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COMPARATIVE ANALYSIS OF CRITICAL HEADWAY ESTIMATION AT URBAN SINGLE-LANE ROUNDABOUTS

ABSTRACT

According to models commonly used in practice, the capacity of roundabouts largely depends on the value of critical headway. The value of critical headway depends on the characteristics of vehicles, driving conditions, and geometric characteristics of intersections, but also on driver behaviour. Driver behaviour is the result of many factors that depend on the influence of the local environment, driver habits, mentality, etc. Accordingly, to calculate the capacity of roundabouts within the operational and planning analyses of roundabouts more accurately, it is necessary to use data that correspond to local conditions. In this paper, the critical headway was estimated at five urban single-lane roundabouts using five methods: Harders', Logit, Raff's, Wu's, and the maximum likelihood method. In order to determine which of the stated methods provides the most realistic estimate of critical headway, a comparison of field capacity values with theoretical capacity values was performed. Based on the comparative analysis performed in MATLAB, as well as the calculation of percentage prediction error, it was found that the Harders' method provides the most accurate estimate of critical headway at observed roundabouts in two cities in Bosnia and Herzegovina. Due to the similarity in the design of roundabouts and driver behaviour, the results obtained in this paper can be applied in the surrounding countries, i.e., Southeast Europe.

KEYWORDS

critical headway; field capacity; conflicting flow rate; urban single-lane roundabouts.

1. INTRODUCTION

The process of gap acceptance is one of the most commonly used techniques for capacity calculation at roundabouts [1–3]. It is based on gaps/lags that are accepted and rejected by drivers from lower priority approaches. Before entering the circulation area of the roundabouts, drivers from the approaches evaluate the available headways in the conflicting flow. When they adjudge that the gap is large and safe enough, they decide to enter the circulation area. The minimum value of this time interval, which the drivers accept and use for minor manoeuvring, is called the critical headway.

The value of critical headway depends on the technical and exploitation characteristics of vehicles, driving conditions, geometric characteristics of intersections, traffic system, and traffic culture. In addition to objective factors, the value of critical headway largely depends on driver behaviour. Although the actions performed by drivers during minor manoeuvring are almost identical, the acceptance of headways for its realisation depends on drivers' decisions. For this reason, the value of critical headway is not identical in all environments and countries. Considering that driver behaviour, in addition to drivers' individual characteristics and abilities, is greatly influenced by the environment, it is recommended that local measurements be taken into account when determining the value of critical headway. According to [4], the critical headway represents the most efficient and most important variable compared to other calibration factors.

The critical headway cannot be measured directly from roundabouts because drivers will accept all headways greater than their critical headway [5]. The headways can only be separated into those that are accepted and those that are rejected by drivers executing lower priority movement. Numerous models and methods for estimating the value of critical headways have been given in current studies, which are based on both field research and mathematical and statistical methods. The basic assumption is that the value of critical headway will be somewhere between the minimum accepted and the maximum rejected headways.

This paper presents a comparative analysis of the values of critical headway estimated by applying different methods in real traffic conditions at roundabouts in Bosnia and Herzegovina. The motive for the research and analysis conducted in this paper is that only in a very modest number of papers was the stated parameter of traffic flow of this region investigated and calculated. Similar research studies were conducted in the neighbouring country Croatia with the aim of determining the most suitable method for calculating the capacity of roundabouts [6–8]. Such studies are needed in order to determine their objective value by mathematical models, for applying it in procedures for capacity calculation and determining the level of service. The accuracy of capacity estimation is primarily determined by the accuracy of estimating the critical headway and the follow-up headway [9]. Therefore, adopting critical headway and follow-up headway values determined in other traffic conditions can lead to wrong conclusions and decisions in plans and projects.

2. LITERATURE REVIEW

Brilon et al. [10] defined the critical headway as the minimum time gap between vehicles in the major stream that a minor-stream driver is willing to accept in order to enter the centre of the intersection. Tian et al. [11] state that the critical headway is one of the main parameters for models based on gap acceptance between vehicles. According to [12], the critical headway is not a constant value. It has different values for individual drivers, and even for the same drivers, its value differs with time and traffic situations. Easa et al. [13] showed that the mean value and variance of the critical headway have the most significant impact on the sight distance at roundabouts. The authors also stated that the proposed method for the design of intersection sight distance is important for improving roundabout safety. In that way, critical headway is indirectly connected to traffic safety as well.

Krishna [14] estimated the critical headway using three methods and found that the method developed by Wu was the most appropriate for traffic conditions in India. Vasconcelos et al. [15] applied five methods to estimate the critical headway in Portugal, and based on a comparison of estimated and real capacity values, they concluded that Raff's, Wu's, and maximum likelihood methods were more reliable than others. Guo [16] also found that the maximum likelihood method is reliable for estimating gaps in China, as well as the revised Raff's method, which takes into account all rejected gaps, including those equal to zero.

