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ANALYSIS OF CAPACITY OF ROUNDABOUTS IN THE CITY OF ZAGREB ACCORDING TO HCM C–2006 AND NING WU METHODS

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Subject review

There are various methods in the world for the calculation of the roundabout capacities. Some methods are very specific and implemented in different countries for different types of roundabouts. The paper presents two advanced scientific methods for the calculation of roundabout capacity – method HCM C-2006 and the method according to Ning Wu. Using the methods and according to the actual field measurements of traffic flows and driving conditions, the intersection capacity and the indicators of effectiveness (congestion level, delay control and vehicle queuing length) were analyzed. The analysis included fifteen roundabouts that are located in urban and suburban areas of the City of Zagreb. Results should also serve as basis for further systematic research of methodology for calculating the capacity of roundabouts in Croatia but also for possible selection of specific foreign method with calibration of certain coefficients according to local conditions of traffic flows.

Keywords: *capacity, capacity calculation methods, delay control, roundabout, vehicle queuing length*

Analiza kapaciteta kružnih raskrižja u gradu Zagrebu metodama HCM C–2006 i Ning Wu

Pregledni članak

Za proračun kapaciteta kružnih raskrižja u svijetu postoje razne metode. Pojedine metode su vrlo specifične i primjenjuju se u različitim zemljama za različite vrste kružnih raskrižja. U radu su prikazane dvije suvremene znanstvene metode za proračun kapaciteta kružnih raskrižja - metoda HCM C-2006 i metoda po Ning Wu-u. Uz pomoć metoda se prema stvarnim terenskim mjerenjima odvijanja prometnih tokova i uvjetima vožnje, analizirani su kapacitet raskrižja i pokazatelji efektivnosti (stupanj zasićenja, kontrola kašnjenja i duljina nakupljanja vozila). Analizom je obuhvaćeno 15 kružnih raskrižja koja se nalaze u urbanim i izvanurbanim područjima grada Zagreba. Rezultati bi trebali poslužiti kao osnova za daljnja sustavna istraživanja metodologije proračunavanja kapaciteta kružnih raskrižja na području Republike Hrvatske, ali i za mogući odabir određene inozemne metode uz potrebnu kalibraciju pojedinih koeficijenata određenih prema lokalnim uvjetima odvijanja prometnih tokova.

Ključne riječi: *duljina nakupljanja vozila, kapacitet, kontrola kašnjenja, kružno raskrižje, metode proračuna kapaciteta*

1 Introduction

Over the last twenty years the roundabouts have been implemented as the most common form of intersections to calm the traffic on the roads of the European countries. The advantages that have affected greater popularity of construction of this type of intersections, compared to the classical at-grade intersections are reflected in improved throughput capacity and traffic safety. For the modelling of the roundabout capacity a large number of models from different countries have been developed, and the very model selection requires good field measurements in order to collect the necessary data [1]. The paper will present the comparative analysis of application of these models to actual data collected through measurements. The necessary data have been collected at fifteen roundabouts in the City of Zagreb with a single-lane entry/exit and a circular roadway. A more detailed analysis of traffic flows at the intersection means the assessment of capacity and adaptability of the observed solution to the needs of various traffic modes and their users. The indicators that are measurable and considered in the qualitative assessment of intersections include: capacity reserve, congestion level, time losses and length of vehicle queues at the intersection entry.

2 Historical development of methods for calculating roundabout capacity

Based on the empirical and regression methods a large number of methods for the calculation of capacity according to the data collected by the measurements in actual traffic conditions have been developed. The development of methods has begun by the implementation of the linear regression based on the theoretical assumptions set by Kimber (1980). Stuwe (1992) developed a procedure which introduced the geometrical intersection parameters in the calculation, but the model did not yield reliable results [2]. Long-term monitoring and measuring of data at roundabouts in Germany enabled the development of new methods, which are based on exponential and linear regression developed by Brilon and Bondzio (1996). The second development of methods was based on exponential regression based on marginal time sequence intervals developed by Troutbeck (1998) and Wu (1997) [3]. In the USA, according to Highway Capacity Manual (HCM) C−2006, the third method was developed, based on the critical time gaps and vehicle headways that are in the circular traffic flow and vehicles that are at the very entry of the circular lane, taking into consideration the behaviour of the participants, i.e. drivers [4]. The latest findings of recent systematic studies (2007÷2010), which are based on previously mentioned ones, have been published in HCM 2010. So, the way to determine the level of service (LOS) for roundabouts is defined, calculations to determine the flow rate of each entry lane and conflicting circulatory roadway and exit flow rates for bypass lanes are presented. Also, the values for the calibration of peak hour factor (PHF) and the conversion of passenger car units (PCU) for heavy vehicles are also defined. Calculation of capacity for each entry lane is analyzed separately and the method is complemented by calculations of the control delay (for each approach and entire intersection) and 95 % queue length. However, for the calculation of roundabout capacity the paper will not apply the findings from the HCM 2010 because calculations are not calibrated for metric units [5].

