent}	15	22.3	15	14.6	14	14	15	17	19	16	12.5	12.6	18	n/a	6 - 25
e_{ex}	5.8	6.4	5.7	4.7	5.3	4.5	5.4	6.4	5.5	6	6.5	4.9	6.5	4.5	3.6 - 10
R_{ex}	16	16	22.3	16	14.6	16	16	18	16	19	n/a	15	11.1	18.5	8 - 50
ϕ	41	33	44	42	39	33	38	40	41.5	40	42	22	38	46	0 - 77
d	11	8.5	9.9	8.4	8.2	6.6	6.3	14.3	n/a	4.7	6.7	6.9	7	6.3	no recommendation
R_c	12	12	12	9	9	9	9	11	11	11	8.5	8.5	8.5	8.5	7.5 - 18
t	2	2	2	1.5	1.5	1.5	1.5	2.5	2.5	2.5	2	2	2	2	min 1

n/a – not applicable.

In these four cases, all applied elements of roundabouts are within the recommended values of the Croatian Guidelines. Deviations from the guidelines’ recommendations are visible in applying the width of the entrance/exit and the size of the entrance and exit radius on some roundabout legs. Namely, the guidelines recommend the application of higher values at the exit from the roundabout compared to the corresponding entrance to the roundabout. The deviation is visible in the width of the entrance of legs A3, B1, C2, D2, and D4 and the size of the entrance radius of legs A2, C2, and D3. When we compare applied values, the biggest difference in applied values can be seen for exit radii and entrance angles, which also Guidelines suggest a very wide range.

4. Results and Discussions

Before-after analyses of roundabouts are very usually based, as was proved in the analyses of existing research - Chapter 2, on the analysis of traffic accidents and/or the analysis of an indirect indicator of traffic safety – speed. The analysis of traffic accidents in Croatia is a very complex task for several reasons - there is no clearly defined method of documenting traffic accidents, which makes

it difficult to compare the circumstances in which traffic accidents occurred, and the problem of under-reporting is extremely present, which is why the data are not a realistic indicator of the traffic safety situation.

During the analysis of the selected 4 locations, it was not possible to obtain systematic data on traffic accidents before and after the reconstruction of the non-signalized intersection into a roundabout. Data on the number of traffic accidents are available for only 2 out of 4 roundabouts. From these very limited data, it is noticeable that traffic accidents in relation to the amount of traffic occur more significantly at night and in slightly greater numbers at the entrance than at other parts of the roundabout. As it is a very small number of traffic accidents in only 2 locations, these data were not included in the analyses of the results. Based on the conclusions of previous research, the traffic safety analysis is based on a detailed analysis of speeds.

Selected roundabouts were analyzed through:

- analyses of the speed before and after the intersection reconstruction
- possible relations between traffic and speed data (operational speed – V85, maximum speed, hourly traffic, and speed) and selected roundabout design elements.

4.1. Operational Speed Before-After Analyses

The operational speed is usually defined as the speed up to which 85% of the vehicles in the traffic stream drive (hereinafter V85), and they are one of the basic parameters used to evaluate intersection safety.

In the case of these four intersections, operating speeds were measured before and after the reconstruction into roundabouts (Table 2). Before the intersection reconstruction, measurements were made so that the approach/departure speed at the intersection was measured. After the reconstruction, the measurements were repeated at the same positions (approach/departure speed) and additionally at the position of the entrance/exit from the roundabout to obtain additional data on the entry/exit speed with the idea of establishing the effect of the implemented roundabouts on traffic in the wider area of the roundabout.

Table 2. Operational speed data (V85) – before and after reconstruction.

		Intersection A			Intersection B				Intersection C			Intersection D			
		A1	A2	A3	B1	B2	B3	B4	C1	C2	C3	D1	D2	D3	D4
before reconstruction	approach														
	approach speed V85-24 h	52	42	59	53	51	53	n/a	44	55	46	76	n/a	78	n/a
roundabout	departure speed V85-24 h	49	44	56	56	51	51	n/a	48	53	45	78	n/a	77	n/a
	approach speed V85-24 h	58	49	44	48	60	48	54	47	30	45	75	36	59	n/a
	approach speed V85-MPH	53	44	32	58	63	48	55	46	29	50	74	36	58	n/a
	approach speed V85-NP	67	54	52	48	74	60	66	65	35	52	77	41	66	n/a
	departure speed V85-24 h	57	53	49	53	64	46	54	53	32	46	75	38	56	n/a
	departure speed V85-MPH	41	51	47	59	63	48	54	51	32	48	75	39	55	n/a
	departure speed V85-NP	63	52	54	54	72	59	59	65	36	53	85	43	62	n/a
	entry speed V85-24h	40	23	33	32	58	38	42	33	35	41	50	44	62	43
	entry speed V85-MPH	38	19	24	32	60	37	44	33	34	42	49	44	61	42
	entry speed V85-NP	51	27	45	40	70	46	51	42	42	51	53	45	70	64

