The Relevant Direction of Vehicle Movement for Checking the Operational Speed at the Roundabout

Sanja Šurdonja, Aleksandra Deluka-Tibljaš, Marijana Cuculić, and Vesna Dragčević

Abstract

The main function of roundabouts is to assure traffic safety and capacity. Operational speed in roundabouts, important for both scopes, is regularly checked in the process of planning and design of roundabouts according to procedures (or models) defined in national technical regulation. There are two mainly used models, one developed in USA and other developed in Netherlands literature. The analyzed regulation for roundabouts from all over the world, except the USA, defines straight direction as a critical movement in the roundabout even there is no available research and comparison with speeds in other directions. In this research, the goal was to experimentally establish critical movement in the roundabout. The operational speed, in this case, was established through measurements done with precise GNSS equipment at single-lane, four-leg roundabout in Croatia. The results showed, with statistical relevance, that there are differences between speeds for different directions and that straight direction is the critical movement regarding the speed at roundabouts.

Keywords

Vehicle • Critical direction • Roundabout • Speed • Models

1 Introduction

The main scope of planning and designing roundabouts is to assure capacity and traffic safety at the certain point of the road network. Design procedures for roundabouts depend very much of the conditions in the field, such as traffic (motorized and non-motorized), location, ambient and environment. The geometric elements of roundabouts are therefore combined in different ways, and national technical regulation serves more as the guidelines than as a standard. This is why the roundabout design is an iterative process. During that process, some necessary checkups including checkup of operating speed through the roundabout, checkup of path-alignment for chosen design vehicle and checkup of sight distance conditions at the entrance are done (Ahac et al. 2016; Easa 2004).

Operating speed is most important for assuring proper safety conditions at roundabouts (Yongsheng et al. 2013) but also for assuring capacity (Gallelli et al. 2014). The geometry of the roundabout and consequently the vehicle path through the roundabout have the greatest impact on operational speed (Šurdonja et al. 2018).

Different studies on traffic safety conditions, before and after roundabouts were implemented, were done all over the world (Ambros et al. 2016; Retting et al. 2001). In the study conducted recently in Middle-European countries (Checkia, Hungary, Poland, Slovakia) based on the analyses of accident, traffic and geometry data of roundabouts, finally developed accident prediction model, showed that injury accident frequency is positively associated with effect of traffic volume and apron width, while negatively associated with deflection in terms of both entry and deviation angles (Ambros et al. 2016).

Even roundabouts are proven to have better performances than the standard type of intersections, regarding traffic safety, there are some typical traffic accidents connected only with roundabouts (Tollazzi 2001; Montella 2011; Daniels et al. 2010), and studies show that those accidents are mainly result of exceeded operational speed. Traffic accident analyses done on roundabouts in USA (Rodegerdts et al. 2010) proved that the most part of the accidents (more than 65% of all accidents) that happen on roundabouts in different part of the world happen during negotiations at the entrance of the roundabout, loose of control at the entrance

S. Šurdonja (✉) · A. Deluka-Tibljaš · M. Cuculić
Faculty of Civil Engineering, University of Rijeka, Rijeka, Croatia
e-mail: sanja.surdonja@uniri.hr

V. Dragčević
Faculty of Civil Engineering, University of Zagreb, Zagreb, Croatia

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and in the roundabout or as rear-end crashes when vehicles brake suddenly at the exit. Analyses of the reasons for those accidents, conducted in the same study, show that reasons are different, but in all cases, the problem is connected with unappropriate operating speeds of vehicles.

Pre-calculation of operating speed and establishment of the critical speed direction in the roundabouts are therefore very important steps in roundabout design procedure. All national regulation analyzed in this paper defines in some way what and how should be checked regarding speed in roundabouts. The direction, mainly defined as critical, on which operational speed is checked, is straight direction even there are no available researches and comparisons of speeds on straight and right/left direction of movement.

The goal of this research is to experimentally establish the critical direction of movement in the roundabout on which the operational speed primarily must be checked. The operational speed, in this case, was established through measurements done with precise GNSS equipment at single-lane, four-leg roundabout in Croatia. Measurement equipment used in the research enables the analyses not only of the operation speed but also of the real vehicle path through the roundabout. The results of both measurements are presented in the paper.

