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# Study of vehicle speed in the design of roundabouts

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Preliminary note

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### Study of vehicle speed in the design of roundabouts

Some roundabout design elements significantly influence the vehicle driving speed, i.e. the trajectory of vehicles at roundabouts, which is directly responsible for the level of service and traffic safety at roundabouts. An "in situ" speed, taken as a significant roundabout-design element, is analysed in the paper using as an example four urban single-lane roundabouts located in the City of Zagreb. The American method and the Australian method are used for the definition and verification of the design speed at roundabouts. Results obtained show correlation between the design speed and the actual vehicle speed measured at roundabouts.

Key words:
single-lane roundabout, urban area, dimensioning and design, vehicle movement trajectory, vehicle speed

Prethodno priopćenje

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### Istraživanje brzine kretanja vozila pri projektiranju kružnih raskrižja

Pojedini oblikovni elementi raskrižja s kružnim tokom prometa značajno utječu na brzinu kretanja vozila koja ima izravan utjecaj na razinu usluge i prometnu sigurnost raskrižja. U radu se kroz prikaz četiri urbana jednotračna kružna raskrižja grada Zagreba, analizira brzina *in situ* kao značajan element pri projektiranju kružnih raskrižja. Za definiranje i provjeru projektne brzine primijenjene su američka i australska metoda. Rezultati istraživanja dovode u korelaciju projektnu brzinu sa stvarno izmjerenom brzinom vozila na kružnom raskrižju.

Ključne riječi:
jednotračno kružno raskrižje, urbana sredina, oblikovanje i projektiranje, trajektorija provoženja vozila, brzina kretanja vozila, sigurnost prometa

Vorherige Mitteilung

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### Untersuchung der Fahrzeuggeschwindigkeit beim Entwurf von Kreisverkehrsplätzen

Einzelne Elemente der Gestaltung von Kreuzungen mit Kreisverkehr beeinflussen bedeutsam die Fahrzeuggeschwindigkeit, bzw. den Fahrweg innerhalb des Kreisverkehrs, und haben eine direkte Einwirkung auf das Leistungsniveau und die Sicherheit der Kreuzung. In dieser Arbeit ist, mittels vier städtischer einspuriger Kreisverkehrsplätze in der Stadt Zagreb, die Geschwindigkeit "in-situ" als wichtiges Element im Entwurf analysiert. Die Berechnungsgeschwindigkeit im Kreisverkehr ist gemäß der amerikanischen und der australischen Methode berechnet. Die Resultate der Untersuchungen führen zur Korrelation dieser Berechnungswerte mit den gemessenen Geschwindigkeiten.

Schlüsselwörter:
einspuriger Kreisverkehr, städtisches Umfeld, Gestaltung und Entwurf, Fahrweg, Fahrzeuggeschwindigkeit

## 1. Introduction

In the road transport network, traffic junctions are considered to be the most complex and the most demanding points where several traffic streams intersect. If traffic junctions with circular flow of traffic (the so called roundabouts) are compared with traditional at-grade urban road junctions with or without traffic lights, it may easily be concluded that appropriately dimensioned and designed roundabouts greatly increase the level of efficiency, i.e. the capacity and level of service, of road junctions [1-7]. In addition, during their useful life, they reduce the total time of travel, vehicle waiting time at road junctions, length of travel and fuel consumption, while also alleviating harmful impacts on environment due to discharge of exhaust gases [8-11]. From the economic standpoint, such intersections bring numerous benefits such as: lower land purchase costs, lower cost of construction and installation of equipment (illuminated traffic signs in particular), less costly maintenance, and lower losses generated by congestions due to excessive traffic load [12]. In addition, the level of traffic safety increases considerably when roundabout-type intersections are used [13-16]. Detailed study of the influence of design elements on the efficiency, level of service, and traffic safety level, is still in its beginnings in the Republic of Croatia [5, 17-20]. In this respect, it is important to mention results of recent studies in which neural networks have been used to calibrate a micro-simulation traffic model on an example of two roundabouts in an urban area. This calibration has inter alia enabled the analysis of efficiency parameters i.e. the time of travel and vehicle queuing length [21].

Therefore, when dimensioning and designing small-size roundabouts ($D_v \leq 35$ m) in restricted urban areas, a greater attention should be paid to the roundabout disposition and to the design of its elements (circular part of the roundabout and approaches) [22]. At that, the influence of roundabout design elements must be properly recognized so as to achieve an appropriate functional efficiency, level of service, and level of traffic safety. As a whole, this is a complex design task in which various civil engineering and traffic requirements have to be taken into account.