exit speed V85-24h	43	n/a	43	38	62	40	46	21	38	45	55	45	58	44
exit speed - V85-MPH	37	n/a	41	39	61	41	46	21	38	44	55	45	57	45
exit speed V85-NP	46	n/a	46	42	68	46	50	23	44	51	58	49	62	47

Note: A1, A3, B1, B3, C1, C3, D1, and D3 represent main approaches; A2, B2, B4, C2, D2, and D4 represent minor approaches; MPH-morning peak hour; NP-night period; n/a – not applicable (measurement was not done on this intersection leg), bold – operational speed higher than regulated speed.

- Speeds are listed separately for specific time periods:
- daily operational speed or V85 – 24h
 - operational speed during peak periods, V85 - MPH (morning peak hour)
 - operational speed during the night, V85 – NP (night period).

According to HR regulations [3], in the urban city network, the speed limit on primary roads is 50 km/h, while minor (secondary) roads may have a lower limit, 40 km/h. In the area of the roundabout, regardless of whether it is a primary or secondary road, the speed limit is 30 km/h for small roundabouts and 40km/h for middle-size roundabouts.

Data from Table 2 (bold values) show that operational speed is often higher than regulated speed (even when regulated speed is increased by 10%), especially on the exit from the roundabout and especially during the night hours.

Figure 3 shows operational speeds (approach and departure speed) measured at intersections before reconstruction into roundabouts. Intersection approaches A2, B2, and C2 represent the minor direction at the classic intersections, and it is evident that the operational speeds exceed the speed limit of 40 km/h, which is common for the minor direction (secondary roads) on the city’s traffic network. The other approaches represent the main direction, with a speed limit of 50 km/h, which was not exceeded only in the case of approaches C1 and C3, while in the case of approaches D1 and D3, it was significantly exceeded (by more than 50%).

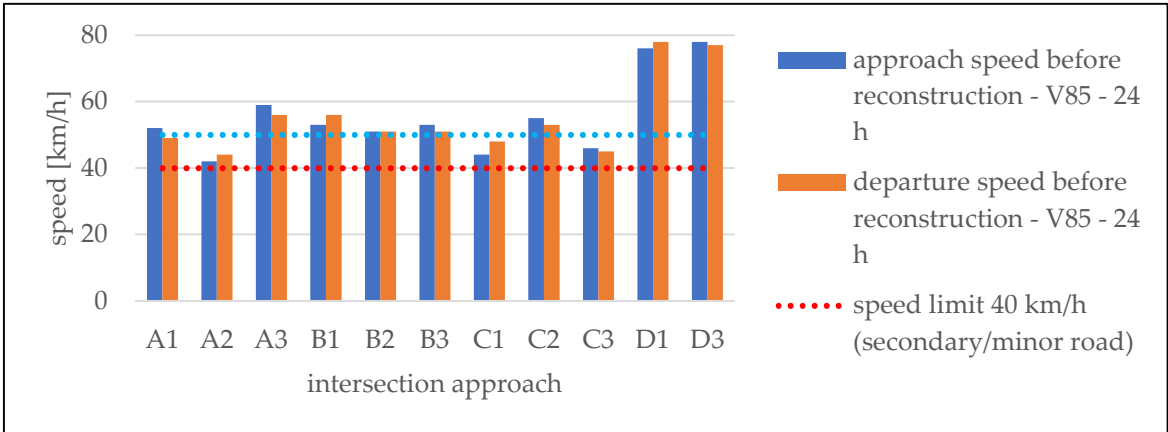


Figure 3. Operational speed before reconstruction.

In Figure 4, in addition to operational speeds measured before the reconstruction, the operational speeds after the roundabout reconstruction are shown, measured approximately at the same positions as before the reconstruction. The recommendation for operational speeds depends on the roundabout size (up to 30 km/h for small urban roundabouts and up to 40 km/h for medium-sized urban roundabouts) [3]. According to the selected outer radius of the roundabout, intersections B and D are small roundabouts, and it is evident that the operational speeds after the reconstruction into a roundabout significantly exceed the recommendation for such intersections (30 km/h) and even for medium-sized roundabouts (40 km/h). In the case of intersections A and C, only in the case of one approach of the intersection (approach C2), the operational speed is lower than the recommended 40 km/h. On all other approaches (A1, A2, A3, C1, and C3), the operational speed is higher than the

recommendations of the guidelines, and in some cases (A1, A2, and C1), the operational speed on the roundabout is higher than the speed at the same position before reconstruction.