In their research, Dahl and Lee [17] proved that the critical headway is higher for heavy vehicles than passenger cars. Fitzpatrick et al. [18] found that passenger car drivers accept a 0.6-seconds shorter gap than heavy vehicle drivers. Lee and Khan [19] recommend that the critical headway be estimated separately for each leg of the roundabout if the percentage of heavy vehicles in entry flows is significantly different. Krishna [14] also reported that driver behaviour changes with the change in the composition of traffic flow, i.e., it was noted that headways were larger when the number of heavy vehicles was higher. The values obtained for the critical headway indicate a very aggressive driving style of drivers in India, which was also confirmed in [20]. Ahmad et al. [21] proposed a new method for estimating the critical headway based on minimisation of the sum of absolute difference between a headway value and accepted/rejected headway that is suitable for mixed traffic conditions in India.

The results of studies conducted in [22–24] show that the values of critical headway at roundabouts in Italy, China, and Spain are significantly lower compared to those values recommended in [25] and [26]. Kim et al. [27] found that the values of this interval in Korea are even lower, more precisely, the authors have established that the values are lower by about 1.5–2.5 seconds compared to other countries. The statistical analysis performed in [28] showed no significant difference in the values of critical headway between California and other U.S. states. The authors have found that the critical headway tends to decrease with increasing the number of vehicles in the major stream and/or speed. On the other hand, Guo and Zhao [29] state that the critical headway increases with increasing vehicle speed in the major stream. The noticeable differences in the critical headway values are due to different traffic cultures and traffic systems between different parts of the world.

Wei and Grenard [30] opined that many of the long gaps that drivers had rejected at a minor approach resulted from the drivers' inability to assess whether other drivers in the circulation area were circling or planning to exit the roundabout. Hagring [31] stated that if the number of vehicles exiting the circulation area is large, the critical headway is overestimated because minor-stream vehicles waiting for exiting vehicles are not taken into account. Barry [32] found that in the case when exiting vehicles are excluded from the calculation, the weighted value of critical headway is 4.17 seconds. On the other hand, when exiting vehicles are included in the analysis, the weighted value of critical headway is 3.34 seconds. Other studies have also noted that the critical headway decreases when exiting vehicles are considered in the calculation [33, 34]. Thus, it may be concluded that models that include exiting vehicles result in higher capacity compared to models that do not include these vehicles in the calculation.

Maslać et al. [35] examined which of the four methods for estimating the critical headway provides the most realistic values, based on a comparative analysis of theoretical models of capacity and actual capacity at a mini-roundabout. They found that the HCM 2010 model is not suitable for determining capacity at mini-roundabouts in Bosnia and Herzegovina. Instead, they used the Brilon-Wu model and, based on a comparative analysis, recommended the Wu's method for estimating the critical headway at mini-roundabouts. They also noticed that drivers tend to be more aggressive and accept shorter time headways when they have to wait longer for entering the main flow, which was also found in [36, 37].

Kusuma and Koutsopoulos [38] investigated dual-lane roundabouts and found that the critical headway largely depends on the lane chosen (outer or inner) and the type of vehicle. According to [39], in the case of the overall circulating traffic flow, the mean value of critical headway for the left lane at entries is higher than the mean value of critical headway for the right lane. When headway distributions in each circulating lane are considered separately, this paper states that for each entry lane the values of critical headway for the inner circulating lane are lower than the same values for the outer circulating lane. Shaaban and Hamad [40] developed a new method for estimating the critical headway at multi-lane roundabouts, and the method itself is based on group gap acceptance.

Lee et al. [41] examined the effect of rain on gap acceptance at roundabouts by developing the logit model using various roundabout variables. The authors concluded that drivers need about a 10 percent longer gap to enter the centre of the roundabout during rainy conditions. Also, gap acceptance probabilities are 10 to 20 percent lower for the same given gap during rainy conditions compared to good weather conditions. Cheng et al. [42] found that the value of the critical headway is lower during peak hours than other hours, but that the difference in values is not significant. In [43] was found that the existence of yield line marking on the road, truck apron marking, as well as an increased entry angle at the roundabout reduce the critical headway.

Throughout their research conducted over a period of four years, Mensah et al. [44] came to a conclusion that the critical headway can be reduced over time as drivers get used to driving in roundabouts. Hainen et al. [45] also found that the values of critical headways are lower than those recommended in [5] precisely because of the greater experience of drivers in driving at roundabouts. Based on the results of the analysis, Stanimirović et al. [46] determined that non-resident drivers accept higher headway values for the desired minor approach manoeuvring.

3. RESEARCH METHODOLOGY

The research was conducted at five urban four-legged roundabouts in Bijeljina and Banja Luka, Bosnia and Herzegovina. Each of these roundabouts has one traffic lane at the entry/exit and one traffic lane in the circulation area. The research on this elementary type of roundabout was performed in order to eliminate the influences of approach geometry on the size of traffic flow parameters as much as possible. As part of the research, a so-called photographic method was applied, which includes the analysis of real traffic flow videos. This method excludes the possibility of research influence on driver behaviour. Video recording was performed using a

Sony HDR-CX240 Full HD camera. The video recording format is MPEG4-AVC/H.264 and the recording resolution is HD: 1920x1080/50p (PS).