The research conducted in [23-25] reveals that, in the scope of realization of this demanding task, the necessary vehicle movement trajectory speed, and the safe passage through the roundabout, are significantly influenced by some design elements such as the external diameter of the roundabout, the width of the circulatory roadway, and the number and the width of approach lanes. The vehicle movement path speed is the speed at which vehicles operate when entering the roundabout, when driving along the circulatory roadway, and when exiting the roundabout, in keeping with an imaginary vehicle movement path. In addition, this speed directly influences the capacity and safety of traffic at roundabouts. This is why properly designed roundabouts reduce relative vehicle speeds between conflicting traffic lanes at roundabouts, requiring vehicles to pass through the roundabout in accordance with an appropriate curved trajectory. It is therefore significant to understand the methodology of defining the influence of correlation between design elements and the vehicle path speed, and to properly anticipate the path speed for vehicles passing through the roundabout. It should be noted that an outdated and/or inadequate legislation related to transport engineering is currently in force in eastern and especially in south-eastern European states with respect to the design and dimensioning of roundabouts [26-32]. Although this legislation does provide partial recommendations, it fails to define rules/requirements when setting design speeds for roundabouts. In such cases, designers rely on their own experience, positive examples from practice, and oftentimes they apply foreign guidelines [33, 34]. Here it should be stressed that no studies relating to vehicle path speed have been conducted so far in the Republic of Croatia, neither in the sense of measurement and analysis of real driving speeds, nor in the sense of anticipating design speed of vehicles passing through roundabouts. In this respect, the applicability of American and Australian methods presented in [23, 24] will be presented in the paper through analysis of the existing small-size roundabouts ($D_v \leq 35$ m) located in the City of Zagreb, in order to correlate the vehicle path with the vehicle path speed to be used at roundabouts. The selection of these methods was influenced by latest results of studies published in documents/guidelines [4, 35] where positive European experience of leading researchers and designers is presented. These studies should be used for partial validation and verification of the method used in local conditions. Furthermore, they provide appropriate roundabout design guidelines for countries that do not have an appropriate traffic engineering legislation, or where the methodology for determining the design speed has not been defined. Nevertheless, the influence of shaping of design elements on the vehicle path speed, i.e. on the functional efficiency, level of services, and the traffic safety level, will not be studied in this paper.

## 2. Evaluation of vehicle speed at roundabouts

### 2.1. Definition of design speed

The path speed for vehicles passing through a roundabout, regardless of the size of such junction, is the major determinant of traffic capacity and safety. An appropriate speed of vehicles passing through a roundabout creates preconditions for a higher traffic capacity and for reducing the traffic accident hazard. The greater the curvature of vehicle trajectories, the lower the speed difference between the entering and circulating vehicles. This creates preconditions for reducing the number of traffic accidents that happen at the instance when vehicles either enter or exit the roundabout. Nevertheless, on circular junctions with several traffic lanes (at accesses to the roundabout, and within the roundabout zone), an increase in vehicle trajectory curvature causes an increase in the pavement friction factor, which may result in a high number of traffic accidents due to vehicle overlapping and skidding. This is why an optimum speed must be designed for every type of roundabout in order to curb down the number of traffic accidents (Table 1), [4, 22, 23]. Recommended maximum design speed values for vehicles entering the roundabout are presented in Table 1.

**Table 1. Recommended maximum design speed for vehicles entering the roundabout [4, 22, 23]**

| Roundabout type | Recommended maximum entry design speed [km/h] |
|---|---|
| Mini roundabout ($RKT_m$) | 25-30 |
| Small single lane [(1)] roundabout ($RKT_M$) | 30-35 |
| Small double-lane [(2)] roundabout ($RKT_M$) | 40 |
| Medium single lane roundabout ($RKT_{SV}$) | 40 |
| Medium double-lane roundabout ($RKT_{SV,2}$) | 50 |

The roundabout design speed is the maximum 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 [23, 36]. Design speeds calculated according to driving path radii can be presented as follows:

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

where:
V - design speed [km/h],
R - vehicle path radius [m],
e - pavement cross slope [m/m],
$f_s$ - coefficient of friction between a vehicle's tyres and the pavement [23].

