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ORIGINAL SCIENTIFIC PAPER

Assessment of critical headway estimation methods across multiple unsignalized intersections

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Abstract: Driver behavior under local conditions has a significant influence on the value of accepted headways required for performing minor maneuvers. In operational analyses and the design of unsignalized intersections, driver behavior is quantified through the value of the critical headway. It is assumed that the critical headway represents the shortest headway that a driver is willing to accept. Since it is not possible to measure the critical headway directly from field observations, measurement results are processed using application software and mathematical tools. To determine the critical headway at three priority intersections in the urban area of the city of Doboj, six different methods were applied: Harders', Logit, Lag, Raff's, Wu's, and the Maximum Likelihood method. In order to identify which of the applied methods provides the best solution for the analyzed intersections, a comparative analysis was conducted between the theoretically obtained capacity values and the actual measured capacity value. The Lag method was the most suitable for intersection I_1, the Maximum Likelihood method was chosen for intersection I_2, while the Raff method was selected for intersection I_3.

Keywords: critical headway estimation, unsignalized intersection

INTRODUCTION

Since the early stages of Traffic Flow Theory, many studies have aimed to define procedures for analyzing the capacity of roads, streets, and intersections, as well as identifying influencing factors. The first research efforts in this field date back to the early 1930s, when capacity studies of uninterrupted road segments were conducted for the first time. The capacity of roads, intersections, and other elements of the roadway and street network continues to be a highly relevant topic that motivates extensive scientific research. The findings of such studies are used to develop procedures and models for the calculation of various components of the road and street network. Although established procedures exist for the capacity analysis of most of these elements, all models and procedures are still being refined and improved through new research and mathematical modeling efforts. In engineering practice, capacity estimation for unsignalized intersections is most commonly performed using the procedures defined in the Highway Capacity Manual (HCM). The HCM represents the most widely cited manual for capacity analysis within the roadway and street network.

When estimating the capacity of unsignalized intersections, one of the traffic flow parameters that most strongly influences both capacity and level of service is the critical headway. The critical headway represents the mathematically determined minimum headway in the major stream that allows a vehicle from the minor stream to complete its maneuver. In theory, it is assumed that the critical headway is smaller than any accepted headway and greater than any rejected headway. Since drivers will accept all headways greater than their critical headway, this value cannot be measured directly at the observed intersections [1]. Therefore, accepted and rejected headways must be extracted and statistically processed so that they can be used in the calculation of intersection capacity and level of service.

The value of the critical headway depends on objective factors, such as the technical and operational characteristics of vehicles and the geometric features of intersections. However, in addition to objective factors, the value of the critical headway equally depends on the driver's subjective assessment and behavior in such traffic situations. Specifically, drivers on the minor approaches of priority intersections assess the value of the headways in the conflicting major streams and choose the headway they perceive as suitable for performing the minor maneuver. In the case of poor judgment, the driver may impede vehicles in the major stream, and in extreme situations this may lead to conflicts or traffic accidents.

Although the HCM provides recommended headway values that can be used under various conditions, more accurate and precise values of the critical headway can be obtained through field observations that account for the specific local conditions of a given area [2]. In this way, calibration is performed by adapting the input parameters to real traffic conditions at the intersections, ensuring that the theoretical models more accurately reflect actual traffic operations [3]. Due to the inability to directly measure the critical headway at every intersection under analysis, numerous methods and procedures have been developed for its estimation.

METHODOLOGY

For the purposes of this research, it was necessary to conduct measurements of the parameters used to determine the capacity and level of service of unsignalized intersections under real traffic conditions. Such studies are very rare in Bosnia and Herzegovina and the broader region, even though the HCM methodology recommends local measurements as the most reliable approach for defining traffic flow parameter values. For this study, the observation of headways in the major stream was conducted at three unsignalized intersections in Doboj, namely:

- The intersection of Sveti Sava Street, Miloš Obilić Street, King Aleksandar Street, and Vidovdanska Street (marked as I_1 in the paper);
- The intersection of Vasilije Ostroški Street and King Aleksandar Street (I_2);
- The intersection of Vojvoda Stepa Street and King Dragutin Street (I_3).