The study areas of the research are the following five intersections (details are provided in *Table 1*):

- the intersection of Neznanih junaka, Gavrila Principa, Svetog Save, and Filipa Višnjića streets, which is in this paper labelled as R_1;
- the intersection of Neznanih junaka, Ive Andrića, Stefana Dečanskog, and Sremska streets, which is in this paper labelled as R_2;
- the intersection of Neznanih junaka, Kulina bana and Dušana Baranina streets, which is in this paper labelled as R_3;
- the intersection of Karađorđeva, and Jovana Raškovića streets, which is in this paper labelled as R_4;
- the intersection of Teodora Kolokotronisa, Cara Lazara, Isaije Mitrovića, and Patre streets, which is in this paper labelled as R_5.

In order to determine critical headway, it is necessary to segregate individual time stamps at the very beginning. For this purpose, the MPC-HC (Media Player Classic Home Cinema) player was used and the extraction of time stamps was done using the command CTRL + G. The particular procedure for extraction time stamps with the purpose of estimating critical headway and follow-up headway is described in detail in [14]. Based on the data processing, the accepted and rejected headways were separated, while the accepted headways longer than 15 seconds were not taken into account. Namely, when the headways are too long, the question arises whether the vehicle from the main flow was in the circulating flow at all when the vehicle from the minor approach entered the roundabout. For this reason, all vehicles that were on 3/4 of the circle from the minor approach were excluded by dividing that peripheral length of the circle by 15 km/h and obtaining the time required for the vehicle from the circulating flow to reach the minor approach. Five

Table 1 – Geometric characteristics of analysed roundabouts

Approaches of the roundabouts		Central island diameter [m]	Circulating width [m]	Inscribed circle diameter [m]	Entry radius [m]	Entry angle [deg]	Entry width [m]
R_1	Gavrila Principa	11.00	5.50	18.80	25.00	40.00	3.50
	Svetog Save	11.00	5.50	18.80	40.00	20.00	3.50
	Neznanih junaka	11.00	5.50	18.80	25.00	40.00	3.50
	Filipa Višnjića	11.00	5.50	18.80	55.00	15.00	3.50
R_2	Neznanih junaka	12.00	6.50	20.50	30.00	30.00	4.00
	Sremska	12.00	6.50	20.50	62.00	30.00	3.80
	Ive Andrića	12.00	6.50	20.50	10.00	60.00	7.50a
	Stefana Dečanskog	12.00	6.50	20.50	92.00	10.00	4.00
R_3	Kulina Bana	9.00	8.04	26.54	55.00	20.00	3.76
	Neznanih junaka	9.00	7.50	26.68	22.00	25.00	3.46
	Dušana Baranina	9.00	7.89	26.39	65.00	15.00	3.72
	Neznanih junaka	9.00	8.18	26.68	40.00	25.00	4.25
R_4	Jovana Raškovića	13.64	6.00	30.00	25.00	40.00	5.00
	Karađorđeva	13.64	6.00	30.00	18.00	30.00	5.38
	Jovana Raškovića	13.64	6.00	30.00	30.00	20.00	4.27
	Karađorđeva	13.64	6.00	30.00	35.00	15.00	5.15
R_5	Cara Lazara	25.60	5.50	35.02	30.00	30.00	5.25
	Teodora Kolokotronisa	25.60	5.50	35.02	15.00	45.00	5.78
	Patre	25.60	5.50	35.02	25.00	30.00	4.50
	Isaije Mitrovića	25.60	5.50	35.02	12.00	30.00	4.50

[a] *there is no splitter island on this approach*

Figure 1 – Analysed roundabouts

different times were obtained for the five analysed roundabouts, and the average value was 15 seconds. Since it is not possible to measure the critical headway directly, numerous methods and procedures have been developed for its estimation. In order to verify the theoretically obtained values as best as possible, five different methods for estimating the critical headway have been applied in this paper: Harders', Logit, Raff's, Wu's, and the maximum likelihood method.

3.1 Raff's method

The earliest method for estimating the value of critical headway is based on the research conducted in [47]. Raff's method involves the empirical distribution of the functions of accepted gaps $F_a(t)$ and rejected gaps $F_r(t)$. According to his conclusions, the critical headway (t_c) is a function of t at the points where the functions $1\text{-}F_r(t)$ and $F_a(t)$ intersect. When the sum of the cumulative probabilities of accepted gaps and rejected gaps is equal to 1, then the headway of t is equal to the critical headway t_c. This means that the number of rejected gaps greater than the critical gap is equal to the number of accepted gaps lower than the critical gap.

$$F_a(t) = 1 - F_r(t) \tag{1}$$

Later, Miller [48] provided some mathematical explanations of this method and stated that the results of estimating the critical gap are directly related to flow rate at approaches. This method was previously used in many countries due to its ease of application, such as in Germany [49].

