Vehicle Speed Impact on the Design of Efficient Urban Single-Lane Roundabouts

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Abstract. Implementing effective roundabouts in urban areas is a highly demanding task and requires optimizing traffic (operational) efficiency (TE) and traffic safety (TS) while considering geometric factors, traffic characteristics and local constraints. To capture a relationship between roundabout design elements, traffic demand flow and vehicle path speed through the roundabout, we studied American and Australian method on four urban single-lane roundabouts located in the Croatian capital of Zagreb. Comparison between design speed and measured vehicle speed show bigger deviations than previous studies. Preliminary validation of the used methods enables better understanding of its application for Croatian conditions. These preliminary results suggest that the used methods can capture the correlation between geometry, traffic flow demand and vehicle speed of urban single-lane roundabouts but with needed calibration for local conditions.

Keywords: Urban single-lane roundabout · Geometry design · Traffic (operational) efficiency · Traffic safety · Vehicle movement trajectory · Vehicle speed

1 Introduction

Implementing effective roundabouts in urban areas is a highly demanding task and requires optimizing traffic (operational) efficiency (TE) and traffic safety (TS) while considering geometric factors, traffic characteristics and local constraints. Studies of roundabouts in various countries, particularly of single-lane roundabouts in urban areas, have shown that proper design can significantly improve TE [1, 2], as well as TS parameters [3–5].

Vehicle movement trajectory speed is another parameter that has influence on TE and TS [3, 6–8]. To capture a relationship between roundabout design elements, traffic demand flow and vehicle path speed through the roundabout, we study existing methodology. Eastern and South-eastern European countries have outdated roundabout design guidelines [9–13]. Although these guidelines do provide partial recommendations, it fails to define rules when setting design speeds for roundabouts. In such cases designers rely on their own experience, examples from good practice, and foreign guidelines [3, 14].

Croatia has approximately more than 200 roundabouts (>60% lie in urban areas), and many of them deviate substantially from international standards for roundabout

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planning, design and modeling, which compromises their TE and TS [15]. The country has no tradition of systematically monitoring TE, TS, vehicle path speed and other key performance indicators of roundabouts, though the government has called for the building and reconstruction of roundabouts as part of its National Traffic Safety Plan 2011–2020 [15]. The most recent national guidelines stipulate where urban single-lane roundabouts should be built, what geometry they should have, and how capacity should be calculated [9]. However, the guidelines do not indicate what models should be used for analyzing vehicle path speeds nor common TE parameters. These characteristics and previous studies [14] make the country attractive for studying impact of vehicle design speed on urban single-lane roundabouts.

The focus of the research is to study the impact of calculated versus measured vehicle design speed when designing urban single-lane roundabouts. This is done by using the same methodology like in [14]. The American and Australian methods [16, 17] are validated using field data from four urban unsignalized single-lane roundabouts located in the Croatian capital of Zagreb. Nevertheless, the influence of design elements on the vehicle path speed, i.e. on the TE and TS level, will not be studied here.

The remainder of the paper is organized as follows. Section 2 describes the used methodology and study area data. Section 3 presents validated model results, and Sect. 4 discusses the results and implications for future work.

2 Methodology

2.1 Design Speed and Vehicle Path Radii

The study concept and methodology of calculating vehicle design speed for vehicle path radii trajectories is the same as presented in [14]. The roundabout design speed is the maximum allowable speed for which the total driving safety is guaranteed in free traffic flow at the roundabout, under optimum conditions and with proper maintenance of the roundabout driving area [16]. Design speed is dependent upon the roundabout geometry and calculated according to driving path radii:

$$V = \sqrt{127R(e + f_s)} \tag{1}$$

where:

V - design speed [km/h],

R - vehicle path radius [m],

e - pavement slope [m/m],

f_s - coefficient of friction between a vehicle's tires and the pavement [16].