2 Operational Speed Estimation at Roundabouts—Review

In this paper, for the purpose of research, guidelines of many European countries, the USA and Australia were analyzed: USA (Federal Highway Administration [FHWA] 2000), Australia (Velth and Arndt 2011), UK (Highways Agency [HA] 2007), Netherlands (CROW 1998; Dutch Ministry of Transport [DMT] 2009), Italia (Ministero delle infrastrutture e dei transporti [MIT] 2006), Slovenia (Ministarstvo za promet Republika Slovenija [MPRS] 2011), Serbia (Putevi Srbije [PS] 2012), Croatia (Hrvatske Ceste [HC] 2014) and German (Forschungsgesellschaft für Strassen und Verkehrswesen [FGSV] 2006).

In the above-mentioned guidelines, the following was analyzed:

- the method of speed check of the vehicles passing through the roundabout,
- critical movement direction through the roundabout (straight, right, left),
- the expected maximum speed of the vehicle passing through the roundabout.

Procedures for estimating speed in roundabouts are defined in most of the existing national regulations for roundabouts design. Models used in the procedures, defined for speed control at roundabouts, can be divided into two main groups:

- Model 1—model based on the calculation of the speed in horizontal curve suggested in (FHWA 2000), developed in (AASHTO 2001)—FHWA model
- Model 2—model based on the correlation of basic design elements suggested in (CROW 1998; HC 2014; MPRS 2011; PS 2012)—CROW model.

Model 1 can be applied in the calculation of operational speed both for vehicles passing straight and for vehicles that are turning right or left. Model 2 has some limitations, and it can be applied only for estimation of operational straight speed at roundabouts designed on the rules defined by Netherlands regulation or similar.

In the regulations defined for the design of roundabouts in the UK and Australia, there is no defined speed calculation model, and the operating speed check is based on meeting the conditions of the appropriate entrance radius of the straight path of the vehicle through the roundabout and on a comparison of the obtained path radius with the one recommended according to the guidelines (HA 2007; Velth and Arndt 2011). In Italy, the existing norm from 2006 (MIT 2006) defines that, in order to prevent inadequate speeds of vehicles in roundabouts, it is important to properly design the entrance angle of vehicle path in a roundabout which ensures a deviation in movement of the vehicle and thus slows it down. Deviation angle defined in these standards is 45° (Montella et al. 2012). The only recommendation given in German regulation is the one about expected speeds in mini roundabouts (FGSV 2006).

Table 1 shows an overview of the analyzed guidelines, suggested speed check models, modalities in which critical directions of movement have been treated in these guidelines regarding the speed check and the expected speed at the roundabouts.

The analysis shows that in the largest number of analyzed guidelines of the EU countries (except for the UK and Germany), model 2 developed in the Netherlands is used for the calculation of the vehicle speed in the roundabout. This model only allows the speed check of vehicles which move straight at the roundabout.

In addition to the aforementioned models, in the scientific literature, there are also examples of models developed by regression analysis based on extensive experimental tests (Bassani and Sacchi 2011; Bashar et al. 2014) enabling speed check in the middle of the roundabout, only for the straight direction of movement.

Table 1 Overview of analyzed guidelines and regulations

State	Regulation	Model used	Critical movement direction	Allowed speed
USA	NCHRP report 672: roundabouts: an informational guide—second edition, 2010 (FHWA 2000)	Model 1	Through, left or right	30–40 km/h
Australia	Guide to road design part 4B: roundabouts (2nd ed.), 2011 (Velth and Arndt 2011)	–	Through	Depends on the entrance radii
UK	Geometric design of roundabouts, 2007 (HA 2007)	–	Through	70 km/h within 100 m of approach
Italia	Norme funzionali e geometriche per la construzione delle intersezioni stradali, 2006 (MIT 2006)	–	–	–
Croatia	Smjernice za projektiranje kružnih raskrižja na državnim cestama, 2014 (HC 2014)	Model 2	Through	25–40 km/h
Netherlands	Roundabouts—application and design: a practical manual, 2009 (CROW 1998; DMT 2009)	Model 2	Through	30–35 km/h
Germany	Merkblatt für die Anlage von Kreisverkehren, 2006 (FGSV 2006)	–	–	–
Slovenia	Tehnička specifikacija za javne ceste TSC 03.341:2011—Krožna križišča, 2011 (MPRS 2011)	Model 2	Through	30–35 km/h
Serbia	Priručnik za projektovanje puteva u Republici Srbiji, 2012 (PS 2012)	Model 2	Through	30–35 km/h

3 Determining the Relevant Direction of Vehicle Movement at the Roundabout

In order to experimentally establish which movement at the roundabout is critical (right/straight/left), extensive field measurements of the vehicle passing in different directions of movement at roundabout were done. The measurements were done on chosen four-leg roundabout with outer radius $R = 35$ m, with a proper layout of intersection legs (Figs. 1 and 2). At the roundabout, standard design elements according to Croatian guidelines (HC 2014) were applied and this roundabout in this sense can be considered as a standard four-leg roundabout.