3.2 Harders' method

Harders [50] developed a method for estimating t_c, which was often used in Germany. The largest number of performed procedures for capacity calculation in Germany is still based on his method of estimating the values of t_c and t_f. In Harders' procedure, lags are not used in the sample observed. The time scale is divided into intervals of equal length, e.g. Δt=0.5 s, and the centre of each interval i is denoted as t_i. For each vehicle in a minor-stream queue, it is necessary to measure all the gaps from the major stream available to the driver and record the accepted gaps. Based on all the above, it is necessary to calculate the following values:

N_i – the number of all measured gaps of i, which are available to minor-stream drivers

A_i – the number of accepted gaps of i

$a_i=A_i/N_i$.

By plotting the value of a_i in the centre of each interval t_i, a curve is obtained that represents $F_c(t)$, i.e., the function of critical gaps. On the other hand, there is no mathematical concept or further proof that $a_i=f(t_i)$ nor that a real curve of critical gaps $F_c(t)$ is thus obtained.

3.3 Maximum likelihood method

The maximum likelihood method for estimating the critical headway was developed in the early 1970s by Miller and Pretty [48, 51]. This method for estimating the critical headway is most accurately explained in [52]. The maximum likelihood method is based on the fact that the value of critical headway is between the largest rejected gap and the accepted gap. The following parameters are used to estimate the critical headway using this method [11]:

y_i – the logarithm of the gap accepted by the i^{th} driver

x_i – the logarithm of the largest gap rejected by the i^{th} driver, $x_i=0$ if no gap is rejected

μ – the logarithm distribution mean of individual critical gaps of drivers

σ^2 – the logarithm distribution variance of individual critical gaps of drivers

$f(\ )$ – probability density function for normal distribution

$F(\ )$ – cumulative distribution function for normal distribution.

The average value of critical headway t_c and the variance s^2 can be calculated as follows:

$$t_c = e^{\mu + 0.5\sigma^2} \tag{2}$$

$$s^2 = t_c^2\left(e^{\sigma^2} - 1\right) \tag{3}$$

3.4 Wu's method

Wu [53] presented a new model for estimating critical headways at unsignalised intersections (Probability equilibrium method). The theoretical background of the model is the probability equilibrium between the accepted and rejected gaps. The author states that in addition to a good theoretical background, the new model has other positive features such as robust results, independence from any assumptions before applying the model, the ability to use all relevant gaps. The advantage is also the possibility of obtaining the empirical probability distribution function of critical headways directly, as well as a simple calculation procedure without iteration. This method is defined by the following mathematical expression:

$$F_{tc}(t) = \frac{F_a(t)}{F_a(t) + 1 - F_r(t)} = 1 - \frac{1 - F_r(t)}{F_a(t) + 1 - F_r(t)} \tag{4}$$

3.5 Logit method

The Logit method uses the negative logarithm of likelihood function. Logit is basically a linear regression model with a mathematical form as shown in the following expression:

$$P = \frac{1}{1 + e^{-(\beta_0 + \beta_1 x)}} \tag{5}$$

where P is the probability of gap acceptance, β_0 and β_1 are regression coefficients, and x is the length of the gap. The critical headway can be estimated by solving the expression above for x by assigning a value from 0.5 to P, i.e., the probability is 50% that the gap will be accepted. This model is often used to check the influence of different independent variables on the critical headway, such as waiting time, average speed, etc.

4. RESULTS AND DISCUSSION

There was no significant participation of pedestrians, so they were not considered in this research. However, the impact of heavy vehicles was taken into account through the heavy-vehicle adjustment factor calculated according to *Equation 6* defined in [26]:

$$f_{HV} = \frac{1}{1 + P_T(E_T - 1)} \tag{6}$$

where E_T is the passenger car equivalent for heavy vehicles which is 2.0 as per [26]. Besides the number of vehicles, *Table 2* also shows the calculated values of this factor for each roundabout.

Table 2 – Traffic structure

	R_1	R_2	R_3	R_4	R_5
Total number of vehicles [veh/h]	1,561	1,183	1,455	1,810	1,481
Percentage of heavy vehicles [%]	4.16	4.73	4.33	6.08	1.96
Heavy-vehicle adjustment factor	0.96	0.96	0.96	0.94	0.98

The critical headway was estimated separately for each of the five observed roundabouts. Specifically, the critical headway was determined as single value for all four approaches for each of the observed intersections. As shown in *Table 3*, the estimated values of critical headway applying the five methods do not vary widely.