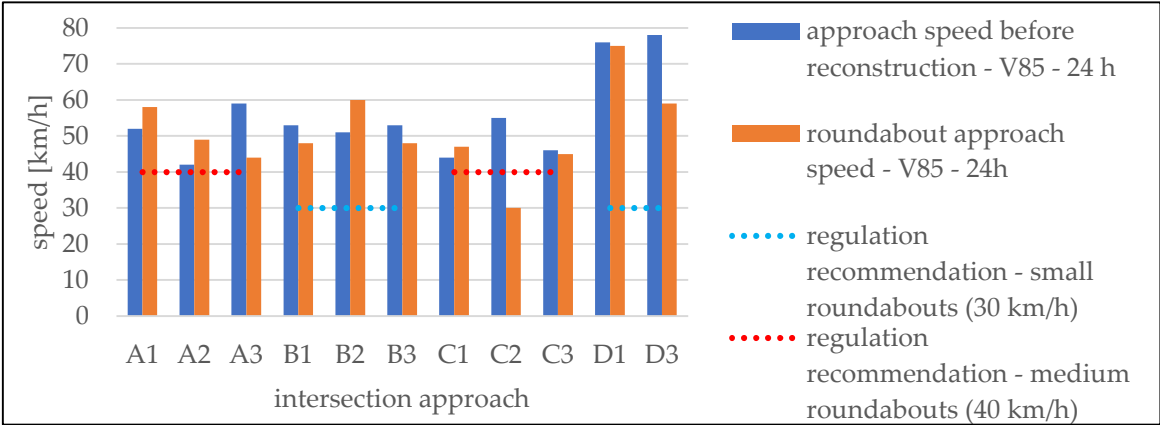


Figure 4. Approach speed- before and after reconstruction.

Table 3 shows descriptive statistics for approach speed before and after reconstruction. The data are not normally distributed, so the non-parametric Mann-Whitney test was used to compare the speeds before and after the reconstruction [22–24]. The test results showed that they were statistically different for all cases of comparison of approach speed before and after reconstruction (measured at the same position).

Table 3. Descriptive statistics – approach speed before and after reconstruction.

approach		number of observations	V85	V _{min}	V _{max}	V _{avg}	Std. deviation	Mann Whitney	p-value
A1	before reconstruction	7904	52	8	78	45	7.6	-22.110	<0.001
	roundabout	10988	58	5	94	47	11.9		
A2	before reconstruction	6382	42	5	70	32	10.5	-50.488	<0.0001
	roundabout	7725	49	6	87	41	8.9		
A3	before reconstruction	7451	59	21	85	52	6.9	99.279	<0.0001
	roundabout	9834	44	5	79	34	11.5		
B1	before reconstruction	11242	53	6	98	45	8.7	36.642	<0.0001
	roundabout	6609	48	8	74	41	8.3		
B2	before reconstruction	3525	51	6	91	42	10.2	-31.827	<0.0001
	roundabout	4085	60	6	106	50	10.9		
B3	before reconstruction	10154	53	10	106	45	8.9	39.1514	<0.0001
	roundabout	7797	48	8	93	40	8.7		
C1	before reconstruction	10363	44	7	101	35	10.0	10.569	<0.0001
	roundabout	6066	47	10	80	37	8.3		
C2	before reconstruction	3121	55	9	87	46	9.1	66.292	<0.0001
	roundabout	3525	30	5	41	24	6.3		
C3	before reconstruction	9142	46	6	89	38	8.3	-16.036	<0.0001
	roundabout	5337	45	10	82	40	7.5		
D1	before reconstruction	4677	76	22	129	66	11.1	6.458	<0.0001
	roundabout	4605	75	14	117	65	10.9		
D3	before reconstruction	4040	78	37	120	69	9.2	68.780	<0.0001
	roundabout	4084	59	24	94	51	7.5		

Figure 5 presents the departure speed results measured before and after roundabout implementation in relation to the regulated speed limit.