3
Universal method according to Ning Wu and method according to HCM C–2006

The roundabout capacity calculation according to Ning Wu is based on the serial serving of vehicles and the number of lanes at entry into the roundabout and on the circular roadway. The method according to HCM C–2006 is based on the critical time gaps and vehicle headways at the entry into the circular traffic flow and the vehicles in the circular traffic flow.

3.1
Universal method according to Ning Wu

In 1997 Ning Wu developed a universal formula for which it is characteristic that it takes into consideration the number of lanes, both in the main traffic stream (circular roadway) and at the entry. The curve obtained by the formula developed by Wu has the advantage that in its closed theoretical concept based on the queuing theory, it describes the conditions at the intersection, which can actually be observed as a serial serving channel.

$$q_{\mathrm{u,max}} = \left[1 - \frac{\tau \cdot q_{\mathrm{k}}}{n_{\mathrm{k}}}\right]^{n_k} \cdot \frac{n_{\mathrm{u}}}{t_{\mathrm{sl}}} \cdot \exp[-q_{\mathrm{k}} \cdot (t_0 - \tau)], \quad (1)$$

where:
$q_{\mathrm{u,max}}$ – roundabout entry capacity, PCU/h
q_{k} – intensity of vehicles in circular flow, PCU/h
n_{u} – number of lanes at entry,
n_{k} – number of lanes in circular flow.

$$t_0 = t_g - \frac{t_{\mathrm{sl}}}{2}, \quad (2)$$

t_{g} – marginal time gap in vehicle flow, s
t_{sl} – time gap between vehicles in a sequence, s
τ – minimal time gap between vehicles in roundabout, s [3, 6].

The values of parameters which appear in the universal formula such as t_{q}, t_{sl} and τ can be taken over from the intersection with a single lane. However, for the calculation Wu took: $t_{\mathrm{g}} = 4{,}12$ s; $t_{\mathrm{sl}} = 2{,}88$ s and $\tau = 2{,}10$ s [3].

These initial values were used to determine the minimal time gap in the circular stream $\tau = 2{,}10$ s which corresponds to actual conditions of vehicle traffic in the circular flow. Fig. 1 shows the results obtained by the linear regression equation and with the new Wu equation. Unlike the linear method, the Ning-Wu method yields better results for the roundabouts which have two or more traffic lanes in the circular roadway.

The implementation of the universal formula for roundabout capacity determination shows good matching with the data recorded in 1-minute interval. Fig. 1 shows that this formula corresponds quite well with the linear regression line for the intersections with a single lane each (1/1). In intersections with several lanes the new formula shows undoubtedly better results. It should be emphasised here that the observed roundabout capacity is the value which one entry may maximally accept to serve the total number of vehicles during one hour. These values can be expected in the construction of new roundabouts which means that they may be basic data in planning. Care should be taken that in case of larger capacities longer queues of vehicles may be expected. Therefore, for the practical capacity 100 PCU/h have to be subtracted from the obtained values [3, 6].

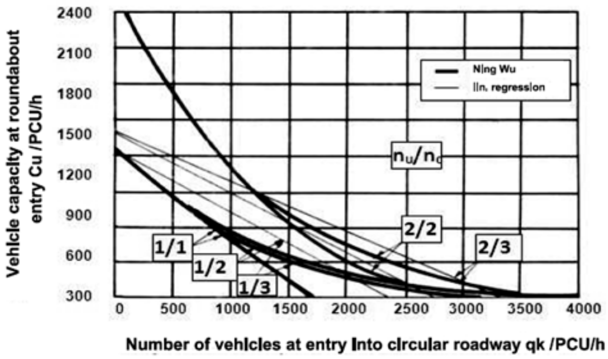

Figure 1 Comparing curves acc. to Wu's equation and linear regression equation [3, 6]