3.1 Research Methodology

Field tests were carried out on a regular four-leg roundabout of the standard characteristics (Fig. 2) with the highlighted main direction (approach 1 and 3) and minor direction (approach 2 and 4) by direct recording the vehicle path through the roundabout. Based on the recorded data, the speeds of the vehicle were determined on several positions.

Objective requirements for research implementation are ensured in the following manner:

– a personal vehicle used for field tests was equipped with the Global Navigational Satellite System (hereinafter referred to as GNSS device),
– the GNSS device recorded very precisely (five points per second, for each point the position coordinates, time, date, position accuracy) each vehicle movement path,
– a vehicle passed through the roundabout 50 times in each direction of movement,
– three drivers were involved in field tests, two males and one female, with more than 15 years of driving experience.

A Hyper V dual-frequency GNSS device, which records the position of the vehicle with high precision, was selected for gathering the speed data and vehicle path through the roundabout.

In the case, where the location is covered by several satellites and there are no physical obstacles (overpasses, treetops, deep cuts, etc.), device records five points/positions per second for the moving vehicle, which enables very precise determining of the vehicle path and speed back calculation from position and time data.

According to American guidelines (Rodegerdts et al. 2010), the construction of the theoretical vehicle path should initiate at a minimum of 50 m before the entrance to the roundabout. In order to meet this criterion, each recording of

Fig. 1 Digital orthophoto view of the roundabout chose for field testing

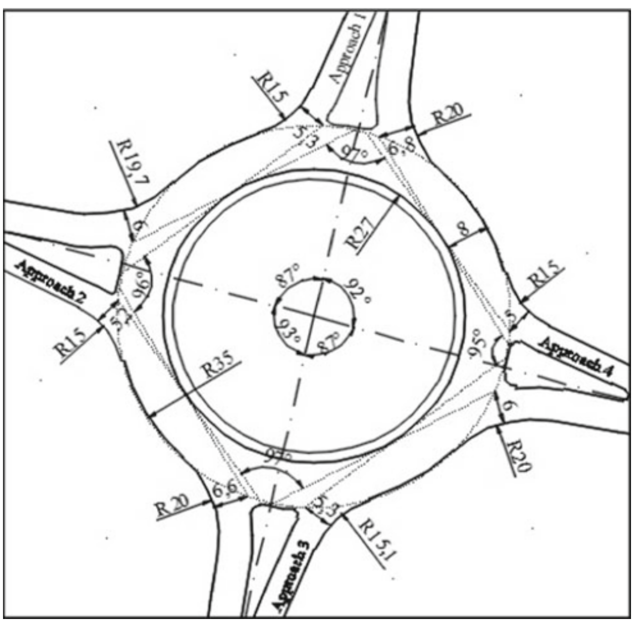

Fig. 2 Roundabout layout with basic design elements

the vehicle path was initiated 50 m before the entrance to the roundabout. Also to determine the speed of the vehicle after it leaves the roundabout each recording of the path ended at a minimum of 50 m after the exit from the roundabout. Only the unobstructed passages of the vehicle in the free-flow traffic conditions were recorded.

For each vehicle passage, speeds were determined on five positions: speed 50 m before the entrance (V_0), speed at the entrance to the roundabout (V_{ent}), speed in the middle of the roundabout (V_{mid}, except in case of the right movement direction), speed at the exit of the roundabout (V_{exit}) and speed 50 m after the exit from the roundabout (V_2).

For the purpose of analyses of data collected by field tests, the average speed V_{avg} was used as referent since these field tests were performed on a homogeneous sample of three drivers, the same vehicle was used, and all conditions of the free-flow traffic were ensured.

The analyses of the available guidelines and other literature showed that usually the critical direction for the speed check is considered to be the one straight-through the roundabout, and only US guidelines (FHWA 2000) take the right direction of movement into the consideration as well. In order to unambiguously determine the critical movement direction at the roundabout at which the vehicles achieve highest operational speeds in average (hereinafter referent direction), tests were carried out as well as comparisons of the operational speeds for the right and straight direction of vehicle movement on a chosen roundabout (Figs. 3 and 4). A left direction of movement was not included in tests because it is a movement on, most commonly, the smallest vehicle path radius on which consequently the speeds will also be lower than the ones when moving right or straight the roundabout.