Table 3 – Estimated values of critical headway

Applied method	R_1	R_2	R_3	R_4	R_5
Harders	4.94	4.98	5.33	5.31	5.06
Logit	4.47	4.47	5.47	4.91	4.71
Raff	4.22	4.45	4.52	4.55	4.47
Wu	4.16	4.11	4.69	4.28	4.70
Maximum likelihood	4.19	4.02	4.66	4.51	4.57

In order to determine which of the listed methods provides the most realistic estimate of critical headway, the measured field capacity values (labelled as Field Q on *Figures 2–6*) were compared with capacity values obtained on the basis of critical headway estimated by different methods. Conflicting flow rate (labelled as CF on *Figures 2–6*) and capacity were measured in the field using the procedures prescribed in [54, 55]. When determining these two parameters, queues of at least three vehicles were only considered. Field capacity is calculated as a quotient of the number of vehicles in the queue and the time elapsed from the moment when the first vehicle in the queue arrives at the stop line to the moment when the last vehicle in the queue arrives at the stop line, with all vehicles in the queue using the same headway in the conflicting flow. During the same observation period, the conflicting flow rate was computed using *Equation 7*:

$$Conflicting\ flow\ rate = \frac{n}{t_n - t_0} \tag{7}$$

where n is the number of conflicting flow vehicles, including the vehicle passing immediately after the last minor-stream vehicle of the queue; t_n is arrival time of the n^{th} vehicle from the conflicting flow at the reference point; t_0 is arrival time of the first vehicle from a queue at the reference line.

On the other hand, for calculating the theoretical capacity based on the estimated critical headways, the calibrated model defined in [26] was applied:

$$c_{pce} = Ae^{(-Bv_c)} \tag{8}$$

$$A = \frac{3600}{t_f} \tag{9}$$

$$B = \frac{t_c - \left(\frac{t_f}{2}\right)}{3600} \tag{10}$$

where c_{pce} is the lane capacity, adjusted for heavy vehicles [pc/h], v_c is the conflicting flow [pc/h], t_c is the critical headway [s], and t_f is the follow-up headway [s].

For the purposes of capacity calculation based on the HCM model, the values of conflicting flows were determined for each approach at the selected roundabouts. Additionally, follow-up headway was measured like the mean headway between queued vehicles at approaches that are using the same headway in the major stream. The descriptive statistics for follow-up headways separately for each of the five observed roundabouts are shown in *Table 4*.

A scatter plot was drawn in MATLAB between field capacity values and the corresponding conflicting flow values. As in some cases, there were significant variations in the values of field capacity, which is quite common in the field measurements [55]. The variations in the data were reducing through a smoothening technique that was based on the moving average method (labelled as Field Qm on *Figures 2–6*). An exponential model was fitted to the field data and compared with the theoretical values of the capacity estimated for the five analysed roundabouts. The values for the x-axis are the conflicting flows determined for each approach of five roundabouts and the values for the y-axis are the capacities estimated by using critical headways from various methods. The best method for estimating the critical headway at the selected roundabouts is the

Table 4 – Descriptive statistics for follow-up headway

	Sample size	Mean	StDev	Variance	Minimum	Median	Maximum
R_1	102	3.01	0.62	0.39	1.20	2.95	4.40
R_2	121	2.86	0.67	0.44	1.30	2.75	5.03
R_3	124	2.92	0.72	0.51	1.45	2.72	5.10
R_4	96	2.87	0.70	0.50	1.15	2.71	5.12
R_5	124	2.57	0.57	0.33	1.18	2.50	4.13

Table 5 – Exponential model statistics

	a	b	SSE	R^2	Dfe	Adjusted R^2	RMSE
R_1	1,272	-0.0009554	$8.5010 \cdot 10^4$	0.8445	30	0.8393	53.2323
R_2	1,494	-0.001083	$2.2782 \cdot 10^4$	0.8914	13	0.8831	41.8625
R_3	1,245	-0.0008957	$1.0113 \cdot 10^5$	0.6483	23	0.6330	66.3112
R_4	1,352	-0.001213	$5.6996 \cdot 10^4$	0.6809	13	0.6563	66.2141
R_5	1,725	-0.001137	$1.3364 \cdot 10^4$	0.8553	7	0.8346	43.6931

one that gives the theoretical capacity closest to the value of field capacity. The accuracy of the method can also be determined based on the RMSE value (Root Mean Square Error), i.e., the lowest RMSE value indicates the best method.

The previously mentioned exponential model has the following form $f(x)=a \cdot \exp(b \cdot x)$. Details of the statistical parameters of each of the exponential models for all selected roundabouts are presented in *Table 5*. The table contains the model parameters a and b, the sum of squares error (SSE), the coefficient of determination R^2, degrees of freedom (Dfe), adjusted R^2, a well as RMSE values referred to deviations of individual points from the developed observed models.