3.2
Method according to HCM C–2006

The method according to HCM C–2006 is based on the drivers' behaviour in critical gaps and headways of vehicles that enter and the vehicles that exit from the circular traffic flow taking into consideration three traffic flows: circular roadway traffic flow, traffic flow of vehicles exiting the roundabout and traffic flow of vehicles entering the circular flow. Fig. 2 shows a four-leg intersection type (1,1) and its respective flows. The conflicting flow for each approach is precisely the flow of the circular roadway which results from individual approach flows. Thus, for the throughput flows of the conflicting flows the following holds:

$$\begin{aligned} v_{\mathrm{C},1,2,3} &= v_4 + v_{10} + v_{11}, \\ v_{\mathrm{C},4,5,6} &= v_1 + v_7 + v_8, \\ v_{\mathrm{C},7,8,9} &= v_1 + v_2 + v_{10}, \\ v_{\mathrm{C},10,11,12} &= v_4 + v_5 + v_7. \end{aligned} \quad (3)$$

Table 1 Conversion into passenger car equivalents [3]

Vehicle type	PCU/h
Passenger car	1,0
Heavy vehicle	2,0

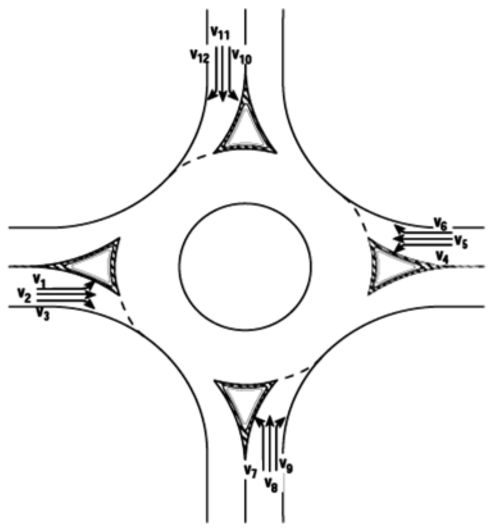

Figure 2 Roundabout flow designations [4]

It should be noted that the roundabouts are often used also for U-turns, so that U-turn flows should be included in the conflicting flows.

The through-flows are expressed in passenger car equivalents per hour as well as in the previous methods, so that every vehicle has a certain value of equivalent units per hour (see Tab. 1). Thus, the capacity of every approach depends on the respective conflicting flow. The formula was obtained based on the survey of roundabouts in the USA in 2003 and it is:

$$C_X = A \cdot \exp(-B \cdot v_{C,X}), \quad (4)$$

where:
C_X – approach throughoutput capacity, PCU/h
$v_{C,X}$ – conflicting traffic flow for manoeuvre x, PCU/h [4].

Values A and B are the coefficients that represent critical time gaps and the headway. The following holds:

$$A = \frac{3600}{t_f}, \quad (5)$$

$$B = \frac{t_c - 0,5 \cdot t_f}{3600}. \quad (6)$$

The headway values and the critical time gaps have been obtained empirically and are presented in Tab. 2.

Table 2 Critical gap and headway interval [7]

Seconds /s	t_c	t_f
Minimal	4,2	2,6
Average	5,1	3,2
Maximal	5,9	4,3

For certain types of intersections certain values t_c and t_f, are taken so that expression (3) will take the following form:

– for a single lane in circular roadway:

$$C_X = 1130 \cdot \exp(-0,001 \cdot v_{C,X}), \quad (7)$$

– for two lanes in circular roadway:

$$C_X = 1130 \cdot \exp(-0,0007 \cdot v_{C,X}). \quad (8)$$

It should be mentioned that the throughput capacity is affected also by time of getting the drivers accustomed, which changes the values t_c and t_f. Thus the throughput capacity becomes higher over time. Higher throughput capacity has been noted in the areas in which there are more roundabouts than in places with few roundabouts [4, 7].

4 Indicators of roundabout effectiveness

In order to get the opinion about the effectiveness of roundabouts and other types of classical intersections, there are several efficiency parameters which make it possible to bring the final judgement about the intersection effectiveness. The parameters that are essential for the presentation of the effectiveness are: the vehicle queue length Q_{95}, vehicle delay control d, degree of saturation flow X and level of service (A, B, C, D, E, F - LOS).

4.1 Delay control

Delay is the standard parameter which is used to measure the effectiveness of the circular and classical intersections. Delay control is the necessary time spent by the driver in waiting for an acceptable moment of merging the circular traffic flows, not endangering himself and other traffic participants by performing the activity of merging into the circular traffic flow. The formula for the presentation of delay control is:

$$d = \frac{3600}{c_x} + 900 \cdot T \cdot \left[\frac{q_u}{c_x} - 1 + \sqrt{\left(\frac{q_u}{c_x} - 1\right)^2 + \frac{\left(\frac{3600}{c_x}\right) \cdot \left(\frac{q_u}{c_x}\right)}{450 \cdot T}} \right], \quad (9)$$

where:
d – average delay control, s/veh
q_u – number of vehicles at the entry into the circular lane, PCU/h
c_x – approach capacity, PCU/h
T – analyzed time period (for a whole hour T = 1, for 15 minutes T = 0,25) [4].