Based on the data collected by the GNSS device, for each passage of the vehicle, the important elements of the vehicle path were determined as well as the speeds of the vehicle (Figs. 5 and 6):

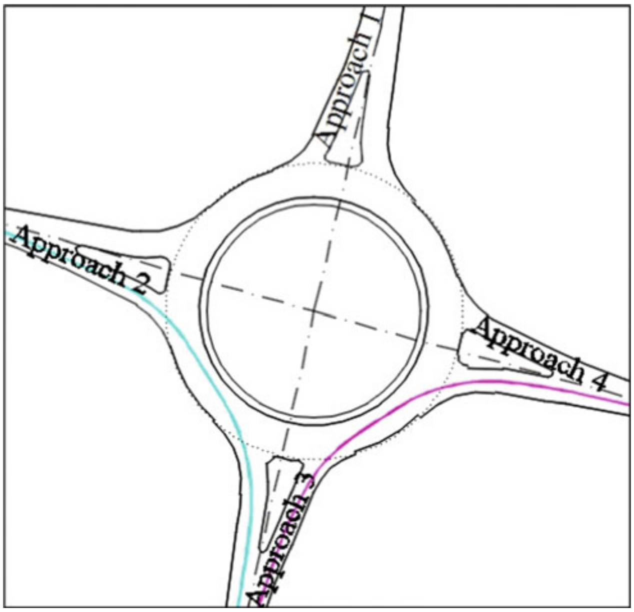

Fig. 3 Right movement directions of the vehicle which were chosen for field tests

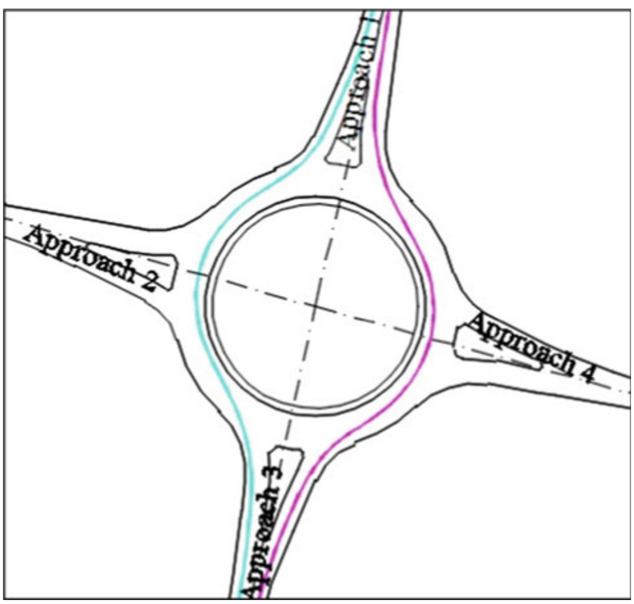

Fig. 4 Straight movement directions of the vehicle which were chosen for field tests

- radii (*R*) and the length of circular arches (*L*) of the path at the entrance, in the middle of the roundabout and at the exit
- the offset of the vehicle path (*X*) from the elevated curbs at the entrance and at the exit (on the right side of the path) and the offset from the curb of the central island or apron of the central island if it exists (on the left side).

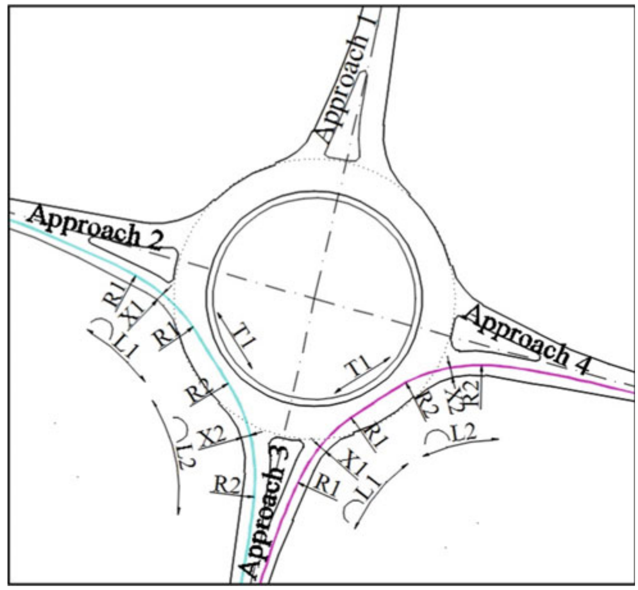

Fig. 5 Example of determining vehicle path elements for the right movement directions