The stability and safety of vehicle passing through the roundabout is defined by the adhesion between the tire and the pavement. The coefficient of friction (f_s) is calculated by means of the coefficient of friction for light vehicles (f_{sLV}) and heavy vehicles (f_{sHV}):

$$f_sLV = 0,30 - 0,00084 \cdot \sqrt{M_VLV} \tag{2}$$

$$f_s HV = 0,30 - 0,00084 \cdot \sqrt{M_V HV} \tag{3}$$

$$f_s = (1 - P_{HV}) \cdot f_s LV + (P_{HV} \cdot f_s HV) \tag{4}$$

where:

f_sLV - coefficient of friction for light vehicles [-],
M_vLV - average weight of light vehicles [kg],
f_sHV - coefficient of friction for heavy vehicles [-],
M_vHV - average weight of heavy vehicles [kg],
f_s - coefficient of friction for vehicles [-],
PHV - percentage of heavy vehicles [17].

Recommended maximum design speed values for vehicles entering the mini roundabout is 25–30 km/h, and for small single-lane roundabouts is 30–35 km/h [16]. In the design process where there is no traffic flow demand and are no marked traffic lanes, the vehicle path is characterized by three movement radii: entry, circulatory roadway, and exit radius. It is assumed that the vehicle width is 2.0 meters, and that a minimum distance of 0.5 m should be maintained from the center of the roadway or concrete curb and painted edge of the splitter island. The imaginary vehicle path line is 1.5 meters away from the concrete curb and 1.0 m away from the painted line of the splitter island [16]. The fastest vehicle path for negotiating the roundabout is a series of reverse paths (the right-side path is followed by the left-side path, and the right-side path). In cases when there is no central island, the operating path will be a straight line. The methodology for defining the fastest vehicle path speed does not provide really expected vehicle operating speeds, but rather a theoretically possible speed of vehicle entry into the roundabout that is needed during the roundabout design [16]. Real vehicle operating speeds may greatly differ for various reasons, including different axle loads and vehicle characteristics, individual driver capabilities, and tolerance to gravity forces [16].

The speed consistency contributes to greater level of TS by reducing the speed difference between the conflicting streams of vehicles and optimizing entry capacity. That is why five critical radii must be checked for each approach: R_1 - the entry path radius; R_2 - the circulating path radius; R_3 - the exit path radius; R_4 - the left-turn path radius; R_5 - the right-turn path radius (Fig. 1). These vehicle path radii are not the same as the curb radii [16]. During design, R_1 should be smaller than R_2, and R_2 should be smaller than R_3, for the fastest vehicle path. This ensures that speeds will be reduced to their lowest level at the roundabout entry and will thereby reduce the likelihood of loss-of-control crashes. It is acceptable for R_1 to be greater than R_2 (maximum difference < 20 km/h). The R_4 radius must be evaluated to ensure that the maximum speed difference between the entering and circulating traffic is no more than 20 km/h. The design speed for radius R_5 should therefore be the maximum design speed for the entire roundabout and should not exceed the design speed of R_4 by 20 (km/h, as R_4 has a conflicting point with R_2 [16].

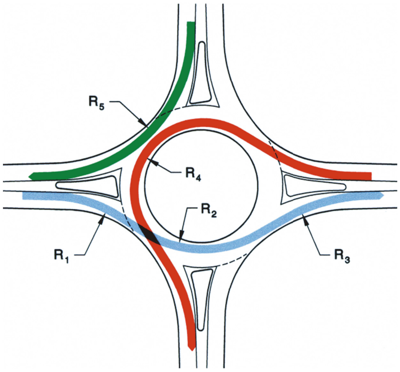

Fig. 1. Vehicle path radii [16]