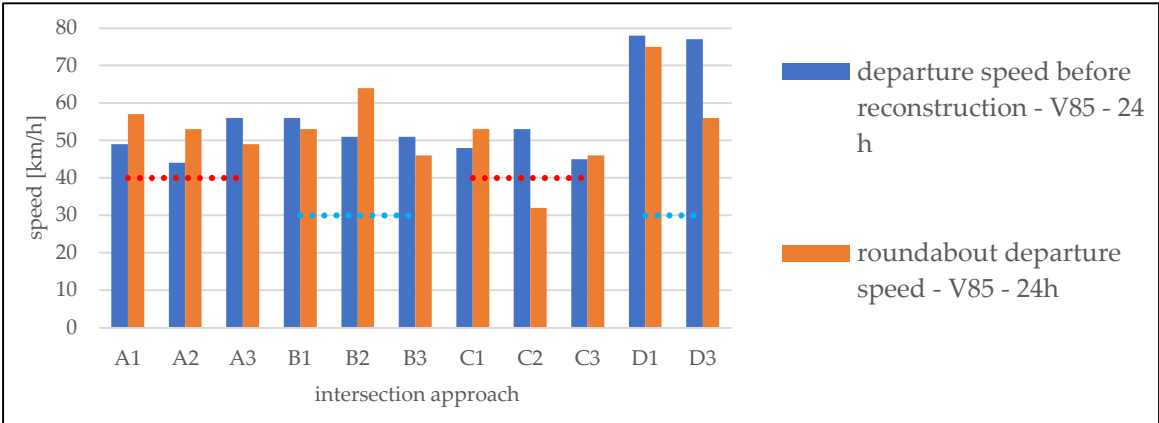


Figure 5. Departure speed - before and after reconstruction.

The departure speeds (more than approach speeds) at all intersection legs exceed the recommendation for a certain roundabout size. At five intersection approaches (A1, A2, B2, C1, C3), like the approach speed, there was an increase in the departure speed compared to the speed measured at the same position before reconstruction.

Table 4 shows descriptive statistics for departure speed before and after reconstruction. The data are not normally distributed, so the non-parametric Mann-Whitney test was used to compare the speeds before and after the reconstruction. The test results showed that they were statistically different for all cases of comparison of departure speed before and after reconstruction (measured at the same position).

Table 4. Descriptive statistics – departure speed before and after reconstruction.

approach		number of observations	V85	V _{min}	V _{max}	V _{avg}	Std. deviation	Mann Whitney	p-value
A1	before reconstruction	10684	49	9	79	43	7.0	-51.863	<0.001
	roundabout	8333	57	9	96	48	10.0		
A2	before reconstruction	3077	44	9	68	37	8.1	-30.700	<0.001
	roundabout	2898	53	12	86	44	9.3		
A3	before reconstruction	8219	56	15	86	50	6.7	64.057	<0.001
	roundabout	8787	49	11	84	42	6.9		
B1	before reconstruction	7916	56	13	107	49	8.4	22.371	<0.001
	roundabout	6045	53	12	75	46	7.1		
B2	before reconstruction	4747	51	8	84	44	7.2	-50.803	<0.001
	roundabout	4606	64	8	117	54	10.3		
B3	before reconstruction	10828	51	7	102	43	9.2	35.054	<0.001
	roundabout	8024	46	7	91	39	7.0		
C1	before reconstruction	8600	48	8	93	39	9.4	-23.361	<0.001
	roundabout	2045	53	15	87	45	8.3		
C2	before reconstruction	3460	53	9	86	44	9.6	60.530	<0.001
	roundabout	2905	32	4	49	27	4.9		
C3	before reconstruction	9101	45	6	89	37	9.9	-32.439	<0.001
	roundabout	3746	46	7	85	43	7.1		
D1	before reconstruction	4074	78	9	119	69	9.9	14.476	<0.0001
	roundabout	3253	75	27	124	66	9.7		
D3	before reconstruction	4934	77	16	134	67	10.9	71.847	<0.0001
	roundabout	4675	56	16	81	49	7.4		

The data shown in Tables 3 and 4 show a smaller standard deviation of departure speed than the standard deviation of approach speed, potentially indicating that many parameters influence vehicle approach speed. Consequently, the approach speed range is higher than the departure speed.

Below (Figure 6), the differences in entry speeds (measured at the entrance to the roundabout) are analyzed in more detail regarding their time distribution within 24 hours:

- daily operational speed,
- operational speeds in the morning peak hour (MPH) and
- operational speeds in the night period (NP).