The delay control increases exponentially as the capacity of entry into the circular roadway increases. Small changes in the capacity have high influence on huge delays of vehicle merging. Special attention should be paid to the capacity of vehicles entering the circular roadway and the degree of saturation flow ($X \geq 1,0$) since on the contrary the delay control increases exponentially regarding maximal delays. The degree of saturation flow X is obtained from the ratio of the load and capacity of approaches [4].

4.2 Queue estimates of vehicle accumulation

Queue estimate of vehicle accumulation represents a significant design parameter of the roundabout regarding its geometrical size. It is defined as the queue length of vehicles waiting to enter the circular roadway. In designing the roundabouts care should be taken that in 95 % of cases the vehicle queuing length in front of the entry into the circular lane is not exceeded. The formula for 95 % accumulation is:

$$Q_{95} = 900 \cdot T \cdot \left[\frac{q_u}{c_x} - 1 + \sqrt{\left(1 - \frac{q_u}{c_x}\right)^2 + \frac{\left(\frac{3600}{c_x}\right) \cdot \left(\frac{q_u}{c_x}\right)}{150 \cdot T}} \right] \cdot \left(\frac{c_x}{3600}\right), \quad (10)$$

where:
Q_{95} – 95 % accumulation of vehicles, veh
q_u – number of vehicles entering the circular roadway, PCU/h
c_x – approach capacity, PCU/h
T – analyzed time period (for the entire hour T = 1, for 15 minutes T = 0,25) [4].

Since the degree of saturation flow should not exceed 1,0 during intersection design care should be taken to take valid lengths of vehicle accumulation.

Table 3 Determination of level of service based on average delay control (s/veh) [4]

Level of service	Average delay control, s/veh
A	0-10
B	>10-15
C	>15-25
D	>25-35
E	>35-50
F	>50

4.3 Level of service (LOS)

The level of service for roundabouts is determined by the average delay control and defined for each traffic lane separately. Tab. 3 shows the criteria of the level of service. In designing a roundabout it is necessary to pay attention that the level of service should be between A-D i.e. neither too low, nor too high, but rather within the limits of optimality. Since the level of service depends on the average delay control, it is necessary to pay great attention to the planning of the construction of the future roundabouts [4].

5 Analysis of roundabout capacities in the City of Zagreb

Previous researches of capacity for the concerned roundabouts [8, 9], which represent certain scientific and empirical basis, have considerably contributed to enforcement and following analysis of research results. For the analysis and estimate of the capacities of roundabouts in the City of Zagreb, fifteen roundabouts have been selected in the central and peripheral part of the city. Measurement of traffic load was conducted on the basis of video surveillance for one hour (morning or afternoon peak hours) during October and November 2008, and for roundabout "Bukovčev trg" in September 2009 (built 2008) [10, 11].

Based on these results, we have been able to determine the values of traffic intensity on entry and in circular flow. The design parameters of the selected intersections are presented in Tab. 4, whereas Tab. 5 presents all the traffic parameters of the selected roundabouts with the traffic capacity calculated according to the mentioned methods (HCM C–2006 method and method according to Ning Wu), as well as the effectiveness indicators. For critical gap and headway interval average values from Tab. 2 were used.

5.1 Analysis and comparison of research results

By implementing the mentioned models for the calculation of capacities at 15 roundabouts, the following results have been obtained which are presented in Figs. 3, 4, 5 and 6. It should be mentioned that the used methods do not use the impact of pedestrian and cycling traffic, which in urban environments play a significant role. The figures lead to the conclusion that the results obtained by the measurements are within the certain limits in relation to foreign results. This has confirmed the thesis that foreign methods may be used in Croatia to calculate the capacity of roundabouts with a single lane at entry/exit and in the circular roadway. However, out of 15 roundabouts only four deviate from the foreign results, i.e. fail to be within the certain limits.