The stability and safety of vehicle passing through the roundabout is defined by the adhesion between the tyre and the pavement. The better the adhesion, the safer will be the vehicle passage along the trajectory. The coefficient of friction ($f_s$) is calculated by means of the coefficient of friction for light vehicles ($f_sLV$) and heavy vehicles ($f_sHV$):

$$f_sLV = 0{,}30 - 0{,}00084 \cdot \sqrt{M_vLV} \quad (2)$$

$$f_sHV = 0{,}30 - 0{,}00084 \cdot \sqrt{M_vHV} \quad (3)$$

$$f_s = (1 - P_{HV}) \cdot f_sLV + (P_{HV} \cdot f_sHV) \quad (4)$$

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,
$P_{HV}$ - percentage of heavy vehicles [24].

### 2.2. Vehicles paths at roundabouts

In order to determine the vehicle path speed at roundabouts, it is significant to determine the maximum allowable (fastest) vehicle path speed. The path is dependent upon the proposed geometry of a roundabout. That is why it is assumed during the vehicle path determination that there is no traffic, and that there are no marked traffic lanes. The vehicle path is characterized by three movement radii: entry radius, circulatory roadway radius, and exit radius. It is assumed that the vehicle width is 2.0 metres, and that a minimum distance of 0.5 metre should be maintained from the centre of the roadway or concrete kerb and painted edge of the splitter island. Thus, the imaginary vehicle path line is 1.5 metres away from the concrete kerb and 1.0 metre away from the painted line of the splitter island [4]. 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. Consequently, the radius of reverse paths depends on the smallest radius that normally occurs when the vehicle is moving around the central island. For all approaches, it is significant to draw the fastest vehicle paths, which can be accomplished by means of appropriate AutoCad tools [4]. According to [4], the methodology for defining the fastest vehicle path speed for roundabouts 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. 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 [4].

### 2.3. Vehicle path radii and design speed

The consistency/invariability of speed must be checked in order to achieve the design speed enabling definition of the fastest vehicle paths. The speed consistency contributes to greater level of traffic safety by reducing the speed difference between the conflicting streams of vehicles. Consequently, it simplifies the task of merging of vehicles into the conflicting traffic stream, minimizing critical gaps, thus 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; (Figure 1). It should be noted that these vehicle path radii are not the same as the kerb radii [4, 24].

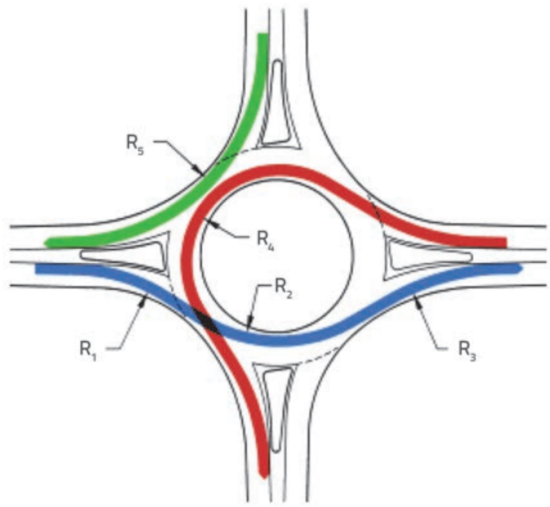


**Figure 1. Vehicle path radii [4]**

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. However, in examples when it is not possible to achieve an $R_1$ value of less than $R_2$, it is acceptable for $R_1$ to be greater than $R_2$, provided the maximum difference in speeds is less than 20 km/h. During design of mini and small roundabouts with intense pedestrian traffic, it is advisable that exit radii be equal or slightly larger than $R_2$. The radius of the conflicting left-turn movement, $R_4$, must be evaluated in order to ensure that the maximum speed difference between the entering and circulating traffic is no more than 20 km/h. The design sped for radius $R_5$ should therefore be the maximum design speed for the entire intersection and should not exceed the design speed of $R_4$ by 20 km/h, as $R_4$ has a conflicting point with $R_2$ [4, 24].