2.2 Study Area and Data

Based on previous studies [14, 18] we apply the same methodology and repeat it on the same four urban single-lane roundabouts situated in the City of Zagreb. Their main design elements are given in Table 1. The roundabout Sveti Duh – Kuniščak has three approaches and all other roundabouts four approaches. Roundabout classification, their function of TE and TS in the city traffic network and layout (i.e. main geometry elements, speed limits of 40 km/h, number of traffic lanes, locations of speed bumps) of the studied roundabouts has not been changed since the last study. On some locations, new residential and office buildings have been build. Under normal traffic flow movements, the roundabout entry speeds (V_1), circulating speeds (V_2) and exit speeds (V_3) were calculated for the radii (R_1, R_2 and R_3). Path speeds for radii (R_4 and R_5), i.e. for the right-turn movements (V_4) and left-turn movements (V_5) through the roundabout, were not measured to assure the same study approach as in [14]. Traffic flow demand was measured by "pen and pencil" on 29th September 2016 (Thursday) in the morning peak hour traffic. At same day and hour, the entry, circulating and exit speeds were collected in 15-min intervals using the GPS (Global Positioning System) device installed in a passenger car (same vehicle and driver as in [14]). Favorable weather conditions enabled good visibility and dry pavement at all roundabouts and their approaches.

Table 1. Design elements at studied roundabouts [14].

Roundabout name	ICD [m]	CID [m]	w [m]	e [m]
Sveti Duh - Kuniščak	20.0	6.0	7.0	3.5/3.6
Petrova - Jordanovac	25.0	12.0	6.5	3.5/4.5
Voćarska - Bijenička	22.0	13.0	4.5	4.0
Radnička road – Petruševec 1	40.0	28.0	6.0	3.0/3.5

Legend: ICD - inscribed circle diameter; CID - central island diameter; circulatory roadway width (w), approach entry width (e).

3 Results

3.1 Results for 2016 Measurement

The sample size consists of again 50 measurements; average vehicle path radii and average path speeds at roundabouts. Design geometry data (i.e. pavement slope) were measured *in situ* by laser range finder (BOSCH PLR 50C) and designed with the help of Autodesk AutoCAD software. Data on pavement slope, percentage of heavy vehicles, and the corresponding coefficients of friction are calculated according to the latest traffic demand flow (Sect. 2.2) and presented in Table 2. Equations (1–4) were used to calculate design speed for negotiating a roundabout, while differences between the measured and calculated design speeds are presented and analyzed in Figs. 2, 3, 4 and 5. In Table 2, light vehicles are all vehicles belonging to categories L, M, M1, M2, and N, N1 and O1, O2, while heavy vehicles are vehicles belonging to categories M3, N2 and N3, and O3 and O4 according to [19].

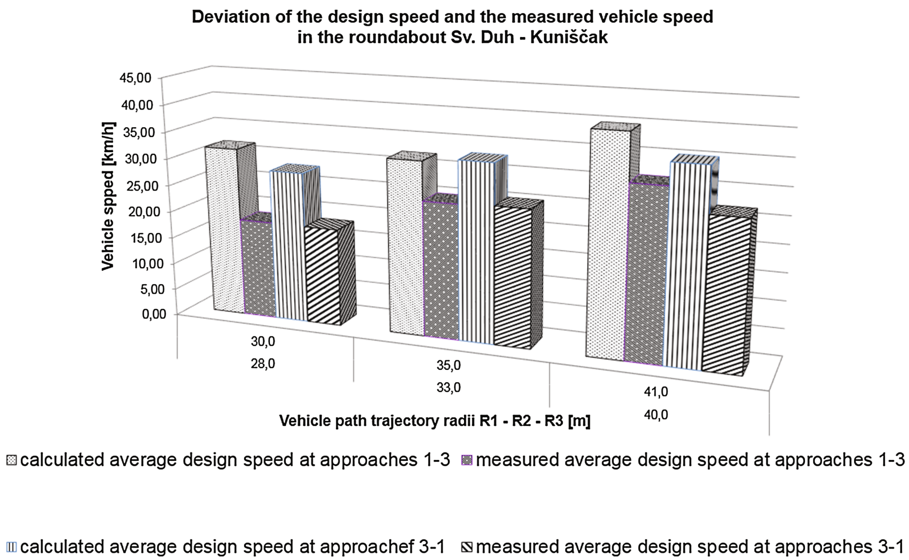

Fig. 2. Relationship between the design and measured speed values at the Sv. Duh – Kuniščak roundabout

Generally, the lowest vehicle path speeds were measured at the roundabout entry, equal or slightly higher speed values were measured around the central island, while the highest speed values were measured at the exit from the roundabout. Calculated average design speed values are generally lower than roundabouts speed limit of 40 km/h, and lower or slightly higher than the maximum recommended speed of 35 km/h, as shown in Table 2. All measured average speeds are lower than the recommended maximum speed of 35 km/h, and are also lower than the speed limit. Deviations between calculated average design speeds and measured average speeds and are presented in Table 2, and discussed as follows.