For the estimation of the critical headway, six different methods were applied, namely: Harders', Logit, Lag, Raff's, Wu's, and the Maximum Likelihood method.

Raff's method

The earliest method for estimating the value of critical headway is based on the research conducted in [4]. 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.

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

Later, Miller [5] 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 [6].

Harders' method

Harders [7] 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 center 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 center 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.

2.3 Maximum likelihood method

The maximum likelihood method for estimating the critical headway was developed in the early 1970s by Miller and Pretty [5, 8]. This method for estimating the critical headway is most accurately explained in [9]. 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 [10]:

- 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:

$$t_c = e^{\mu + 0,5\sigma^2} \tag{2}$$

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

Wu's method

Wu [11] presented a new model for estimating critical headways at unsignalized 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:

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

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:

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

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.

The lag method

This method is based on the lag in the major stream, that is, the time between the arrival of a vehicle in the minor stream and the arrival of a vehicle in the major stream. It assumes homogeneous drivers and independence of minor-stream arrivals from traffic conditions in the major stream [12]. The underlying premise is that the probability of accepting a lag t is equal to the probability that the driver's critical headway is smaller than t, meaning that the critical headway lies between the largest rejected and the accepted lag. Therefore, it can be stated that:

$$P_{a,lag} = F_c(\mathrm{t}) \tag{6}$$

For this method, it is necessary to measure all intervals, both accepted and rejected. A scale of W segments of size Δt (e.g., $\Delta t = 1$ s) is then formed, and for each segment i the following values are analyzed:
N_i = the number of observed lags within the interval i
A_i = the number of accepted lags within the interval i
$a_i = A_i/N_i$

If it is assumed that the value t_1 represents the center of interval i, then:

$$F_c(\mathrm{t}_i) = a_i \tag{7}$$

which represents an approximation of the cumulative distribution function of the critical headways. The mean critical headway in that case is:

$$t_c = \sum_{i=1}^{W} t_i \cdot \left[F_c(\mathrm{t}_i) - \mathrm{F}_c(\mathrm{t}_{i-1}) \right] \tag{8}$$

where W is the number of intervals of size Δt.

Comparative analysis of methods for critical headway estimation

To determine which of the applied methods provides the most realistic estimate of the critical headway, a comparison was made between the measured field capacity values and the theoretical capacity values, i.e., the capacity values obtained based on critical headways calculated using different methods. For the comparative analysis of the mentioned capacity values, the method developed and presented in [13, 14, 15] was applied, which requires determining the values of the field capacity and the conflicting flow rate. For the purpose of defining these two parameters, only headways observed in queues consisting of at least three vehicles were considered. The field capacity is obtained as the ratio between the number of vehicles in the queue and the time elapsed from the moment the first vehicle in the queue reaches the stop line to the moment the last vehicle in the queue reaches the stop line, during which all vehicles in the queue use the same headway in the conflicting stream [14]. During the same observation period, the conflicting flow rate is calculated using *Equation (9)*:

$$\text{Conflicting flow rate} = \frac{\mathrm{n}}{\mathrm{t_n} - \mathrm{t_0}} \tag{9}$$

where:

- n is the number of vehicles in the conflicting stream, including the vehicle that passed immediately after the last vehicle from the queue on the minor approach,
- t_n is the arrival time of the nth vehicle from the conflicting stream in front of the minor approach,
- t_0 is the arrival time of the first vehicle from the queue at the stop line.

On the other hand, for the capacity calculation based on the obtained critical headway values, the model defined in [16] was applied. Afterwards, a scatter plot was created in MATLAB using the values of the field capacity and the conflicting flow rate.

RESEARCH RESULTS

Table 1 presents the calculated critical headway values obtained using the previously mentioned methods.

Critical headway values equal to zero in the table correspond to situations in which the applied method did not produce results. Such cases occur due to an insufficient number of collected observations, i.e., accepted and rejected headways/lags. The primary reason for this issue in the case of the right turn maneuver from the minor approach is that this movement has the smallest number of conflicting streams compared to all other minor maneuvers. In addition, the traffic volume in the conflicting streams for this maneuver was relatively low, allowing most drivers to complete the right turn from the minor approach unimpeded. Therefore, within this comparative analysis of methods, in such cases the critical headway and follow-up headway values recommended in [16] were adjusted to local conditions.