## 3. Research methods

The analysis of the vehicle path and speed, as conducted in this paper, is a significant extension of the research results presented at CETRA 2012 [37]. In the light of this fact, and considering the qualitative and quantitative traffic data base that has been collected [17, 18], this research resulted in the conduct of a more detailed analysis of the vehicle path speed at roundabouts. The research was conducted on four selected roundabouts situated in the centre and at periphery of the City of Zagreb. According to their type, these are single-lane roundabouts, with three or four single-lane approaches. Their basic design elements are given in Table 2. The disposition of these roundabouts, as given in Table 2, is the result of research conducted in [17, 18]. Here, mini roundabouts (Petrova – Jordanovac and Voćarska – Bijenička), although characterised by smaller external diameter of $D_v$ = 26 m, belong to the group of small roundabouts ($RKT_M$), because of their role and function in the transport network (primarily with regard to the structure and properties of traffic streams), and because of properties of the corresponding design elements. For the mentioned reasons the Radnička – Petruševec 1 roundabout also belongs to the group of small roundabouts ($RKT_M$) regardless of the fact that its external diameter is greater $D_v$ = 40 m. Considering the above and according to [17, 18] the analyzed roundabouts are taken to be representative of their respective groups, i.e. they represent the group of urban mini and small roundabouts of the City of Zagreb. The analysis of the vehicle path speed for the selected roundabouts was conducted at all approaches under conditions of normal traffic flow. Thus 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 $R_3$) (Figure 2). However, path speeds for radii (*R4* and *R5*), i.e. for the right-turn movements ($V_4$) and left-turn movements (*V5*) through the roundabout, were not measured/analysed because of roundabout disposition in the transport network of the City, because of movement of vehicle streams during the conduct of "in situ" measurements, due to the need to conduct measurements during the morning peak traffic on the same day, and because of funding available for passenger car use in the conduct of measurements. It should be noted that the Voćarska – Bijenička roundabout had speed bumps at the approach 2 (Mesićeva) at 30 m from the roundabout, and at approach 3 (Voćarska) at 50 m from the roundabout, during the vehicle path speed measurements. During realisation of the study [17], speed bumps were present at all approaches immediately before the entry/exit from the roundabout at the Radnička – Petruševec 1 roundabout. However, some speed bumps were not present at the approach 2 (Petruševec 1) and approach 3 (Radnička cesta – South) during the path speed measurements.

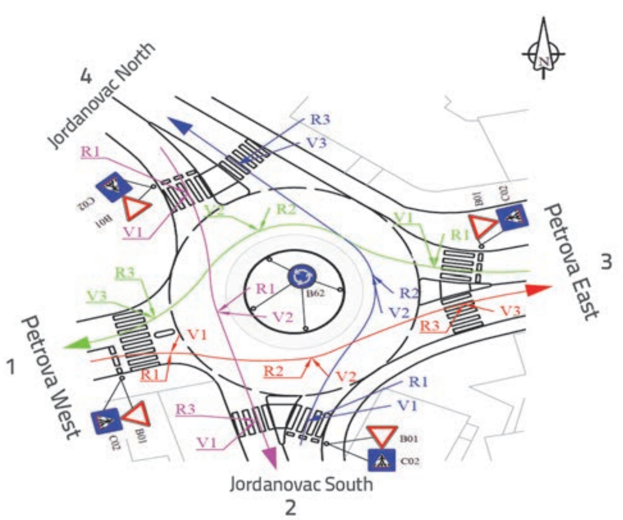


**Figure 2. Example of vehicle paths analysed at the Petrova – Jordanovac roundabout**

Table 2. Design elements at selected roundabouts [17, 18]

| | | | Circulatory roadway (c.r.) | | | Approaches (ap) | | |
|---|---|---|---|---|---|---|---|---|
| No. | Designation | Name of intersection / roadway | $D_v$ external diameter [m] | $D_u$ internal diameter [m] | B circulatory roadway width [m] | No [-] | $b_u$ Width at entry [m] | Number of traffic lanes [c.r./ap] |
| | a) m - Mini $RKT_m$ ($D_v$ ≤ 26 m ) | | | | | | | |
| 1. | $RKT_m$ | Sveti Duh - Kuniščak | 20,0 | 6,0 | 7,0 | 3 | 3,5/3,6 | 1/1 |
| | b) M - Small $RKT_M$ (22 m ≤ $D_v$ ≤ 35 m) | | | | | | | |
| 2. | $RKT_M$ | Petrova - Jordanovac | 25,0 | 12,0 | 6,5 | 4 | 3,5/4,5 | 1/1 |
| 3. | $RKT_M$ | Voćarska - Bijenička | 22,0 | 13,0 | 4,5 | 4 | 4,0/4,0 | 1/1 |
| 4. | $RKT_M$ | Radnička cesta - Petruševec 1. | 40,0 | 28,0 | 6,0 | 4 | 3,0/3,5 | 1/1 |