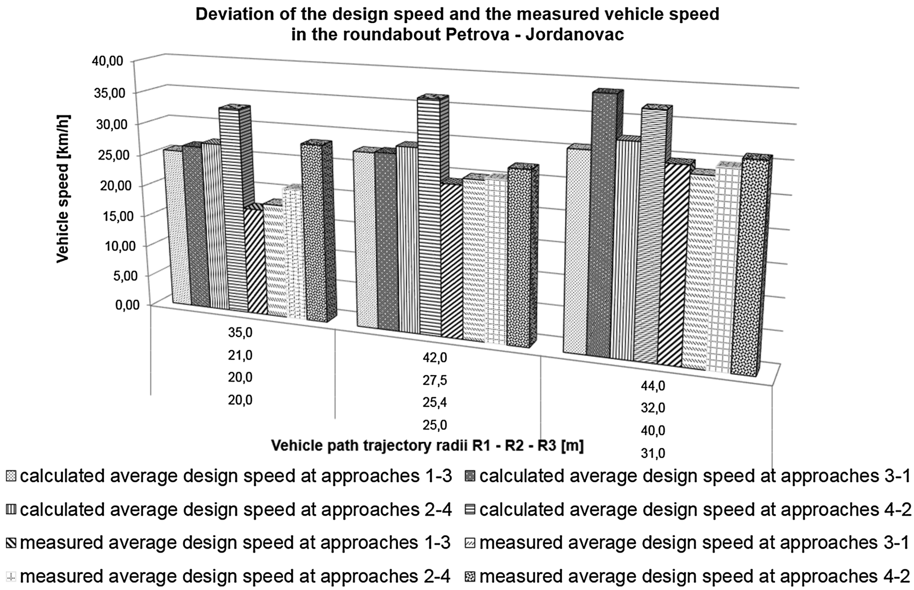

Fig. 3. Relationship between the design and measured speed values at the Petrova – Jordanovac roundabout

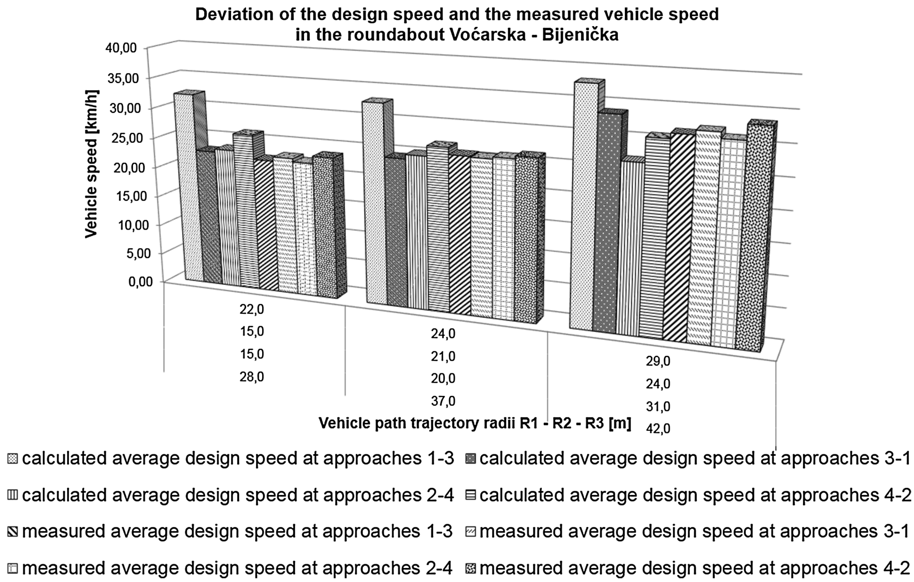

Fig. 4. Relationship between the design and measured speed values at the Voćarska - Bijenička roundabout