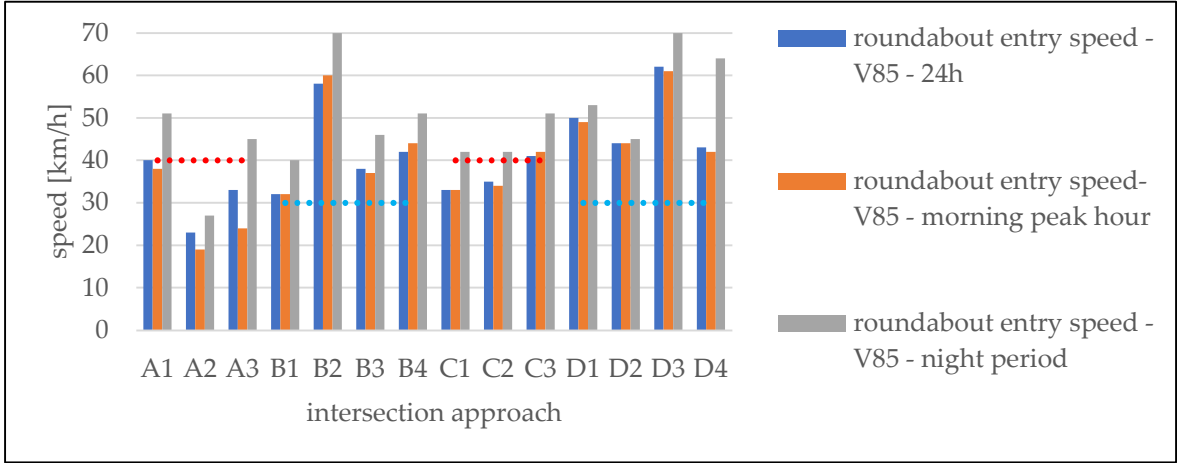


Figure 6. Roundabout entry speed.

Figure 6 shows that the roundabout entry speed on 11 out of 14 approaches in the morning peak hour (V85 – MPH) is lower than the roundabout daily entry speed (V85 - 24h). This is expected since the traffic load on the approaches to the intersection increases during the peak hour, which decreases operating speed. What is also expected is that the speed in the night period increases due to the lower traffic load (on all 14 approaches). However, the percentage of this increase is worrying - on average, it is an increase of 22%, and on some approaches, it is even up to 50%.

If the average entry speed for all roundabouts in the same size group is analyzed, it is shown that for roundabouts with a recommended speed of 30 km/h (small urban roundabouts), it is 46 km/h, and for roundabouts with a recommended speed of 40 km/h (medium-large urban roundabouts), it is 34 km/h.

The operating speeds at the exit from the roundabout (Figure 7) are higher than the recommended for the specific size of the roundabout on 11 of the 13 approaches (on approach A2, there is no data on the speed at the exit from the roundabout). Operational speeds in the peak period are lower or equal to operational daily speeds, while in the night period, they are higher, but the increase is lower than at the entrance to the roundabout, on average 10%, maximum 16%.

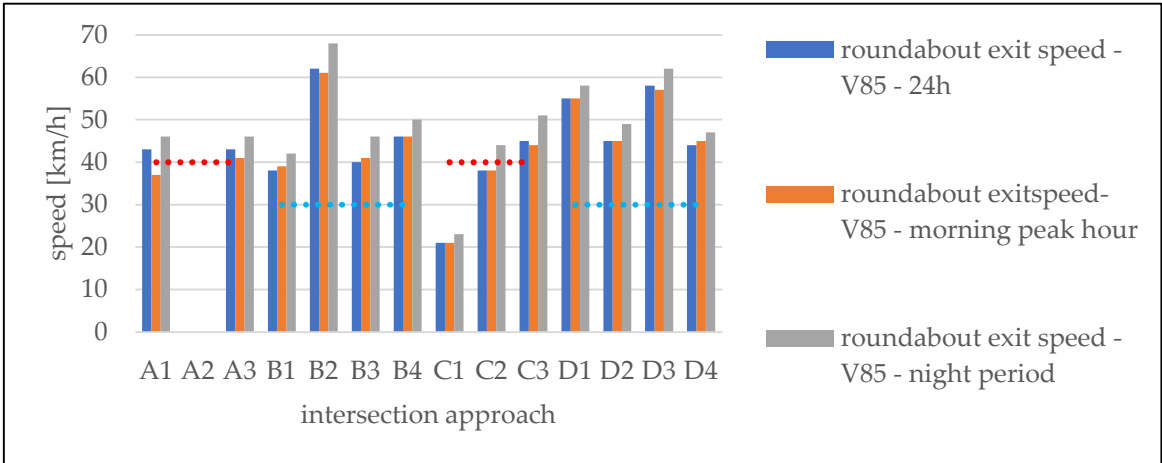


Figure 7. Roundabout exit speed.