As the analysed roundabouts are situated in the vicinity of primary school buildings, motor vehicle speed limits are restricted to 40 km/h both at roundabouts and at their approaches. Vehicle speeds at approaches only were measured in cooperation with the Ministry of the Interior on 7 July 2008 (Tuesday) during the morning peak hour traffic, at 5, 10 and 15 min intervals. Weather conditions were appropriate: it was mostly sunny and partly cloudy which ensured good visibility at all roundabouts, with dry pavement conditions. The MULTANOVA 6F device was used because of the specific nature of these roundabouts, speed information required, and technical characteristics of the device. A civilian police car and police officer in plain clothes were use during the measurement so as to eliminate the influence of police presence on the behaviour of drivers, i.e. on the vehicle driving speed [18, 19]. The data on the operating speed at approaches, on the circulatory roadway, and at the exit from roundabout, were collected in the scope of a more extensive study. This study was conducted on 15 September 2011 (Thursday) during the morning peak traffic in 15-minute intervals using the GPS (Global Positioning System) device installed in a passenger car. Favourable weather conditions enabled good visibility and dry pavement at all roundabouts and their approaches.

## 4. Analysis of research results

The information on the measured average vehicle path radii (Figure 2), real slope of the pavement, percentage of heavy vehicles, and the corresponding coefficients of friction calculated according to the reference traffic load [18] are presented in Table 3 on the sample of 50 measurements using AutoCad. In addition, the data on the measured average path speeds at roundabouts are also presented for the sample consisting of 50 measurements. Formulas [1-4] were used to calculate design speed for negotiating a roundabout, while differences between the measured and calculated design speeds are presented and analysed below.

In Table 3, 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 [38]. To enable clearer comparison of results, path speeds for roundabouts are presented in the figures 3 through 6.

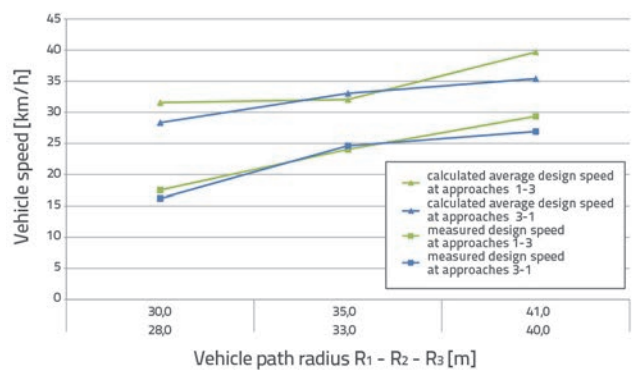


Figure 3. Relationship between the design and measured speed values at the Sv. Duh – Kuniščak roundabout

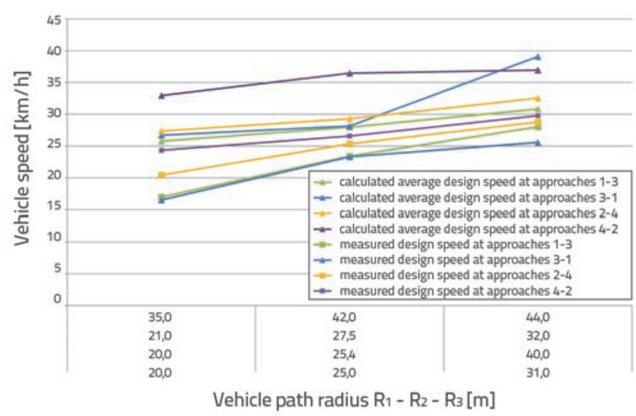


Figure 4. Relationship between the design and measured speed values at the Petrova – Jordanovac roundabout

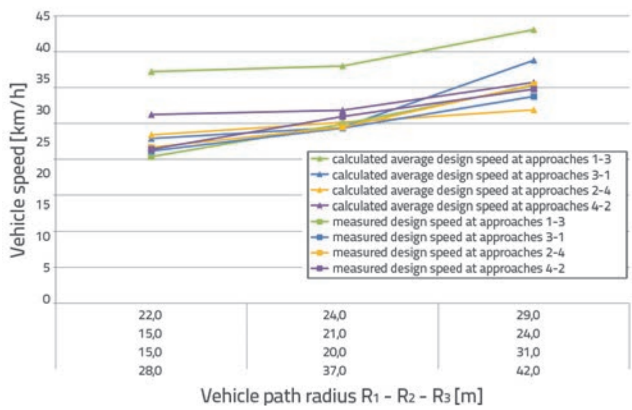


Figure 5. Relationship between the design and measured speed values at the Voćarska - Bijenička roundabout