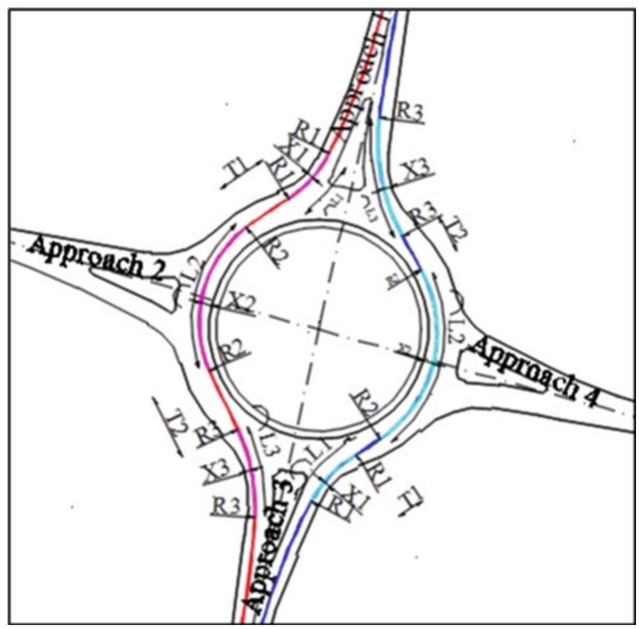

Fig. 6 Example of determining vehicle path elements for the straight movement directions

3.2 Right Direction of Movement

Speed check on the right direction of movement was carried out for direction 2–3 and for direction 3–4 (Fig. 3). As the main traffic flow at this intersection is 1–3 and 3–1, the chosen right turns represent the engaging from minor traffic flow to the main one (2–3) and disengaging from the main traffic flow to the minor (3–4).

Due to poor signal coverage of the GNSS device, which resulted in the insignificant number of points along the path, a certain number of passages on every right direction were rejected. The analysis was made based on 26 passages of the vehicle for the direction 2–3 and 26 passages for direction 3–4. Statistic data processing was performed, and it included the determination of the average value μ, standard deviation SD and minimal and maximal values.

Figure 7 shows the speed profiles for both right turns. It can be noticed that the speeds 50 m before the entrance to the roundabout are higher for direction 3–4 (V_{0avg} = 61.7 km/h) than those for direction 2–3 where average speed on the approach is V_{0avg} = 52.6 km/h. This is because the direction 2–3 represents the engaging of the vehicle from minor direction to main and direction 3–4 disengaging of the vehicle from the main direction to the minor. The main direction has a speed limit of 80 km/h outside of the intersection zone.

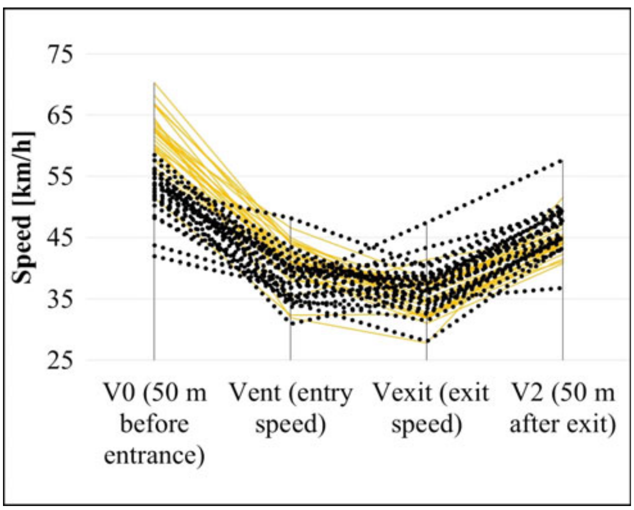

Fig. 7 Speed profiles for all right direction of movement

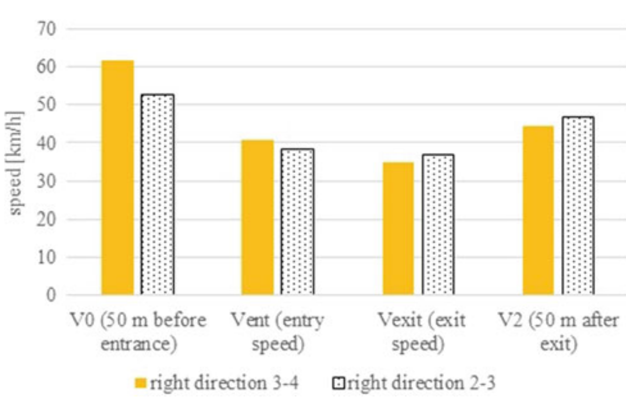

Fig. 8 Average speeds for right directions 2–3 and 3–4

Table 2 Average values of the right vehicle path elements

	R_1 (m)	L_1 (m)	X_1 (m)	R_2 (m)	L_2 (m)	X_2 (m)
Right direction 3–4	40.7	19.2	1.6	42.3	23.9	1.9
Right direction 2–3	40.8	21.1	1.8	42.7	24.0	1.7

The biggest difference between the average speeds is 50 m before the entrance to the roundabout (V_0) (Fig. 8). At the entrance to the roundabout, direction 3–4 has higher average speed which is assumed to be the consequence of the higher approach speed.