The data show that the average exit speed at roundabouts with a recommended speed of 30 km/h (smaller urban roundabouts) is 49 km/h, and at roundabouts with a recommended speed of 40 km/h (medium-sized urban roundabouts), it is 38 km/h.

4.2. Comparison of Different Analyzed Parameters

In continuation, the correlation analyses between selected parameters from different groups (traffic, design) were done to detect possible reasons for roundabout performance regarding operational speed, which in most of the previously analyzed cases resulted in higher than expected.

As for the analyzed roundabouts, there is very detailed data on traffic load and operational speeds (throughout 24 hours); the influence of hourly traffic load on hourly operational speeds for 1 of the 4 analyzed roundabouts is presented below. Analysis is done separately for the entrance to the roundabout (entry speed) and separately for the exit from the roundabout (exit speed). The influence of the traffic load on the operational speed is shown, separately for the main direction at the intersection (normally more loaded) and the secondary/minor direction.

Figures 8 and 9 show that the entry/exit traffic load affects the entry/exit operational speed as expected, with higher traffic load-lower speed, a somewhat stronger trend in the minor direction, and lower traffic loads.

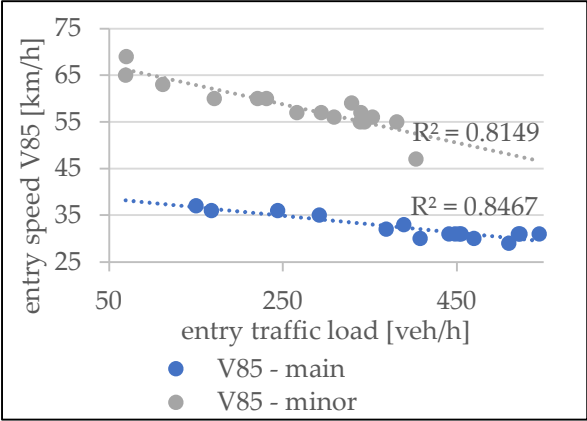


Figure 8. The influence of the entry traffic load on the entry speed V85.

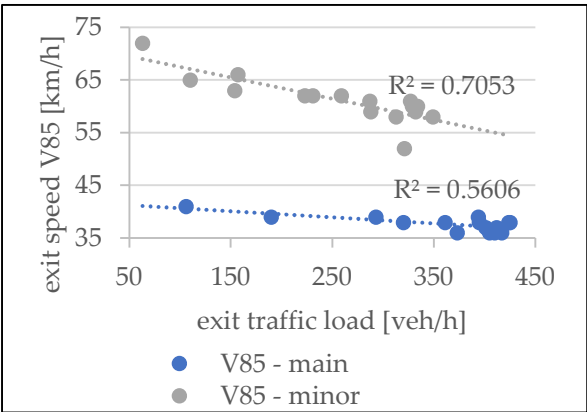


Figure 9. The influence of the exit traffic load on the exit speed V85.

The influence of applied design elements on operating speeds was also analyzed. Although the applied width of the circulatory roadway is greater than the minimum recommended values (4,0 m), the analysis did not show the expected impact on speed, similar to the size of the outer radius of the roundabout or the design elements of the entrance and exit (entry/exit radius, entry/exit width) (Figure 10 and 11). A very weak influence was also found between other design elements (radius of the central island, width of traversable apron of the central island).

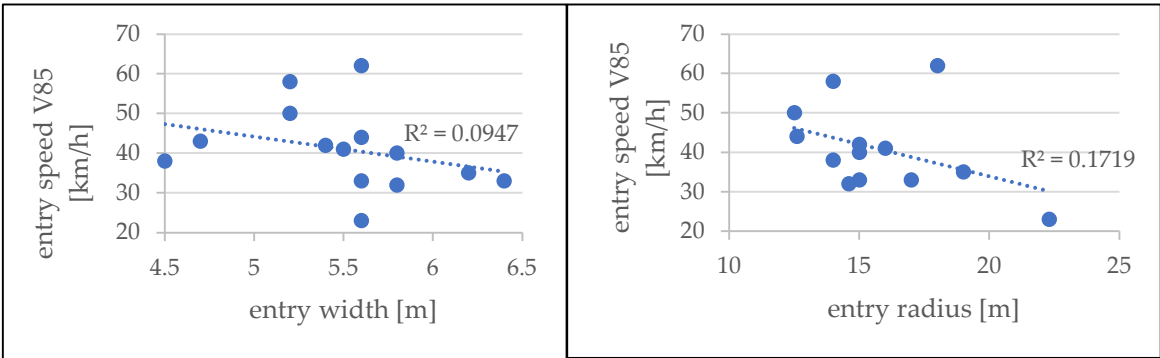


Figure 10. The influence of the entry width (left) and entry radius (right) on the entry speed V85-24h.