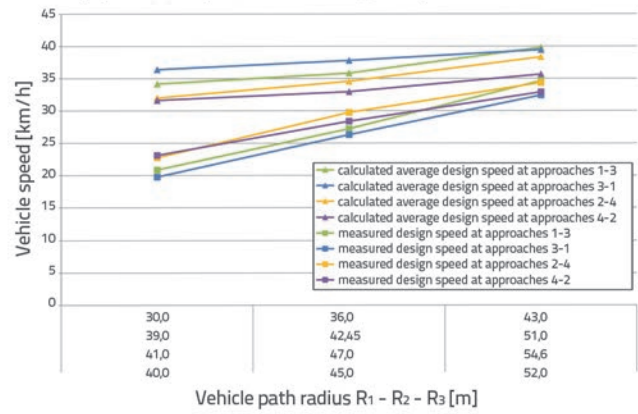


Figure 6. Relationship between the design and measured speed values at the Radnička – Petruševec 1 roundabout

The comparison between really measured average speed values and calculated average design speed values for personal-vehicle paths is shown in Figures 3 through 6. 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. Study results also show that calculated average design-speed values are generally lower than the intersection speed limit (40 km/h), and lower or slightly higher than the maximum recommended speed (35 km/h) according to Table 1. All average speeds obtained by measurement are lower than the recommended maximum speed (35 km/h), and are hence also lower than the speed limit. Deviations registered between the measured average speeds and the calculated average design speeds are presented in Table 3, and are analysed below in more detail.

Table 3. Calculated average design speed and average vehicle speed measured at selected roundabouts a) Input data

| Name of roundabout / roadway | Average path radii (sample N = 50) | | | Slope | | | |
|---|---|---|---|---|---|---|---|
| | $R_1$ [m] | $R_2$ [m] | $R_3$ [m] | e [m/m] | | | $P_{HV}$ |
| | | | | Approach | Circ. roadway | Approach | [dec] |
| **Sveti Duh - Kunišćak** | | | | **$R_1$** | **$R_2$** | **$R_3$** | |
| Sv. Duh South - Approach 1 | 28,0 | 33,0 | 40,0 | 0,02 | -0,015 | 0,05 | 0,148 |
| Sv. Duh North - Approach 3 | 30,0 | 35,0 | 41,0 | -0,05 | -0,015 | -0,02 | 0,141 |
| **Petrova - Jordanovac** | | | | | | | |
| Petrova West - Approach 1 | 20,0 | 25,0 | 31,0 | 0,00 | -0,015 | -0,02 | 0,102 |
| Jordanovac South - Approach 2 | 20,0 | 25,4 | 40,0 | 0,02 | -0,015 | 0,04 | 0,115 |
| Petrova East - Approach 3 | 21,0 | 27,5 | 32,0 | 0,02 | -0,015 | 0,00 | 0,115 |
| Jordanovac North - Approach 4 | 35,0 | 42,0 | 44,0 | -0,04 | -0,015 | -0,02 | 0,052 |
| **Voćarska - Bijenička** | | | | | | | |
| N. Grškovića - Approach 1 | 28,0 | 37,0 | 42,0 | 0,05 | -0,03 | 0,01 | 0,117 |
| M. Mesića - Approach 2 | 15,0 | 20,0 | 31,0 | 0,01 | -0,03 | 0,03 | 0,061 |
| Voćarska - Approach 3 | 15,0 | 21,0 | 24,0 | 0,02 | -0,03 | -0,03 | 0,025 |
| Bijenička - Approach 4 | 22,0 | 24,0 | 29,0 | -0,02 | -0,03 | -0,01 | 0,043 |
| **Radnička cesta - Petruševec 1.** | | | | | | | |
| Radnička North - Approach 1 | 40,0 | 45,0 | 52,0 | 0,00 | -0,005 | 0,01 | 0,538 |
| Petruševec 1. - Approach 2 | 41,0 | 47,0 | 54,6 | 0,01 | -0,005 | -0,02 | 0,331 |
| Radnička South - Approach 3 | 39,0 | 42,4 | 51,0 | -0,02 | -0,005 | 0,00 | 0,578 |
| Žitnjak - Approach 4 | 30,0 | 36,0 | 43,0 | 0,02 | -0,005 | -0,01 | 0,354 |

Legend: $P_{HV}$ – percentage of heavy vehicles in traffic stream [decimal], $M_{vLV}$ – average weight of light vehicles (1400 – 1500) [kg], MvHV – average weight of heavy vehicles (11000 – 15000) [kg]