For comparison of the previously mentioned capacity values, it was necessary to determine the field capacity and conflicting flow values based on the procedure described in the Methodology section. When it comes to the observed minor roads at intersections I_1 and

Table 1. Calculated critical headway values at the three unsignalized intersections

Method	Intersection						
	I_1			I_2		I_3	
	Through traffic on minor	Right turn from minor	Left turn from minor	Right turn from minor	Left turn from minor	Right turn from minor	Left turn from minor
Lag	7,20	0,00	8,17	0,00	9,00	6,83	10,66
Harders	6,84	0,00	7,75	6,64	7,23	0,00	7,56
Logit	6,24	0,00	6,83	5,93	7,13	0,00	7,08
Raff	6,22	0,00	7,50	6,15	6,65	6,00	6,85
Wu	6,40	0,00	7,07	6,19	6,01	6,49	6,97
MLM	5,58	4,71	7,12	5,85	6,33	4,27	6,46

Table 2. Adjusted recommended values of critical headway and follow-up headway in the HCM manual

Intersection	Parameters	Through traffic on the minor road	Right turn from the minor road	Left turn from the minor road
I_1	Critical headway	6.53	6.21	7.10
	Follow-up headway	4.03	3.31	3.50
I_2	Critical headway	-	5.54	5.53
	Follow-up headway	-	3.34	3.62
I_3	Critical headway	-	6.23	6.42
	Follow-up headway	-	3.33	3.52

Table 3. Descriptive statistics for the follow-up headway

Intersection	Maneuver	Arithmetic Mean	Standard Deviation	Variance	Minimum	Median	Maximum
I_1	Through traffic on the minor road	3.55	0.90	0.82	2.02	3.34	5.53
	Right turn from the minor road	3.26	0.65	0.43	1.81	3.42	4.57
	Left turn from the minor road	4.18	0.69	0.47	3.69	4.18	4.66
I_2	Left turn from the minor road	3.33	0.87	0.75	1.61	3.13	5.72
	Right turn from the minor road	3.71	0.69	0.47	2.46	3.61	5.48
I_3	Left turn from the minor road	4.26	0.84	0.70	2.58	4.23	6.13
	Right turn from the minor road	3.44	0.74	0.55	2.17	3.52	4.94

I_3, it was impossible to find a sufficient number of waiting queues with at least three vehicles performing the same minor maneuver for the calculation of field capacity and conflicting flow. The main reason for this impossibility is that all minor maneuvers share a single lane at the analyzed minor roads at the intersections. Therefore, for these two intersections, data were extracted for the calculation of field capacity and conflicting flow in situations where at least three vehicles performed the same or different maneuvers to enter the center of the intersection. On the other hand, intersection I_2 has separate minor roads for left and right turns, so it was possible to identify traffic situations where at least three vehicles performed the same movement maneuver to enter the center of the intersection.

For the purposes of calculating the theoretical capacity based on the HCM model, the values of conflicting flows for each maneuver at the observed unsignalized intersections were determined. Additionally, the values of follow-up headways were calculated separately for each maneuver, and are presented in *Table 3.*

Considering the previously described case at intersections I_1 and I_3, which refers to data extraction when at least three vehicles form a queue, the capacity of the shared traffic lane was calculated for these two intersections and used in further analysis. On the other hand, due to the physically separated minor roads at intersection I_2, the capacities for left and right turns from the minor road were calculated separately at this intersection.

Due to the specific geometric characteristics of intersection I_2, modifications were made to the original equation for calculating the capacity of the left turn movement from the minor approach, as defined in [16]. More precisely, the adjustment primarily concerns the exclusion of the left turn flow from the major approach ($2v_4$) from the equation used to calculate the conflicting flow for the left turn from the minor approach. This modification was introduced because vehicles turning left from the major approach use a separate, physically divided lane located in front of the lane used by vehicles turning left from the minor approach. In addition, vehicles turning left from the major approach decelerate before executing the maneuver due to higher priority vehicles approaching from the opposite direction. As a result, vehicles turning left from the minor approach can perform their maneuver unimpeded. The adjusted equation for calculating the capacity of the left turn from the minor approach, adopted as a consequence of neglecting the influence of the left turn from the major approach, is given as $c_{m,7} = c_{p,7}$ (i.e., the movement capacity is equal to the potential capacity).