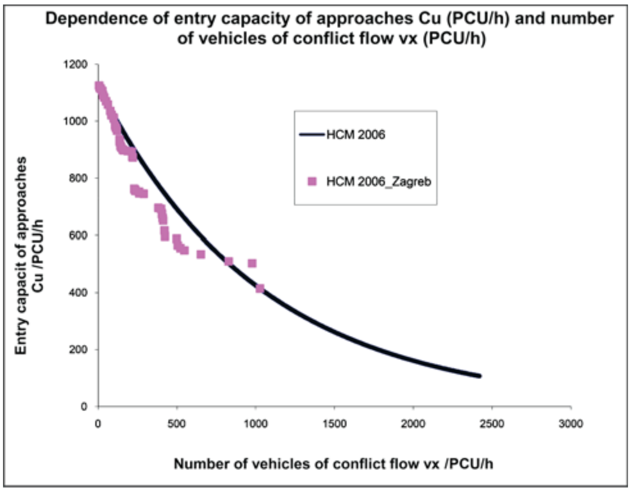

Figure 3 Dependence of entry capacity of approaches and number of vehicles of conflict flow

Table 4 Design parameters of the selected roundabouts [10, 11]

Ord. No.	Symbol	Intersection name	Circular roadway				Approaches			Remark
			D_v /m	D_u /m	b_k / m	q /±%	n / -	b_p / m	entry/ exit /m	n-lanes (circ.ro./app.)
	a) m -	**Mini RKT ($D_v \le 26$ m)**								
01.	RKTm	Sv. Duh - Kunišćak	20	6	7	-1,5	3	7,1	3,5/3,6	1
02.	RKTm	Bukovčev trg	20	8	6	-2	4	6,25	3,0/3,25	1
03.	RKTm	Ljudevita Posavskog - Zavrtnica A	19	6	6,5	-	3	7	3,5/3,5	1/1 (2×RKT)
04.	RKTm	Ljudevita Posavskog - Zavrtnica B	19	6	6,5	-	3	7	3,5/3,5	1/1 (2×RKT)
	(m) M -	**Mini intersections as small ones**								
05.	RKT(m) M	Petretićev trg	22,2	5,7	8,5	-1,5	3	8,5	4,5/4,0	1
06.	RKT(m) M	Bundek - S.R. Njemačke	26	10	5,5	-1,5	3	7,25	4,0/3,25	1
07.	RKT(m) M	Šestinski vijenac - Pantovčak	25	9	8	-4	3	9	4,5/4,5	1
08.	RKT(m) M	Vinogradska - Podolje	10	4	3	-	4	7	3,5/3,5	1
	b) M -	**Small RKT (22 m $\le D_v \le$ 35 m)**								
09.	RKTM	Petrova - Jordanovac	25	12	6,5	-1,5	4	8	3,5/4,5	1
10.	RKTM	Lavoslava Ružičke - Ivana Lucića	32	21	5,5	-1,5	3	8	4,0/4,0	1
11.	RKTM	Petrova - Bukovačka	30	10	7,5	-2	4	7	3,0/4,0	1
12.	RKTM	Bukovačka - Barutanski j.	30	15	6	-3	3	7,5	3,5/4,0	1
13.	RKTM	Voćarska - Bijenička	22	13	4,5	-3	4	8	4,0/4,0	1
14.	RKTM	Miroševečka - Sunekova	24	7	5	-1,5	4	7	3,5/3,5	1
15.	RKTM	Radnička cesta - Petruševec	40	28	6	-0,5	4	6,5	3,0/3,5	1

Table 5 Capacity and presentation of other traffic indicators of the selected roundabouts