Table 3. b) Comparison of calculated and measured design speed values

| Coefficient of friction | | | Direction of travel | Calculated average design speed | | | Calculated average speed | | | Deviation from design speed | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $f_{sLV}$ | $f_{sHV}$ | $f_s$ | Approach | $V_1$ | $V_2$ | $V_3$ | $V_1$ | $V_2$ | $V_3$ | $V_1$ | $V_2$ | $V_3$ |
| | | | | [km/h] | | | [km/h] | | | [%] | | |
| **Sveti Duh - Kuniščak** | | | | | | | | | | | | |
| 0,27 | 0,21 | 0,26 | 1-3 | 31,5 | 32,0 | 39,6 | 17,52 | 24,04 | 29,34 | -44,49 | -25,00 | -26,09 |
| 0,27 | 0,21 | 0,26 | 3-1 | 28,3 | 33,0 | 35,3 | 16,20 | 24,60 | 26,90 | -42,81 | -25,55 | -24,00 |
| **Petrova - Jordanovac** | | | | | | | | | | | | |
| 0,27 | 0,21 | 0,26 | 1-3 | 25,7 | 27,9 | 30,8 | 16,96 | 23,40 | 28,02 | -34,18 | -16,34 | -9,11 |
| 0,27 | 0,21 | 0,26 | 3-1 | 26,7 | 28,1 | 39,0 | 16,52 | 23,31 | 25,56 | -38,12 | -17,19 | -34,59 |
| 0,27 | 0,21 | 0,26 | 2-4 | 27,3 | 29,2 | 32,5 | 20,42 | 25,34 | 28,78 | -25,36 | -13,49 | -11,57 |
| 0,27 | 0,21 | 0,26 | 4-2 | 32,9 | 36,4 | 36,9 | 24,34 | 26,56 | 29,78 | -22,93 | -27,17 | -19,41 |
| **Voćarska - Bijenička** | | | | | | | | | | | | |
| 0,27 | 0,21 | 0,26 | 1-3 | 32,2 | 33,0 | 38,0 | 20,36 | 24,90 | 30,24 | -38,87 | -24,57 | -20,60 |
| 0,27 | 0,21 | 0,27 | 3-1 | 22,8 | 24,4 | 33,8 | 21,15 | 24,34 | 28,76 | -7,62 | -0,40 | -14,90 |
| 0,27 | 0,21 | 0,27 | 2-4 | 23,3 | 25,1 | 26,8 | 21,66 | 24,48 | 30,40 | -7,39 | -2,66 | 13,07 |
| 0,27 | 0,21 | 0,27 | 4-2 | 26,2 | 26,8 | 30,7 | 21,38 | 25,96 | 29,78 | -18,48 | -3,24 | -3,05 |
| **Radnička cesta - Petruševec 1.** | | | | | | | | | | | | |
| 0,27 | 0,20 | 0,23 | 1-3 | 34,1 | 35,8 | 39,7 | 20,86 | 27,22 | 34,64 | -38,92 | -24,03 | -12,92 |
| 0,27 | 0,20 | 0,24 | 3-1 | 36,3 | 37,7 | 39,4 | 19,76 | 26,30 | 32,40 | -45,69 | -30,40 | -17,83 |
| 0,27 | 0,20 | 0,23 | 2-4 | 32,0 | 34,5 | 38,3 | 22,74 | 29,74 | 34,34 | -28,95 | -13,95 | -10,41 |
| 0,27 | 0,20 | 0,24 | 4-2 | 31,6 | 32,9 | 35,6 | 23,12 | 28,38 | 32,88 | -26,90 | -13,89 | -7,74 |

Legend: $f_{sLV}$ – coefficient of friction for light vehicles, $f_{sHV}$ – coefficient of friction for heavy vehicles, $f_s$ – coefficient of friction for vehicles

An average vehicle speed measured at the Sveti Duh – Kuniščak roundabout on the path from approach 1 (Sveti Duh – South) to approach 3 (Sveti Duh – North) was lower by 44.49 % that the calculated average design speed. An average vehicle speed measured at the Petrova - Jordanovac roundabout on the path from approach 3 (Petrova - East) to approach 1 (Petrova - West) was lower by 38.72 % that the calculated average design speed. An average vehicle speed measured at the Voćarska - Bijenička roundabout on the path from approach 1 (N. Grškovića) to approach 3 (Voćarska) was lower by 38.87 % that the calculated average design speed, while for the path from approach 2 (Mesićeva) to approach 4 (Bijenička) it was greater by 13.07 % that the calculated average design speed. An average vehicle speed measured at the Radnička – Petruševec 1 roundabout on the path from approach 3 (Radnička – South) to approach 1 (Radnička – North) was lower by 45.69 % that the calculated average design speed.