It is important to point out that the vehicles disengaging from the main to the minor direction (3–4) despite higher approach and entrance speed achieve lower average speed at the exit and 50 m after the exit from the roundabout. This is probably a consequence of the speed limit on the minor direction. In addition, vehicles, which engage the main direction from the minor, achieve a higher speed at the exit and 50 m after the roundabout exit since the expected (and well-marked) speed limit in the main direction is higher than the speed limit from which they disengaged.

Analysis of the collected data on vehicle path shows that every right movement of the vehicle in the roundabout is best approximated with three elements (Fig. 5):

- entry path radius R_1 (length L_1),
- exit path radius R_2 (length L_2),
- tangent between entry and exit radius (length T_1).

Aforementioned path elements are determined for every recorded vehicle passage as well as values of the offsets X_1 and X_2. Average values are shown in Table 2.

According to American and Croatian guidelines (HC 2014; FHWA 2000), right movement of the vehicle at the roundabout consists of only one radius. This fact was not confirmed by the performed tests. Taking into account 52 passages, the path is best (±10 cm) approximated with two curves (R_1 and R_2) and one middle tangent (T_1) between the arches. In addition, average measured offsets (X_1 = 1.6–1.8 m and X_2 = 1.7–1.9 m) of the path from the elevated curbs at the entrance and the exit deviate from the recommended values (1 m) according to Croatian guidelines (HC 2014) and 1.5 m according to American guidelines (FHWA 2000).

3.3 Straight Direction of Movement

Tests of the straight direction of movement through the roundabout have been carried out on the same roundabout for vehicle movement direction 1–3 and direction 3–1. Both chosen straight directions of movement are on the main traffic flow, with speed limit of 80 km/h outside of the wider zone of the intersection.

On each straight direction, the same number of vehicle passages has been performed (50), and during every passage, the GNSS device recorded the vehicle path. Due to poor signal coverage of the GNSS device, which resulted in an insufficient number of points on the path, a certain number of straight passages have been rejected. A total of 62 valuable straight passages of the vehicle were taken into account, out of which 29 vehicle passages for direction 1–3 and 33 vehicle passages for direction 3–1. Statistic data processing was performed, and it included the determination of the average value μ, standard deviation SD and minimal and maximal values.

Figure 9 shows the speed profiles for both straight directions on the roundabout. Speeds for both directions are fairly uniform except for the speed 50 m before the roundabout entry where the established difference is approximately 6 km/h.

Figure 10 shows the comparison of the average speeds for both straight directions. The biggest difference, as already mentioned, is between average speeds at the roundabout approach. Tests on all 62 straight passages on this roundabout indicate the fact that each vehicle path for straight direction is best approximated (±10 cm) with curves at the entrance and exit of the roundabout as well as in the middle of the roundabout (Fig. 3 right). For each formed circular arch, the corresponding values of the path offset from the curb at the entrance and exit of the roundabout (X_1 and X_3) are determined as well as the path offset from the curb (X_2) of the central island or the apron of the central island. Part of the path between the circular arches is best approximated by short tangents (T_1 and T_2). Average values are shown in Table 3.

According to American and English guidelines (FHWA 2000; HA 2007), path radius at the entrance corresponds to the smallest radius formed at the area of vehicle path at the entrance, and its length should be between 20 and 25 m. In addition, the offset of the path from elevated curbs at the entrance and the exit (X_1 and X_3) and the offset of the path from the curb of the apron of the central island (X_2) deviate from the values recommended by Croatian guidelines (1 m) and American guidelines (1.5 m).

3.4 Speed Comparison for the Right and Straight Movement Direction in the Roundabout

After the detailed analysis of the speed and vehicle path for the right and straight direction of movement at the roundabout, Fig. 11 shows average speeds at the entrance and at the exit (Fig. 12) at the roundabout. Speed in the middle of the roundabout has been measured only in case of the straight direction of movement and in this comparison has been left out.

The speed at the entrance in case of right direction is in average lower for 3–5 km/h compared with the speed at the entrance in case of the straight direction of movement (Fig. 11).