In MATLAB, a scatter plot was created with points determined by the field capacity values (labeled as Field Q in *Figures 1*, *2*, *3*, and *4*) and conflicting flow values (labeled as CF in *Figures 1*, *2*, *3*, and *4*). In some cases, there were significant variations in the field capacity values, which is quite common in field measurements [14]. For this reason, a smoothing technique based on the moving average method was applied to reduce the variations in the data. In this way, the exponential model was adjusted to the field data and compared with the theoretical capacity values. After applying the aforementioned method, the field capacity values are labeled as Field Qm, while the exponential curve, i.e., the model, is labeled as Fit in *Figures 1, 2, 3,* and *4*.

The values on the *x*-axis represent the conflicting flows determined for each maneuver at the analyzed intersections, while the values on the *y*-axis represent the capacities estimated based on the critical headways obtained using different methods. The best method for calculating the critical headway is the one that yields the theoretical capacity value closest to the field capacity value for the same conflicting flow value.

Based on *Figure 1*, it can be observed that the theoretical capacity value obtained using the Lag method is the closest to the field capacity value at intersection I_1.

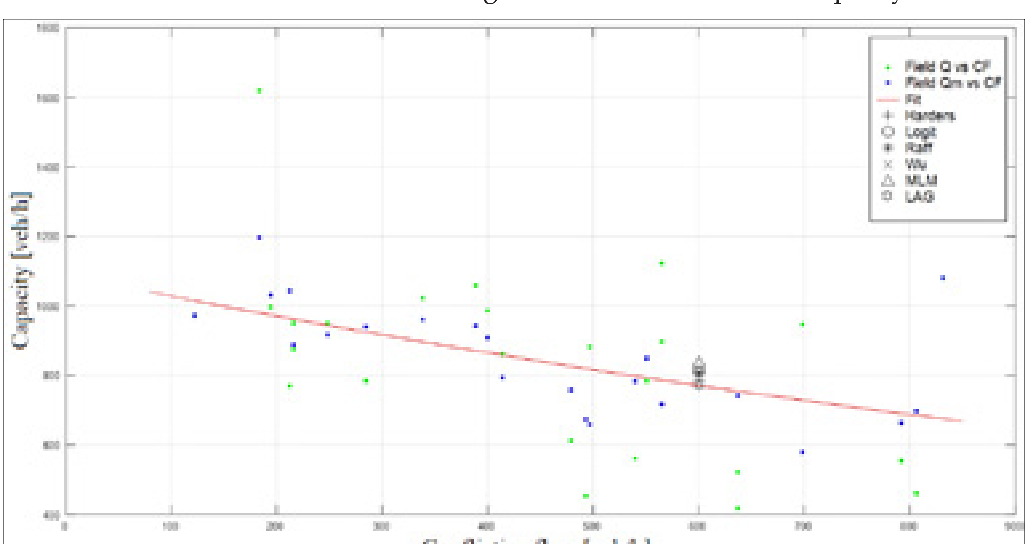