Based on *Figures 2–6* and *Table 6*, it can be seen that the maximum likelihood method is most suitable for roundabout R_3, Raff's method for roundabout R_5,

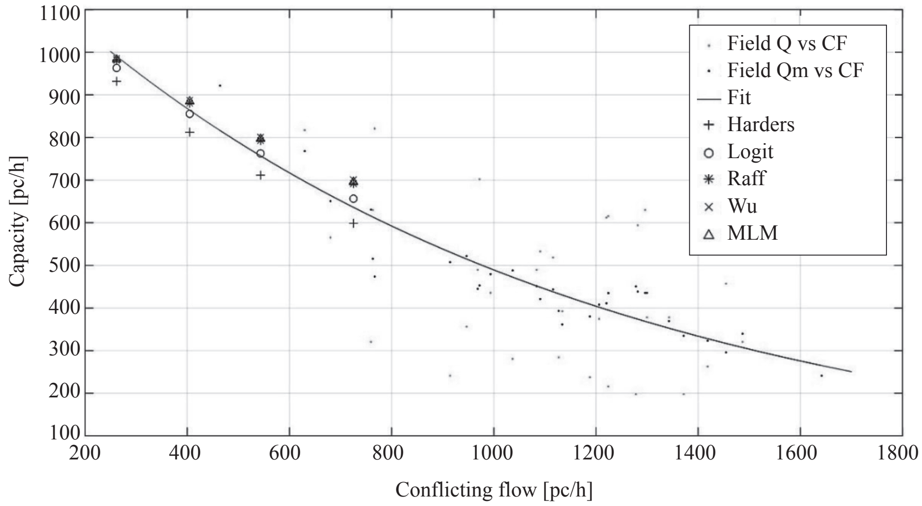

Figure 2 – Comparative analysis of capacity values at the first roundabout (R_1)

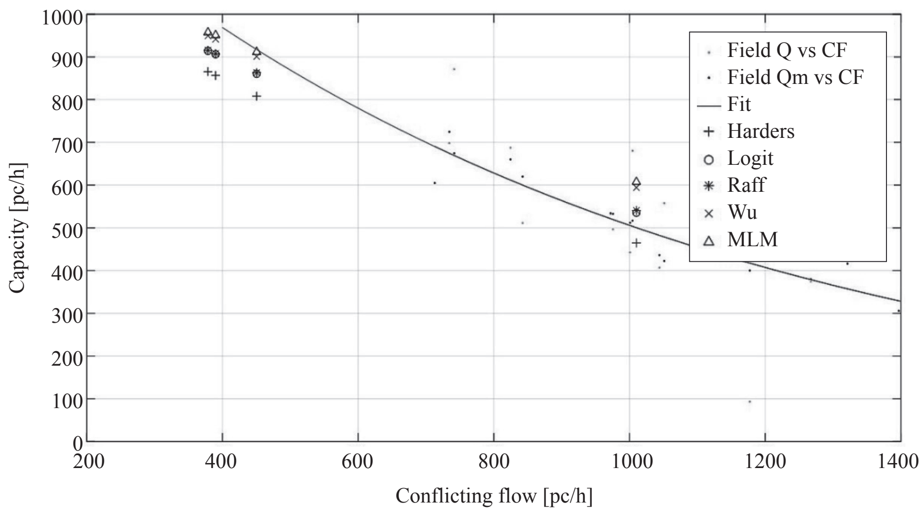

Figure 3 – Comparative analysis of capacity values at the second roundabout (R_2)

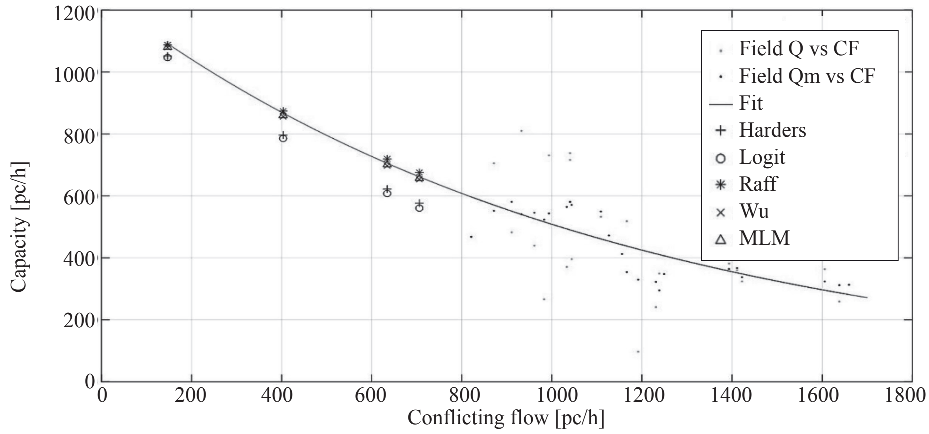

Figure 4 – Comparative analysis of capacity values at the third roundabout (R_3)