A similar comparison is performed for exit speeds (Fig. 12) where it was proved that the exit speeds in case of the straight direction of movement are in average 5–7 km/h higher than the exit speeds on the right direction of movement.

From Figs. 11 and 12, it is possible to notice the difference between the entrance and exit speeds for the straight and the right direction of movement; however, it is not possible to determine whether this difference is statistically significant. This was verified by *t*-test of two independent samples (Šošić 2006).

The first step was to verify if the average value of the entry speed is different between two straight directions of movement and between two right directions of movement. Results of the performed *t*-test (Table 4) show that the zero-hypothesis claiming that there is no significant

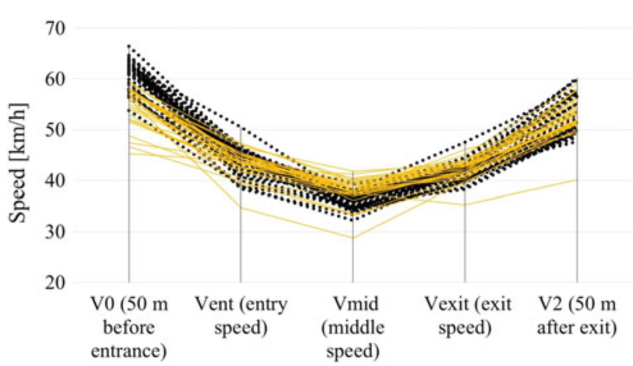

Fig. 9 Speed profiles for all straight directions of movement

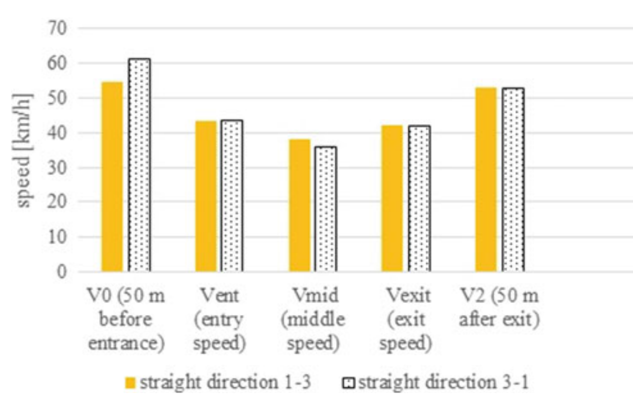

Fig. 10 Average speeds for straight directions 1–3 and 3–1

Table 3 Average values of the straight vehicle path elements

	R_1 (m)	L_1 (m)	X_1 (m)	R_2 (m)	L_2 (m)	X_2 (m)	R_3 (m)	L_3 (m)	X_3 (m)
Straight direction 1–3	38.5	21.0	1.6	29.9	39.5	1.9	45.7	25.0	1.5
Straight direction 3–1	39.8	23.0	1.5	30.6	40.7	1.7	46.7	27.6	1.8

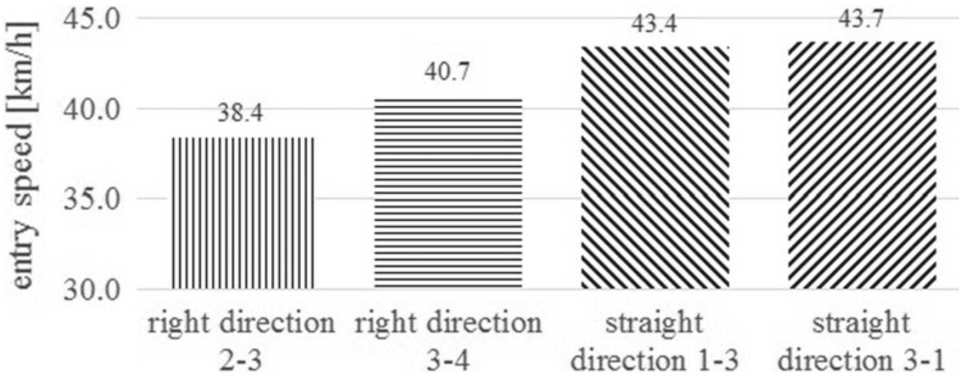

Fig. 11 Comparison of average entry speeds for right and straight direction of movement