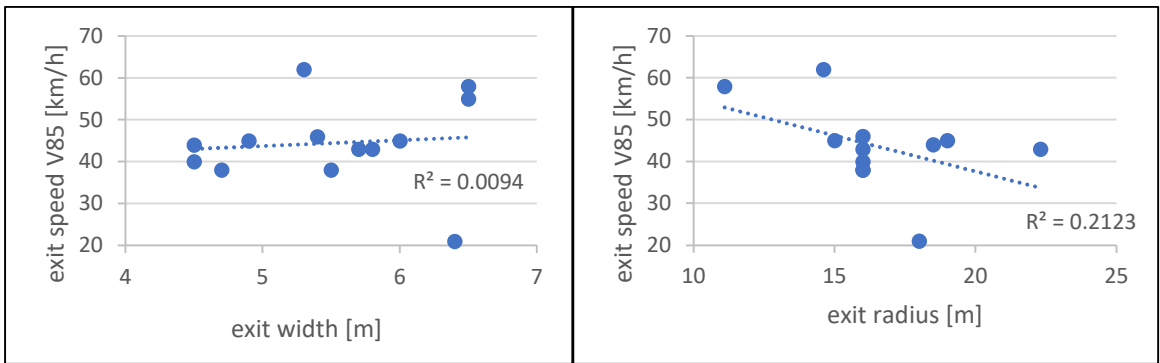


Figure 11. The influence of the exit width (left) and exit radius (right) on the exit speed V85-24h.

In addition to the directly applied design elements mentioned above, the influence of other parameters, such as the entry angle and deflection, which are a consequence of the applied design elements, were also checked. The influence of the entry angle on the operational speeds was not confirmed, and only a weak influence of the deflection on the entry and a slightly stronger influence on the exit speed (Figure 12) was confirmed.

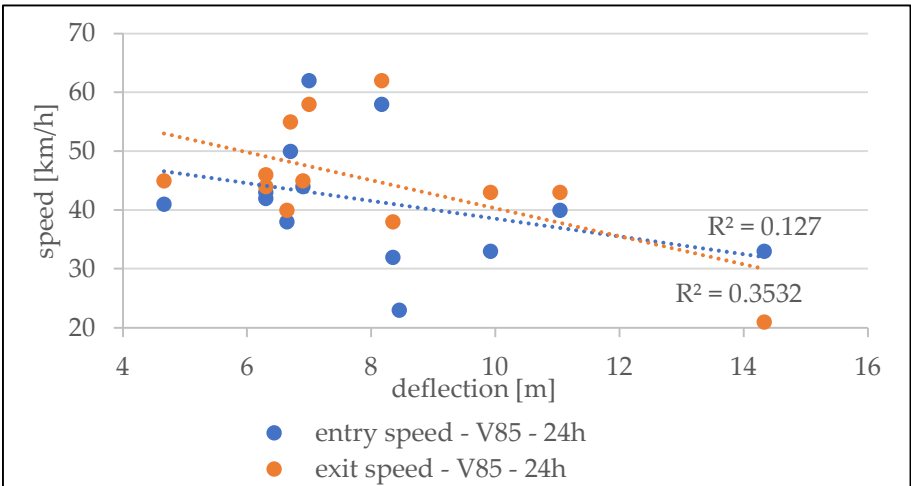


Figure 12. The influence of deflection on entry/exit operational speeds of the roundabout.

5. Conclusions

Croatian guidelines for the roundabout design, which in their basic settings are very similar to the guidelines of several neighboring countries (Slovenia, Serbia, Bosnia and Herzegovina), have been applied since 2015, but a systematic analysis of their impact on the expected effects related to

traffic safety has never been carried out, which is a common practice of developed countries where better results are shown when it comes to traffic safety.

This paper presents an analysis of the functionality of selected roundabouts based on data collected at the locations before and after roundabout implementation, primarily from the aspect of traffic safety.

Given that data on traffic accidents in Croatia is collected in a very unsystematic way and that there is also the problem of under-reporting, accident data can't be used as a relevant basis for the before-after analysis of the safety of the traffic infrastructure in this case roundabouts.