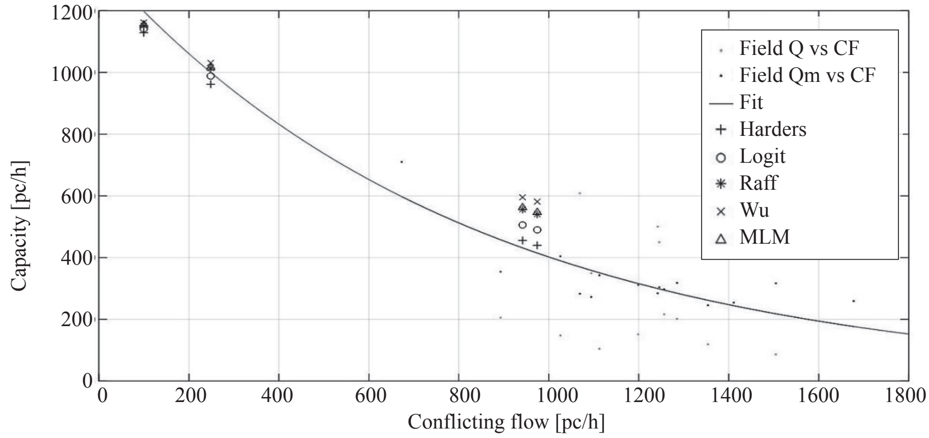

Figure 5 – Comparative analysis of capacity values at the fourth roundabout (R_4)

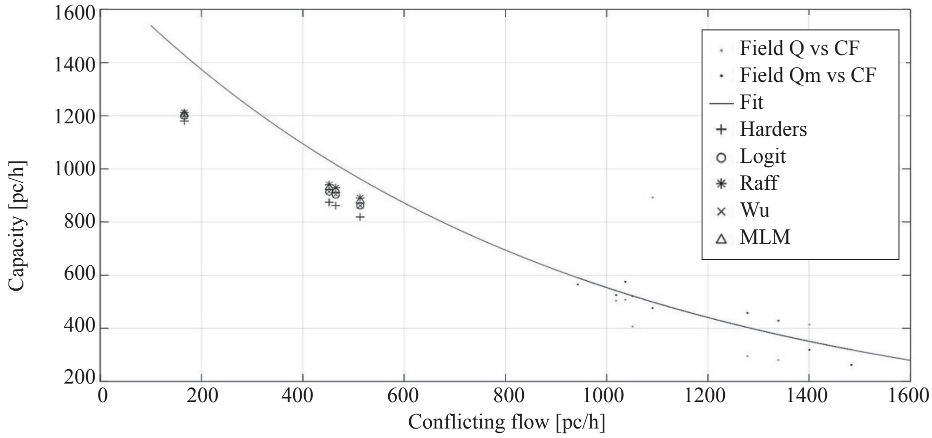

Figure 6 – Comparative analysis of capacity values at the fifth roundabout (R_5)

Table 6 – RMSE values

	Harders	Logit	Raff	Wu	MLM[b]
R_1	49.15	17.89	34.71	41.04	37.65
R_2	104.74	62.83	61.80	55.04	58.13
R_3	72.16	84.03	10.71	9.79	7.59
R_4	43.50	60.35	91.84	119.46	95.56
R_5	181.05	150.53	130.07	149.59	137.90

[b] *Maximum likelihood method*

Wu's method for roundabout R_2, Harders' method for roundabout R_4, while the Logit method provides the best results for roundabout R_1.

Based on the obtained results, it cannot be concluded which method is actually the most suitable. For that reason, a new analysis has been performed that included the capacity formula, follow-up headway, and conflicting flow. In that way, the value of critical headway was found by minimising the errors sum of squares between the field capacity and theoretical capacity (based on *Equation 8*). The optimisation was carried out using the Solver function in Excel. The value of critical headway corresponding to the minimum value of the objective function was selected as the final value. This was then compared with the critical headway values obtained from other methods, which is given in *Table 7*.

Thus, based on the calculation of percentage prediction error in estimated critical headway, it is possible to conclude which method is the most suitable for traffic conditions at these five urban single-lane roundabouts. *Table 8* presents the values of percentage error in prediction which show that, except in a case for R_3, the Harders' method gives the best estimate. Namely, each of the applied methods proves to be relatively better for individual roundabouts, however, the prediction by these methods are characterised by greater variances at other roundabouts. Therefore, the Harders' method has been proposed as the most suitable for estimating the critical headway at the analysed roundabouts.

Table 9 represents a comparison of the critical headway and follow-up headway values on the obtained roundabouts with the values of the same parameters from other researches.

Table 7 – Optimization of critical headway values

Applied method	R_1	R_2	R_3	R_4	R_5
Harders	4.94	4.98	5.33	5.31	5.06
Logit	4.47	4.47	5.47	4.91	4.71
Raff	4.22	4.45	4.52	4.55	4.47
Wu	4.16	4.11	4.69	4.28	4.70
Maximum likelihood	4.19	4.02	4.66	4.51	4.57
Optimization	4.73	4.65	4.55	5.41	4.99

Table 8 – Percentage prediction error in the critical headway estimation

Applied method	R_1	R_2	R_3	R_4	R_5	Average
Harders	4.40	7.08	17.26	1.80	1.41	6.52
Logit	5.53	3.88	20.35	9.20	5.60	9.03
Raff	10.81	4.31	0.56	15.86	10.41	8.50
Wu	12.08	11.62	3.18	20.85	5.80	10.81
Maximum likelihood	11.45	13.56	2.52	16.60	8.41	10.61

Table 9 – Critical headway and follow-up headway values for single-lane roundabouts