Significant deviations of average measured speeds from average calculated speeds can be explained in the following way. The Sveti 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 (Sveti Duh – South) to approach 2 (Kuniščak), which is generated by the Zagreb brewery complex located 500 m to the east of the roundabout, the intersection was realized with a traversable central island. In addition, as a primary school is located to the east of the intersection between the approaches 1 and 3 (Sveti Duh – South and North), and in order to calm down the traffic, the speed limit at approaches was set to 40 km/h. Taking all this into consideration, as well as the information about the percentage of heavy vehicles in the total traffic (14.8 %), we can easily explain the -44.49 % 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 at 4 %) while other approaches and the circulatory roadway are not characterized by greater terrain limitations. However, due to restricted space, shaping elements are smaller and this greatly affects traffic operated at the roundabout and in the roundabout zone. As a primary school is located to the east of the intersection between approaches 2 and 3 (Jordanovac – South and Petrova – East), and in order to calm down the traffic, the speed at these approaches was limited to 40 km/h. The above information, and the data about the percentage of heavy vehicles in the total traffic (11.5 %, including public transport vehicles), provide proper explanation for the -38.12 % 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 intersection is realised at the grade of 3 %, while the grade at the approach 1 (N. Grškovića) amounts to 5 %. Due to restricted space, shaping elements are smaller and this greatly affects the traffic operated at the roundabout and in the roundabout zone. As a primary school is located to the south of the intersection, while the Faculty of Science, Institute for Physics, and the Ruđer Bošković Institute, are located some 300 m to the north of the interchange, the speed at these approaches was limited to 40 km/h to calm down the traffic. 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 (11.5 %). The above information suitably explains the -38.87 % 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. As a primary school is located to the west of the intersection between approaches 2 and 3 (Petruševec 1 and Radnička - South), and in order to calm down the traffic, the speed at these approaches was limited to 40 km/h] The above information, and the data about the percentage of heavy vehicles in the total traffic (57.8 %, including public transport vehicles), provide proper explanation for the -45.69 % deviation of the calculated speed from the measured speed.

## 5. Conclusion

The design of roundabouts in urban areas is a highly demanding task. When selecting a microlocation and the method that will be used for solving the roundabout, it is significant to make a proper analysis of each individual case, and to always look for an optimum solution, because a poorly defined and designed roundabout, especially in restricted urban zones with predefined traffic streams, will greatly reduce the efficiency and safety of traffic for all participants. When designing and dimensioning small roundabouts ($D_v \leq 35$ m), a special attention must be paid to the design of individual roundabout elements (external diameter and internal diameter, width of circulatory roadway, and width of approach lanes) so as to comply with the vehicle path speed needed for proper negotiation of the roundabout. It is therefore necessary to conceive a method for defining the influence of correlation between the design elements and path speed, and to anticipate the operating speed that is needed for safe negotiation of the roundabout geometry. This is needed for defining an appropriate functional efficiency, level of service, and level of traffic safety, both at the new roundabout modelling phase, and during analysis of existing roundabouts.

According to results obtained during the study of vehicle path speeds under condition of normal traffic at four single-lane roundabouts (number of approaches = 3/4; circulatory roadway/approach = 1/1) located in the City of Zagreb, it can be concluded that the basic roundabout design requirement of $R_1, R_2 < R_3$, according to [4, 24], has been met.

According to general analysis of results obtained for the intersections under study, deviations between the design speeds and measured speeds vary from -45.69 % to +13.07 %. These deviations result from: methods used in the analysis of design speed, specific features of intersections and their location within the municipal transport network, roundabout area design elements, roundabout equipment and devices, various axle loads and properties of vehicles, traffic stream properties and structure, and the behaviour and level of training of drivers as registered during the study. The results of this research can also be used for partial validation and verification in local conditions.

A particular emphasis is placed on the fact that the developed "in situ" method [17], and the vehicle path speed results, should be used as foundation for further systematic and extensive research of the causality between the speed and vehicle path. It would also be necessary to investigate other design elements and influencing factors in order to define an appropriate functional efficiency, level of service, and level of traffic safety at roundabouts, especially in the territory of the Republic of Croatia. Further study would involve a greater number of similar roundabouts with greater number of samples, and the vehicle path speed for left and right turns at roundabouts. It would also be necessary to study the structure and behaviour of vehicles during measurement, and to analyse their influence on the vehicle speed at roundabouts. In addition, it would be useful to calibrate the method used to local conditions, and to study the vehicle path speed according to the method proposed in [39]. Final conclusions will be possible only after comparison of the research results obtained, and after comparison with the actual number, type and causes of traffic accidents at the roundabouts under study.

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