					METHODS									
					NING WU METHOD					HCM 2006 METHOD				
Name of the roundabout/road	No. of vehicles passing the intersection				Capacity	Degree of saturation	Time and number of waiting vehicles		Level of service	Capacity	Degree of saturation	Time and number of waiting vehicles		Level of service
	no. of entries	no. of exits	circular flow	conflict flow										
	qu (PCU/h)	qi (PCU/h)	qk (PCU/h)	vx (PCU/h)	Cu (PCU/h)	X	d (veh/s)	Q95% (veh)	A - F	Cu (PCU/h)	X	d (veh/s)	Q95% (veh)	A - F
Sveti Duh - Kunišćak														
Approach 1	418	410	527	117	712	0,59	7,16	4,14	A	1004	0,42	6,12	2,08	A
Approach 2	216	306	535	229	705	0,31	2,26	1,31	A	900	0,24	5,26	0,94	A
Approach 3	427	345	445	100	785	0,54	5,46	3,5	A	1021	0,42	6,04	2,10	A
Bukovčev trg (Mašićeva)														
Approach 1	480	274	386	112	839	0,57	5,72	3,92	A	1009	0,48	6,76	2,62	A
Approach 2	434	472	592	120	656	0,66	10,61	5,58	B	549	0,79	26,99	7,47	D
Approach 3	224	264	554	290	689	0,33	2,52	1,43	A	616	0,36	9,14	1,66	A
Approach 4	3	131	514	383	723	0,00	0,02	0,015	A	652	0,00	5,55	0,01	A
Ljudevita Posavskog - Tuškanova A														
Approach 1	184	194	279	85	944	0,19	0,92	0,72	A	534	0,34	10,24	1,52	B
Approach 2	429	242	269	27	954	0,45	3,08	2,42	A	510	0,84	34,20	8,60	D
Approach 3	141	318	456	138	775	0,18	1,03	0,66	A	556	0,25	8,66	1,00	A
Ljudevita Posavskog - Tuškanova B														
Approach 1	250	865	943	78	396	0,63	15,37	4,81	C	1125	0,22	4,11	0,85	A
Approach 2	583	166	328	162	895	0,65	7,46	5,41	A	566	1,03	68,03	15,91	F
Approach 3	438	240	745	505	536	0,82	27,89	10,95	D	695	0,63	13,56	4,48	B
Pertetićev trg														
Approach 1	50	55	244	189	979	0,05	0,19	0,16	A	936	0,05	4,06	0,17	A
Approach 2	306	208	239	31	984	0,31	1,65	1,34	A	1092	0,28	4,58	1,15	A
Approach 3	214	307	337	30	886	0,24	1,29	0,95	A	1093	0,20	4,10	0,73	A
Bundek - S.R. Njemačke														
Approach 1	475	693	744	51	537	0,88	42,93	15,36	E	1071	0,44	6,02	2,32	A
Approach 2	275	122	526	404	713	0,39	3,17	1,86	A	760	0,36	7,40	1,66	A
Approach 3	507	442	679	237	587	0,86	34,35	14,01	D	893	0,57	9,18	3,66	A
Šestinski vijenac - Pantovčak														
Approach 1	305	194	292	98	931	0,33	1,88	1,45	A	1023	0,30	5,01	1,26	A
Approach 2	283	171	403	232	823	0,34	2,29	1,56	A	898	0,32	5,84	1,36	A
Approach 3	229	452	515	63	722	0,32	2,32	1,38	A	1058	0,22	4,34	0,82	A
Vinogradska - Podolje														
Approach 1	447	453	538	85	703	0,64	8,87	5,03	A	1036	0,43	6,09	2,21	A
Approach 2	300	309	526	217	713	0,42	3,67	2,15	A	588	0,51	12,34	2,89	B
Approach 3	323	302	523	221	715	0,45	4,15	2,44	A	907	0,36	6,14	1,62	A
Approach 4	39	45	544	499	697	0,06	0,3	0,17	A	693	0,06	5,51	0,18	A
Petrova - Jordanovac														
Approach 1	467	391	590	199	659	0,71	13,04	6,81	B	927	0,50	7,76	2,90	A
Approach 2	139	242	666	424	597	0,23	1,83	0,9	A	745	0,19	5,94	0,68	A
Approach 3	384	427	563	136	681	0,56	6,81	3,78	A	986	0,39	5,96	1,87	A
Approach 4	190	120	520	400	718	0,26	1,81	1,075	A	763	0,25	6,28	0,98	A
Lavoslava Ružičke - Ivana Lucića														
Approach 1	125	495	505	10	731	0,58	6,81	4,05	A	1114	0,11	3,64	0,38	A
Approach 2	12	14	435	421	794	0,02	0,06	0,04	A	747	0,02	4,90	0,05	A
Approach 3	498	426	433	7	796	0,63	7,51	4,85	A	1117	0,45	5,79	2,34	A
Petrova - Bukovačka - Prilesje														
Approach 1	373	192	1219	1027	230	1,62	1178	78,61	F	414	0,90	49,60	9,51	E
Approach 2	985	1141	1400	259	136	7,24	11598	427,95	F	875	1,13	86,32	27,32	F
Approach 3	202	267	1244	977	216	0,94	121,23	14,25	F	895	0,23	5,19	0,87	A
Approach 4	984	944	1179	235	252	3,90	5331,02	369,98	F	895	1,10	76,21	25,54	F
Bukovačka cesta - Barutanski j.														
Approach 1	242	165	312	147	911	0,27	1,43	1,08	A	975	0,25	4,91	0,98	A
Approach 2	318	372	389	17	836	0,38	2,64	1,82	A	1107	0,29	4,56	1,20	A
Approach 3	156	179	335	156	888	0,18	0,86	0,63	A	967	0,16	4,44	0,57	A
Voćarska - Bijenička														
Approach 1	478	318	840	522	488	0,98	97,88	24,39	F	677	0,71	17,03	5,83	C
Approach 2	171	358	768	410	519	0,33	3,42	1,46	A	755	0,23	6,16	0,87	A
Approach 3	436	598	813	215	486	0,90	51,12	15,96	F	913	0,48	7,50	2,63	A
Approach 4	427	238	651	413	609	0,70	13,61	6,56	B	753	0,57	10,85	3,61	B
Miroševečka - Sunekova														
Approach 1	179	272	677	405	588	0,30	2,69	1,3	A	759	0,24	6,20	0,91	A
Approach 2	819	545	584	39	664	1,23	449,79	91	F	1083	0,76	12,81	7,57	B
Approach 3	40	30	858	828	454	0,09	0,77	0,28	A	503	0,08	7,77	0,26	A
Approach 4	416	607	868	261	447	0,93	70,06	18,4	F	873	0,48	7,82	2,61	A
Radnička cesta - Petruševec I.														
Approach 1	664	593	701	108	570	1,16	338	62,84	F	1013	0,66	10,05	5,11	B
Approach 2	122	120	772	652	516	0,24	2,17	0,92	A	597	0,20	7,57	0,76	A
Approach 3	572	631	774	143	514	1,11	259,58	47,18	F	979	0,58	8,71	3,92	A
Approach 4	153	167	715	548	559	0,27	2,43	1,12	A	660	0,23	7,09	0,89	A