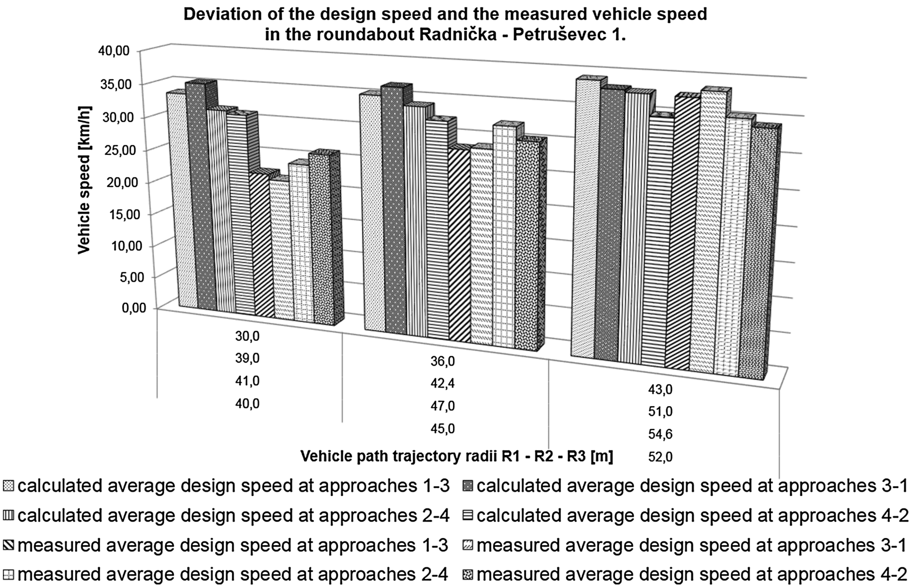

Fig. 5. Relationship between the design and measured speed values at the Radnička – Petruševec 1 roundabout

An average vehicle speed measured at the Sv. Duh – Kuniščak roundabout on the path from approach 1 (Sv. Duh – South) to approach 3 (Sv. Duh – North) was lower by 42.15% that the calculated average design speed. An average vehicle speed measured at the Petrova - Jordanovac roundabout on the path from approach 1 (Petrova Street - West) to approach 3 (Petrova Street - East) was lower by 32.76% that the calculated average design speed. An average vehicle speed measured at the Vočarska - Bijenička roundabout on the path from approach 1 (N. Grškovića Street) to approach 3 (Vočarska Street) was lower by 31.05% that the calculated average design speed, while for the path from approach 2 (Mesićeva Street) to approach 4 (Bijenička Street) was greater by 16.30% that the calculated average design speed. An average vehicle speed measured at the Radnička – Petruševec 1 roundabout on the path from approach 3 (Radnička cesta – South) to approach 1 (Radnička cesta – North) was lower by 38.91% that the calculated average design speed.

Deviation of average measured speeds from average calculated speeds could be explained as follows. The Sv. Duh – Kuniščak roundabout is located at the transition from the mountainous terrain to a flat zone, and the entire intersection is inclined by 5–7%. Due to space restrictions and the need to accommodate heavy vehicle traffic from approach 1 (Sv. Duh – South) to approach 2 (Kuniščak Street), which is generated by the Zagreb brewery complex located 500 m to the east of the roundabout, the roundabout was realized with a traversable central island. Primary school is located to the east of the roundabout between the approaches 1 and 3 (Sv. Duh – South and North). Taking all this into consideration, as well as the information about the percentage of

Table 2. Calculated average design speed and average vehicle speed measured at selected roundabouts in 2016.