Figure 1. Comparative analysis of methods at intersection I_1

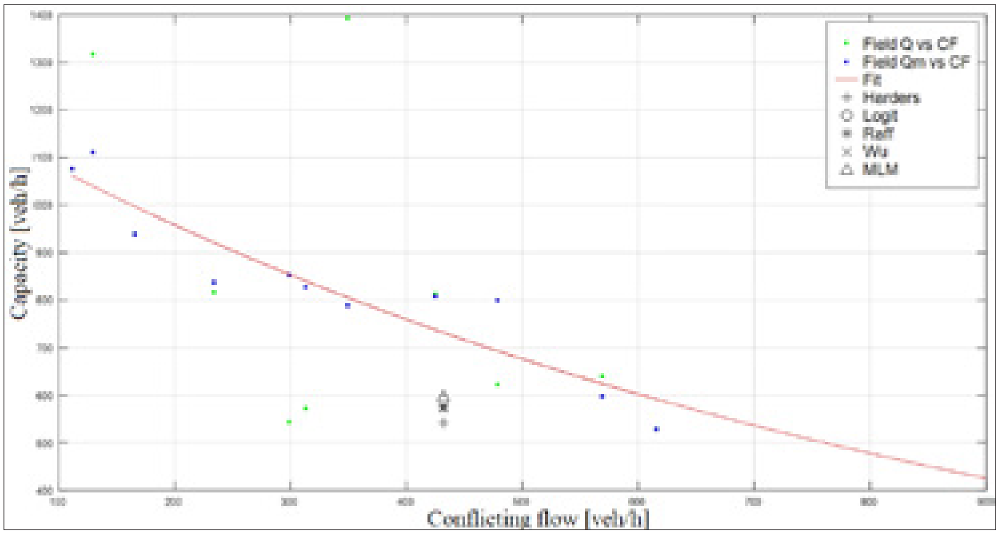

Figure 2. Comparative analysis of methods for right turn from the minor road at intersection I_2

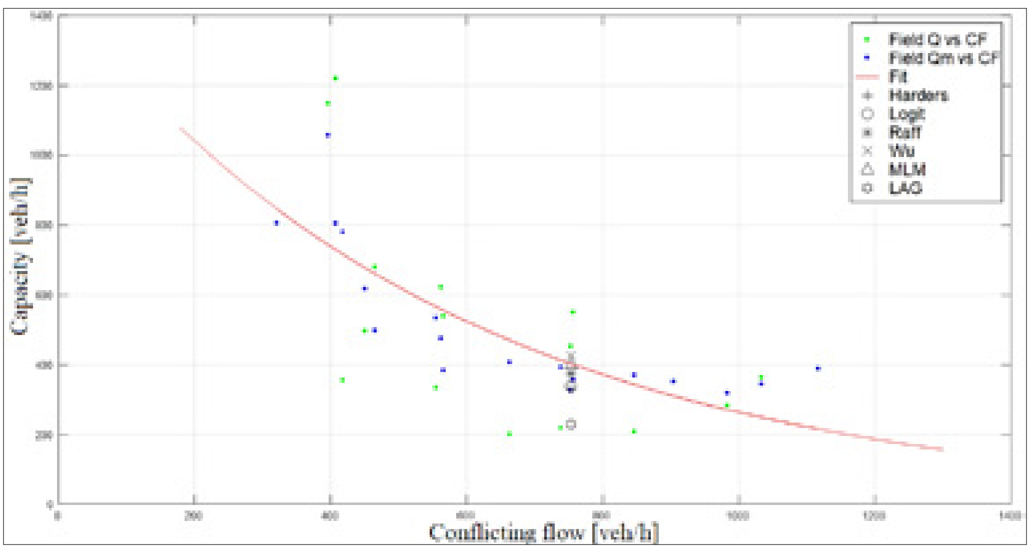

Figure 3. Comparative analysis of methods for left turn from the minor road at intersection I_2

The Lag method showed the best results at intersection I_1, as it is particularly effective in practice for urban four-leg intersections with complex traffic patterns, lacking dedicated turning lanes from the minor roads in the observed case, and featuring high variability in driver behavior caused by a mix of driver types (novice, elderly, professional, etc.).

Figure 2 shows that the theoretical capacity values are quite distant from the exponential model at intersection I_2. The reason lies in the calculated follow-up headway, which is higher than the recommended value due to the specific radius on the road designed for right turns. Since the HCM model, on which the theoretical capacity values are based, does not consider the radius to be one of the influencing factors on capacity, these theoretical capacity values are far from the actual capacity values. Through a comparative analysis of theoretical capacity values calculated in this way, it can be established that the Maximum Likelihood method is the most suitable for right turns from the minor road.