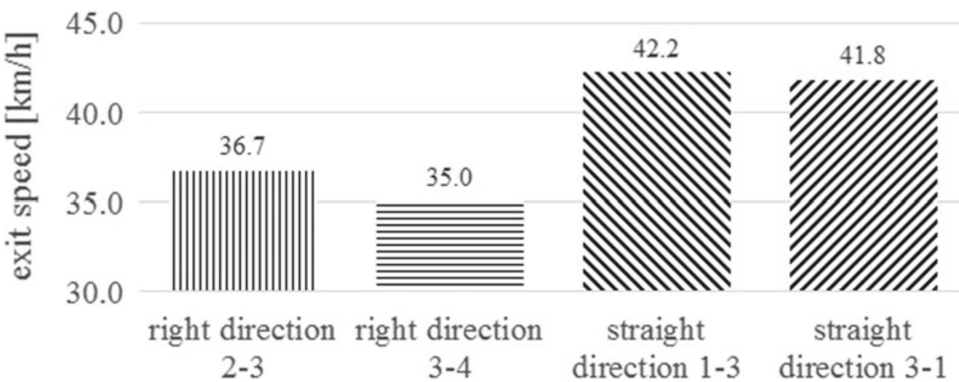

Fig. 12 Comparison of average exit speeds for right and straight direction of movement

Table 4 Results of the *t*-test, for comparison of the average speeds at the entry and the exit for the roundabout

	Entry speed			Exit speed		
	Comparison of two straight directions (1–3 and 3–1)	Comparison of two right directions (3–4 and 2–3)	Comparison of straight and right direction	Comparison of two straight directions 1–3 and 3–1	Comparison of two right directions 3–4 and 2–3	Comparison of two right directions 3–4 and 2–3
p-value	0.609	0.068	<0.0001	0.483	0.066	<0.0001
α-level of significance	0.05	0.05	0.05	0.05	0.05	0.05

difference between average entrance speed for straight direction 1–3 and 3–1 (p = 0.609) and for right direction 3–4 and 2–3 (p = 0.068) should be accepted since all p-values are higher than significance α = 0.05. The same test was performed for exit speeds, and results of the performed t-test confirm that zero-hypothesis which claims that there is no significant difference between average exit speed for straight direction 1–3 and 3–1 (p = 0.483) and right direction 3–4 and 2–3 (p = 0.066) should be accepted since all p-values are higher than the significance level α = 0.05.

Considering the above, it was concluded that all straight passages at the roundabout (1–3 and 3–1) can be analyzed together as well as all right passages at the roundabout (3–4 and 2–3).

In order to determine if there is any significant difference between the newly calculated average entrance/exit speeds for the straight and right direction of movement, the *t*-test has been performed again. All the values of the *t*-test < 0.0001 in case of comparison of the average entry speed of the straight and average entry speed of the right direction of movement point to the fact that it is necessary to reject zero-hypothesis of the test which claims that the average entry speeds of the straight and right movement are equal. In addition, value $p < 0.001$ in case of comparison of the average exit speed of the straight and average exit speed of the right movement point to the fact that it is necessary to reject zero-hypothesis of the test which claims that the average exit speeds of the straight and right movement are equal.

4 Conclusion

This paper analyzes the operational speeds at roundabouts with the aim to experimentally define critical movement direction at the roundabouts.

The analysis has shown that two models are commonly used for speed checkup during roundabout design: Dutch and American. The analysis of roundabout regulations regarding the critical direction of movement at the roundabout has shown that regulation of almost all countries (except the USA) foresees speed checkup in the straight direction of movement at the roundabout. There are no studies in the available literature to validate the critical direction of movement at the roundabout.

In this paper, by using precise GNSS equipment, vehicle paths were recorded and the speeds were calculated from the GNSS data for two directions of movement at the roundabout: right and straight direction of movement. Right turn from the main to the minor direction and vice versa and straight movement in the main direction were analyzed.

Regarding vehicle path, the results showed:

- in the case of right direction of movement, the vehicle path consists of two curves and middle tangent;
- in the case of the straight direction of movement, the vehicle path consists of three curves, and between each curve is middle tangent.

Comparing the entry and exit speeds on the straight and right direction of movement at the roundabout, it was confirmed that the higher average speed, at both the entry and exit of the roundabout, was achieved on the straight direction of movement at the roundabout.

The speed analysis for the right direction of movement has shown that higher entry speeds can be expected in the case of turning from the main direction to the minor, which can be a problem since the roundabout does not have a favored direction of movement, and it is imperative to slow down at the entrance from each direction.

From the above, it can be concluded that for the speed checkup at the roundabout, as the relevant direction of movement, in the case a regular four-leg roundabout of the standard characteristics, at which the axes of neighboring legs close an angle of approximately 90°, it can be suggested to choose a straight direction of movement. In the case of the speed checkup for the right direction of movement, it is appropriate to check the speed for the entry from the approach where the speed limit is higher (main direction).

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