Roundabout/approach name	Average path radii (N = 50) [m]			Slope e [m/m]						
	R_1	R_2	R_3	App. R_1	C. r. R_2	App. R_3	P_{HV} (dec)	f_{SLV}	f_{SHV}	f_S
Sveti Duh - Kuniščak										
Approach 1	28.0	33.0	40.0	0.02	−0.015	0.05	0.11	0.27	0.21	0.26
Approach 3	30.0	35.0	41.0	−0.05	−0.015	−0.02	0.18	0.27	0.21	0.26
Petrova - Jordanovac										
Approach 1	20.0	25.0	31.0	0.00	−0.015	−0.02	0.15	0.27	0.21	0.26
Approach 2	20.0	25.4	40.0	0.02	−0.015	0.04	0.18	0.27	0.21	0.26
Approach 3	21.0	27.5	32.0	0.02	−0.015	0.00	0.17	0.27	0.21	0.26
Approach 4	35.0	42.0	44.0	−0.04	−0.015	−0.02	0.04	0.27	0.21	0.27
Voćarska - Bijenička										
Approach 1	28.0	37.0	42.0	0.05	−0.03	0.01	0.12	0.27	0.21	0.26
Approach 2	15.0	20.0	31.0	0.01	−0.03	0.03	0.07	0.27	0.21	0.26
Approach 3	15.0	21.0	24.0	0.02	−0.03	−0.03	0.03	0.27	0.21	0.27
Approach 4	22.0	24.0	29.0	−0.02	−0.03	−0.01	0.05	0.27	0.21	0.27
Radnička road – Petruševec 1										
Approach 1	40.0	45.0	52.0	0.00	−0.005	0.01	0.65	0.27	0.20	0.22
Approach 2	41.0	47.0	54.6	0.01	−0.005	−0.02	0.55	0.27	0.20	0.23
Approach 3	39.0	42.4	51.0	−0.02	−0.005	0.00	0.68	0.27	0.20	0.22
Approach 4	30.0	36.0	43.0	0.02	−0.005	−0.01	0.51	0.27	0.20	0.23

(*continued*)

Table 2. (*continued*)

Direction of travel	Calculated average speed [km/h]			Measured average speed [km/h]			Deviation from design speed [%]		
Approach	V_1	V_2	V_3	V_1	V_2	V_3	V_1	V_2	V_3
Direction of travel	Calculated average speed [km/h]			Measured average speed [km/h]			Deviation from design speed [%]		
Approach	V_1	V_2	V_3	V_1	V_2	V_3	V_1	V_2	V_3
Sveti Duh - Kuniščak									
1–3	31.69	32.20	39.83	18.33	25.02	31.23	−42.15	−22.29	−21.60
3–1	28.18	32.89	35.23	18.22	25.31	27.01	−35.34	−23.05	−23.33
Petrova - Jordanovac									
1–3	25.63	27.81	30.65	17.23	24.01	29.58	−32.76	−13.66	−3.48
3–1	26.51	27.93	38.83	18.24	25.00	28.33	−31.21	−10.48	−27.04
2–4	27.20	29.09	32.34	21.03	25.32	29.66	−22.68	−12.97	−8.29
4–2	33.01	36.52	37.01	28.33	27.15	31.01	−14.17	−25.66	−16.21
Voćarska - Bijenička									
1–3	32.21	33.00	38.07	22.21	25.69	31.54	−31.05	−22.15	−17.16
3–1	22.87	24.41	33.77	22.89	25.55	32.21	0.08	4.67	−4.61
2–4	23.38	25.13	26.87	22.36	25.88	31.25	−4.35	2.97	16.30
4–2	26.20	26.81	30.69	23.59	26.31	33.59	−9.97	−1.85	9.45
Radnička road – Petruševec 1									
1–3	33.56	35.19	39.12	22.36	28.36	37.58	−33.38	−19.42	−3.94
3–1	35.26	36.55	38.05	21.54	28.69	38.56	−38.91	−21.50	1.34
2–4	31.44	34.00	37.72	24.25	32.11	35.26	−22.88	−5.55	−6.51
4–2	30.96	32.19	34.79	26.00	30.21	34.22	−16.02	−6.14	−1.63