Source	Country	Value of critical headway [s]	Value of follow-up headway [s]
Present study	Bosnia and Herzegovina	4.94–5.33	2.57–3.01
[2]	India	1.60	1.24
[15]	Portugal	3.20–3.70	2.10–2.30
[20]	India	2.20	1.20
[22]	Italy	3.86	2.63
[25]	USA	5.19	3.19
[26]	USA	4.98	2.61
[28]	USA	4.50–5.30	2.50
[30]	USA	3.47	2.20
[32]	USA	4.17[c]; 3.34[d]	3.46[c]; 2.80[d]
[35]	Bosnia and Herzegovina	4.19–4.46	2.90
[46]	Bosnia and Herzegovina	5.39–5.41	3.43–3.51
[56]	Slovenia	4.80	2.90

[c] *exiting vehicles excluded;* [d] *exiting vehicles included*

5. CONCLUSIONS

The use of recommended values of traffic flow parameters in application software can cause wrong investment decisions. Consequently, five different methods were applied in this paper to estimate the critical headway. In order to determine the most reliable method, a comparative analysis of field capacity values with theoretical capacity values was performed. The results obtained based on the model in MATLAB have shown that the maximum likelihood method is most suitable for roundabout R_3, Raff's method for roundabout R_5, Wu's method for roundabout R_2, Harders' method for roundabout R_4, while the Logit method provides the best results for roundabout R_1. However, this analysis did not narrow down to a single method that could be applicable to all the intersection that were studied. The values of percentage prediction error of the critical headway was then computed and on its basis, it was concluded that Harders' method is characterised by lower values of variance in comparison to other methods, except for the roundabout R_3.

The area of the location of the roundabout, as well as the vehicle volume, have a significant impact on the value of critical headway. Namely, the increased volume of vehicles at the roundabout can result in increased value of the critical headway, especially on urban roads. Based on the optimised values of the critical headway from *Table 7*, it can be concluded that the largest value corresponds to the roundabout R_4. It is just at this roundabout that the highest volume of vehicles during peak hour was established compared to the other four intersections, and very frequent vehicle stops were also observed due to traffic congestion. Future research should be directed towards calculation of the critical headway values at suburban roundabouts in order to compare them with the values at urban ones presented in this paper.

The values of the critical headway vary from country to country, and this is due to cultural differences, differences in driver's behaviour, their habits, and customs. As a result of these variations in the headway values, there are differences in the capacity calculation at roundabouts in individual countries. The research conducted in this paper is one of the few in this area and furthermore, the results are based on single-lane roundabouts from a limited number of cities. Future research should take into account a larger number of roundabouts at different locations across the country in order to make the results more relevant. Finally, it can be concluded that there is a lot of room for improvement and adaptation of existing models for estimating the capacity of roundabouts in traffic conditions in Bosnia and Herzegovina.

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UPOREDNA ANALIZA PROCJENE KRITIČNOG INTERVALA SLJEĐENJA NA URBANIM JEDNOTRAČNIM KRUŽNIM RASKRSNICAMA

REZIME

Prema modelima koji se uobičajeno koriste u praksi, kapacitet kružnih raskrsnica u velikoj mjeri zavisi od vrijednosti kritičnog intervala sljeđenja. Veličina kritičnog intervala sljeđenja zavisi od karakteristika vozila, uslova kretanja i geometrijskih karakteristika raskrsnica, ali i od ponašanja vozača. Ponašanje vozača je rezultat djelovanja mnogobrojnih faktora koji zavise od uticaja lokalne sredine, navika vozača, mentaliteta itd. U skladu sa tim, radi preciznijeg proračuna kapaciteta kružnih raskrsnica u okviru operativnih i planskih analiza kružnih raskrsnica, potrebno je koristiti podatke koji odgovaraju lokalnim uslovima. U ovom radu je izvršena procjena kritičnog intervala sljeđenja na pet urbanih jednotračnih kružnih raskrsnica primjenom pet metoda: Harders-ova, Logit, Raff-ova, Wu-ova i metoda maksimalne vjerodostojnosti. Kako bi se utvrdilo koja od navedenih metoda pruža najrealniju procjenu kritičnog intervala sljeđenja, izvršeno je poređenje vrijednosti terenskog kapaciteta sa teorijskim vrijednostima kapaciteta. Na osnovu uporedne

analize izvršene u MATLAB-u, kao i proračuna procentualne greške predikcije, ustanovljeno je da Harders-ova metoda pruža najprecizniju procjenu kritičnog intervala slijeđenja na posmatranim kružnim raskrsnicama u dva grada u Bosni i Hercegovini. Zbog sličnosti u dizajnu kružnih raskrsnica i ponašanju vozača, rezultati dobijeni u ovom radu mogu se primijeniti i u državama regiona, odnosno Jugoistočne Evrope.

KLJUČNE RIJEČI

kritični interval slijeđenja; terenski kapacitet; konfliktni tok; urbane jednotračne kružne raskrsnice.

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