As in previously conducted research, a clear connection between speed and traffic accidents at roundabouts was confirmed, detailed data on speed measured at the location was used for the traffic safety analysis in this case [2,8,20]. The analysis included four four-leg roundabouts with standard outer radii ranging from 15 to 19 m reconstructed from standard at-grade non-signalized intersections. Selected roundabouts have the usual size of the radius of roundabouts in urban areas where, as a rule, smaller radii are used due to the built-up surrounding area.

Comparison with the Guidelines shows that all the applied design elements are within the Croatian Guidelines' recommended values. Deviations from the guidelines' recommendations are visible when applying the width of the entrance/exit and the size of the entrance and exit radius on some roundabout legs. Croatian Guidelines recommend using larger values for the exit width of the exit radius in relation to the corresponding entrance width and the entrance radius. The assumption is that the values applied in this way enable faster exit from the roundabout compared to slowing down the vehicle at the corresponding entrance. Considering the deviation from the recommendations on roundabout legs A2, A3, B1, C2, D2, D3, and D4, the entry and exit operational speeds on the mentioned roundabout legs were analyzed and compared, and it was shown that on all roundabout legs (except D3) exit speed is higher than entry speed, which did not confirm the stated assumption. The design elements show a very weak influence on entry and exit speed.

The analysis of design elements indicates that in all four cases, the applied width of the circulatory lane is greater than the minimum recommended. It can be assumed that such a choice is related to ensuring the maneuvering of larger vehicles, but it can be questioned when analyzing the curvature of the path of smaller vehicles and, consequently, the speeds they can achieve. In all cases, vehicles passing through roundabouts can also use a transverse apron, suggested by Guidelines as an obligatory element, which makes their trajectory straighter.

The analysis of the operating speeds measured in 24 hours at the same positions at the standard at-grade intersections (before reconstruction) and roundabouts showed that the speeds do not show a unique legality of the ratio of speeds between the main and secondary directions, and in the same ratio, there are speeds higher than those allowed in the main and side directions.

Speeds measured at roundabouts show that although a significant reduction in speeds was expected due to the implementation of the roundabout, this did not happen. In only 7 out of 14 analyzed cases (measured in 24 hours), the speed at the entrance is lower than the limit, while at the exit from the roundabout, the speeds are lower in only 5 out of 14 measurement locations. This does not contribute to the goal of increasing safety in the area of the roundabout.

Such results motivated further analysis of speeds in the peak hour and those developed in the night hours. It was relatively expected that the average speeds at the entrance and exit would be lower in the morning peak hour and higher during the night hours. This points to a significant influence of traffic volumes on speed and raises the question of the influence of applied design elements on speed control at roundabouts. In the following, the impact of the amount of traffic and design elements on the operational speed at the entrance and exit from roundabouts was analyzed in more detail.

The influence of the amount of traffic was analyzed based on the analysis of the amount of traffic and operating speed for 16 daily hours (6 a.m. to 10 p.m.), and it was determined that there is a significant correlation between the amount of traffic and operating speed V85.

The analysis of the main design elements showed that the width and size of the radius of the entrance/exit from the roundabout have no influence on the operational speed at the entrance and

exit from the roundabout. The deflection was proved to have an influence, which affects both the entrance and exit speeds, with some more influence on exit speeds.

Ultimately, the conclusions of the research are:

- Analysis of the impact of traffic volume on the speed at the entrance/exit of the roundabout shows that the traffic volume significantly impacts the operational speed.
- It is shown that the entrance/exit width and the radius have no influence on the speed of the vehicle, but it is important to analyze the deflection that is a consequence of the combination of applied design elements - the entrance radius, the width of the circular road, the radius of the central island and the width of the radius at the exit.

Considering the above, it can be concluded that roundabouts designed according to the Croatian guidelines for roundabouts do not, by their very application, improve traffic safety because they do not significantly affect speed reduction, nor do they assure the expected traffic speeds defined with respect to the size of the outer radius. Even speed checks, which are suggested in the Guidelines as part of the design procedure, do not ensure speed control.

To ensure that roundabouts effectively reduce speed and consequently increase traffic safety, the influence of design elements on deflection must be analyzed for every combination of applied elements, and guidelines should be upgraded with more precise suggestions in this sense. A clear definition of deflection sizes is an option to control operational speed effectively.

The research will continue by increasing the base of collected data and analyzing the influence of roundabout geometry on speed by creating a traffic microsimulation model to test different combinations of design elements.

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