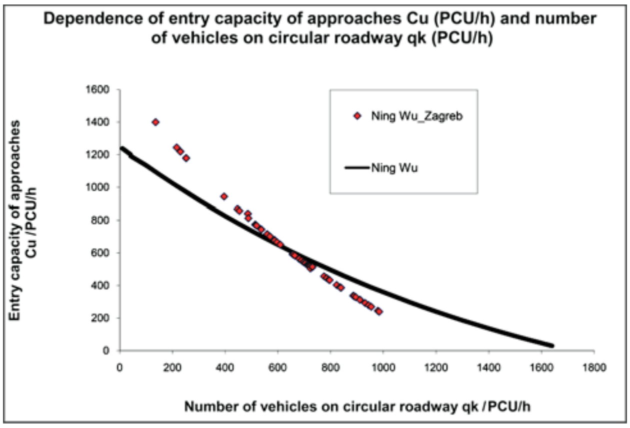

Figure 4 Dependence of the entry capacity of approaches and the number of vehicles in the circular roadway

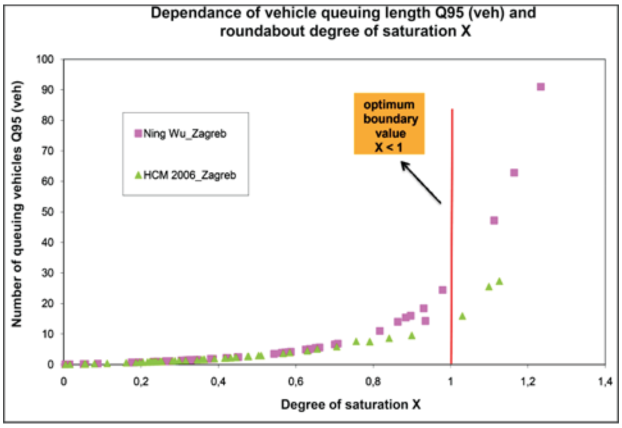

Figure 6 Dependence of the vehicle queue length and degree of saturation at roundabouts

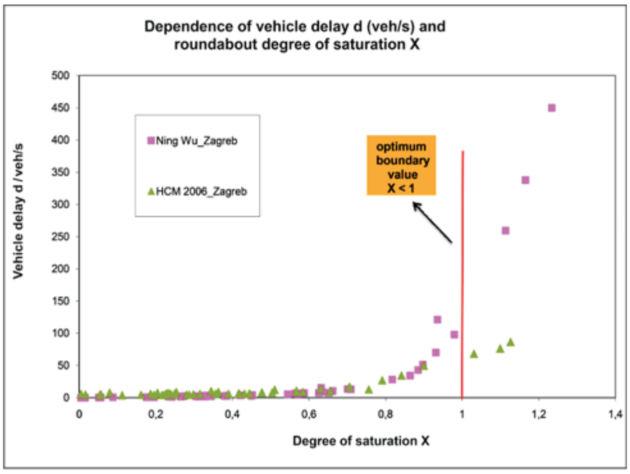

Figure 5 Dependence of the delay of vehicles and the degree of saturation at roundabouts