Legend: App. - approach, C. r. - circulatory roadway, P_{HV} - percentage of heavy vehicles in traffic flow [decimal], M_{vLV} - average weight of light vehicles (1400–1500) [kg], M_{vHV} - average weight of heavy vehicles (11000–15000) [kg], f_{SLV} - coefficient of friction for light vehicles, f_{SHV} - coefficient of friction for heavy vehicles, f_s - coefficient of friction for vehicles.

heavy vehicles in the total traffic (11%), we can explain the –42.15% deviation of the calculated speed from the average measured speed.

The Petrova – Jordanovac roundabout is located at the foot of a hillside (approach 4 (Jordanovac – North) inclined by 4%) while other approaches and the circulatory roadway are not characterized by greater terrain limitations. Due to restricted space, design elements are smaller and this greatly affects roundabout TE. Primary school is located to the east of the intersection between approaches 2 and 3 (Jordanovac – South and Petrova – East). Having this in mind, and the data about the percentage of heavy vehicles in the total traffic (13.5%, including public transport vehicles), provide proper explanation for the −32.76% deviation of the calculated speed from the measured speed.

The Voćarska - Bijenička roundabout is located at the transition from the hillside to the flat terrain, and the entire roundabout is realized at the grade of 3%, while the grade at the approach 1 (N. Grškovića) amounts to 5%. Due to restricted space, design elements are smaller and this greatly affects roundabout TE. Primary school is located to the south of the roundabout, while the Faculty of Science, Institute for Physics, and the Ruđer Bošković Institute, are located some 300 m to the north. The positioning of these institutions calls for a greater intensity of public transport traffic, as can be seen from the data on the proportion of heavy vehicles in the total traffic (6.75%). The above information suitably explains the −31.05% deviation of the calculated speed from the measured speed.

The Radnička – Petruševec 1 roundabout is situated in a flat area, but is located at the heavily trafficked Radnička street in the south-eastern part of Zagreb. The roundabout was built to properly link the south-eastern part of Zagreb, i.e. the nearby industrial zone situated 500 m to the north of the roundabout, with the Zagreb Bypass (Kosnica Interchange), and the Pleso Airport, via the Homeland Bridge. Primary school is located to the west of the intersection between approaches 2 and 3 (Petruševec 1 and Radnička – South). The above information, and the data about the percentage of heavy vehicles in the total traffic (59.75%, including public transport vehicles), provide proper explanation for the −38.91% deviation of the calculated speed from the measured speed.

3.2 Results Comparison

Here the studied results from previous work [14], and the 2016 measurements will be briefly presented (Table 3). Only total average data deviations for all four roundabouts will be shown. The latest *in situ* measurements of average vehicle speed are greater from 4 to 8% in total comparing the measurements from 2011. Regarding the average increase of percentage of heavy vehicle of 28.4%, the calculated average design speeds remain the same (from 29 to 35 km/h). Deviations of measured and calculated design speeds are for 2016 smaller than for 2011, by; V1 (−28%), V2 (−126%), and V3 (−65%). The biggest deviations of measured versus calculated design is registered on Petrova – Jordanovac roundabout; approach 3 to 1 has decrease of 1256.8%, and approach 2 to 4 increase of 24.74%.

Table 3. Deviation between 2011 and 2016 data measurements.

Direction of travel	Deviation in 2011 [14] [%]			Deviation in 2016 [%]			Deviation [%]		
Roundabout Approach	V_1	V_2	V_3	V_1	V_2	V_3	V_1	V_2	V_3
Sveti Duh - Kuniščak									
1–3	−44.4	−25.0	−26.0	−42.1	−22.2	−21.6	−5.2	−10.8	−17.2
3–1	−42.8	−25.5	−24.0	−35.3	−23.0	−23.3	−17.4	−9.7	−2.7
Petrova - Jordanovac									
1–3	−34.1	−16.3	−9.1	−32.7	−13.6	−3.4	−4.1	−16.4	−61.8
3–1	−38.1	−17.1	−34.5	−31.2	−10.4	−27.0	−18.1	−39.0	−21.8
2–4	−25.3	−13.4	−11.5	−22.6	−12.9	−8.2	−10.5	−3.8	−28.3
4–2	−22.9	−27.1	−19.4	−14.1	−25.6	−16.2	−38.2	−5.5	−16.5
Voćarska - Bijenička									
1–3	−38.8	−24.5	−20.6	−31.0	−22.1	−17.1	−20.1	−9.8	−16.6
3–1	−7.6	−0.4	−14.9	0.08	4.6	−4.6	−101.0	−1256.8	−69.0
2–4	−7.3	−2.6	13.0	−4.3	2.9	16.3	−41.1	−211.3	24.7
4–2	−18.4	−3.2	−3.0	−9.9	−1.8	9.4	−46.0	−42.9	−410.3
Radnička road – Petruševec 1									
1–3	−38.9	−24.0	−12.9	−33.3	−19.4	−3.9	−14.2	−19.1	−69.5
3–1	−45.6	−30.4	−17.8	−38.9	−21.5	1.3	−14.8	−29.2	−107.5
2–4	−28.9	−13.9	−10.4	−22.8	−5.5	−6.5	−20.9	−60.2	−37.4
4–2	−26.9	−13.8	−7.7	−16.0	−6.1	−1.6	−40.4	−55.7	−78.9

4 Discussion and Conclusion

Implementing safe and effective roundabouts in urban areas is a highly demanding task and requires optimizing TE and TS while considering geometric factors, traffic characteristics and local constraints. In designing urban single-lane roundabouts a special attention must be paid to the design of individual roundabout elements (i.e. ICD, CID, width of circulatory roadway and approach lanes) to comply with the vehicle path speed needed for proper negotiation of the roundabout. Determination of a method for defining design speed for safe negotiation of the roundabout geometry is needed. This is also for better understanding TE and TS parameters, both at the new roundabout modelling phase, and during analysis of existing roundabouts.

In this paper we repeated the study of single-lane roundabout vehicle design speed using the same methodology as we used in [14]. In general, it can be concluded that the basic roundabout design requirement of R_1, $R_2 < R_3$, according to [16], has been met. Deviations between the average design speeds and measured speeds vary from −42.15% to +16.30% for all studied roundabouts. The latest *in situ* measurements of average vehicle speed are greater from 4 to 8% comparing the measurements from 2011. Regarding the average increase of percentage of heavy vehicle of 28.4%, the calculated average design speeds remain the same (from 29 to 35 km/h). Deviations of measured and calculated design speeds are for 2016 smaller than for 2011, by;

V_1 (−28%), V_2 (−126%), and V_3 (−65%). These deviations result from: used design speed methods, location features of intersections and their disposition within the city traffic network, roundabout area design elements and traffic equipment, various axle loads and properties of vehicles, traffic flow characteristics, and driver behavior and experience.

Limitations of the study reflects the same limitations that are emphasized in our previous study [14]; we did not study path radii (R_4 and R_5, i.e. (V_4) and (V_5)); sample size - 50 measurements for vehicle path radii and design speed on four single-lane roundabouts; and we did not study the influence of design elements on the vehicle path speed (i.e. on the TE and TS).

Future study should involve a greater number of similar roundabouts with greater size samples of vehicle path radii and design speed, and vehicle path speed for left/right turns at roundabouts. It could also be necessary to study and correlate the driver behavior and type of vehicles with vehicle speed during measurement. In addition, it would be useful to calibrate the used methods to local conditions. If the used methods can be validated, it may be possible to expand it to include several parameters, pedestrian and bicyclist demand flow. In addition, future studies should examine this approach on other urban/suburban single and multi-lane roundabout types - turbo roundabouts [20–22]. Development and validation of such methods would be useful to better understand the TE and TS parameters for Croatian conditions or other. Therefore, further work is needed to confirm the validity of our approach.

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