Further analysis of Figs. 5 and 6 indicates the marginal value of the degree of saturation $X \leq 1$, whereas all other degrees of saturation $X \geq 1$ cannot support the roundabout capacity and other traffic parameters, since these results in large waiting queues and large time losses resulting in turn in great delays. When studying the mentioned four roundabouts that have degrees of saturation greater than $X \geq 1$ it is obvious that large waiting queues are formed of 50 to 430 vehicles, and especially delays from 700 to 12 000 (s/veh), which is absolutely unacceptable. The reason for such deviations in values can be reflected in the number of parameters, the most significant ones being: location of the roundabout in the city traffic network, impact of the adjacent intersections, design roundabout elements, traffic flow quality and the drivers' behaviour. Obviously the four mentioned intersections, not only differ when being compared, but also fail to satisfy the majority of the mentioned traffic indicators, thus significantly reducing the capacity and safety of the roundabouts which over time has to result in the need for their major or minor reconstruction.

6 Concluding considerations

The aim of the paper has been to verify in national conditions the agreement of the capacity and traffic indicators with the foreign methods and experiences. The results of the comparison can only indicate partial conclusions that the capacity and the traffic indicators are within certain limits and acceptable values, which can be seen in Figs. 3, 4, 5 and 6. The application of the foreign methods and experiences in national conditions is applicable and useful for further research. Out of the fifteen

Table 6 Presentation of calculated values that deviate significantly from the tolerance limits

					METHODS									
					NING WU METHOD					HCM 2006 METHOD				
Name of the roundabout/road	No. of vehicles passing the intersection				Capacity	Degree of saturation	Time and number of waiting vehicles		Level of service	Capacity	Degree of saturation	Time and number of waiting vehicles		Level of service
	no. of entries	no. of exits	circular flow	conflict flow										
	qu (PCU/h)	qi (PCU/h)	qk (PCU/h)	vx (PCU/h)	Cu (PCU/h)	X	d (veh/s)	Q95% (veh)	A - F	Cu (PCU/h)	X	d (veh/s)	Q95% (veh)	A - F
Ljudevita Posavskog - Tuškanova B														
Approach 1	250	865	943	78	396	0,63	15,37	4,81	C	1125	0,22	4,11	0,85	A
Approach 2	583	166	328	162	895	0,65	7,46	5,41	A	566	1,03	68,03	15,91	F
Approach 3	438	240	745	505	536	0,82	27,89	10,95	D	695	0,63	13,56	4,48	B
Petrova - Bukovačka - Prilesje														
Approach 1	373	192	1219	1027	230	1,62	1178	78,61	F	414	0,90	49,60	9,51	E
Approach 2	985	1141	1400	259	136	7,24	11598	427,95	F	875	1,13	86,32	27,32	F
Approach 3	202	267	1244	977	216	0,94	121,23	14,25	F	895	0,23	5,19	0,87	A
Approach 4	984	944	1179	235	252	3,90	5331,02	369,98	F	895	1,10	76,21	25,54	F
Miroševečka cesta - Sunekova														
Approach 1	179	272	677	405	588	0,30	2,69	1,3	A	759	0,24	6,20	0,91	A
Approach 2	819	545	584	39	664	1,23	449,79	91	F	1083	0,76	12,81	7,57	B
Approach 3	40	30	858	828	454	0,09	0,77	0,28	A	503	0,08	7,77	0,26	A
Approach 4	416	607	868	261	447	0,93	70,06	18,4	F	873	0,48	7,82	2,61	A
Radnička cesta - Petruševec 1.														
Approach 1	664	593	701	108	570	1,16	338	62,84	F	1013	0,66	10,05	5,11	B
Approach 2	122	120	772	652	516	0,24	2,17	0,92	A	597	0,20	7,57	0,76	A
Approach 3	572	631	774	143	514	1,11	259,58	47,18	F	979	0,58	8,71	3,92	A
Approach 4	153	167	715	548	559	0,27	2,43	1,12	A	660	0,23	7,09	0,89	A

roundabouts, the results of only four roundabouts failed to be within certain limits. The values of capacity and traffic indicators deviate largely from the marginal foreign values and place the studied roundabouts under a big question mark regarding their capacity and safety of roundabouts (Tab. 6). The designing of roundabouts needs to be performed with optimal capacity reserve and efficiency parameters. The waiting queues and vehicle delay control in the near future will represent the fundamental base for the capacity and safety of traffic flows at roundabouts. Furthermore, for the selection of specific foreign method further systematic researches and analysis of all existing same type roundabouts, located on the Croatian territory, are required. Such researches should consist of long-term monitoring of traffic flows, driver behavior and studies of other local conditions in order to calibrate the individual coefficients. Also, special attention should be paid to the research of the very traffic safety at the roundabouts.

7
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