Figure 3 shows that for left turn from the minor road at the same intersection I_2, the Maximum Likelihood method provides the best results. The main reason for this lies in the favorably channeled intersection geometry, the small number of conflicting traffic flows, and the clearly defined movement directions, all of which contribute to stable and consistent driver behavior. These conditions align well with the fundamental assumptions of the Maximum Likelihood method.

Figure 4 shows that the Raff method is the best solution for intersection I_3. Geometric characteristics of this intersection, such as limited visibility, lack of dedicated lanes, and the presence of a “STOP” sign, collectively contribute to high variability in driver behavior, unpredictable decisions, and a greater number of rejected headways. These conditions make the Raff method suitable for calculating the critical headway, as it does not model driver logic but instead relies on actual observed driver behavior.

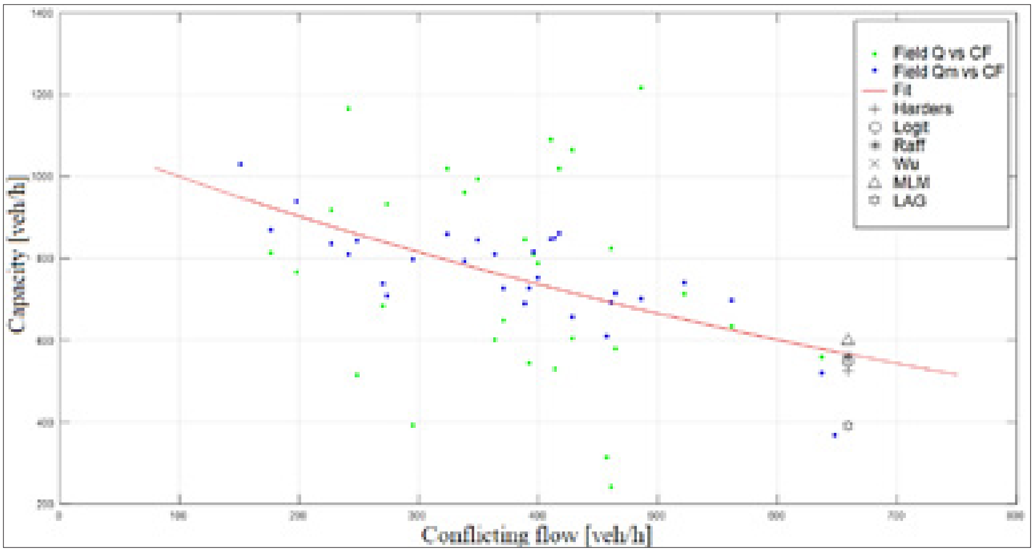

Figure 4. Comparative analysis of methods at intersection I_3

CONCLUSION

Practically all studies have shown that the capacity of unsignalized intersections largely depends on the critical headway. The value of the critical headway is influenced by vehicle characteristics, traffic conditions, and geometric features of the intersection, but also to a great extent by driver behavior. Driver behavior is shaped by numerous factors influenced by local conditions, habits, mentality, and similar influences. To properly analyze performance indicators of unsignalized intersections, it is essential to obtain reliable estimates of the critical headway for each maneuver. Variations in driver behavior therefore have a substantial impact on capacity, level of service, and overall traffic safety. Inaccurately estimated critical headway values for unsignalized intersections may lead to a misleading representation of traffic conditions and the performance of the traffic network.

As a result of the aforementioned variations in critical headway values, applying the same method can lead to differences in the calculated capacity at unsignalized intersections. Therefore, using recommended critical headway values derived for one country may lead to incorrect decisions when applied in another. For this reason, a comparative analysis of six different methods for estimating the critical headway was conducted in this study, with the aim of verifying the theoretically obtained values. The Lag method was the most suitable for intersection I_1, the Maximum Likelihood method was chosen for intersection I_2, while the Raff method was selected for intersection I_3.

Comprehensive research findings indicate an undeniable need for conducting local measurements of key parameters used in the capacity calculation of unsignalized intersections, in order to ensure that the obtained results are more relevant and applicable. It is expected that the research results will, in subsequent steps, initiate further research to be implemented in procedures for calculating capacity and service levels, and also encourage other researchers to conduct similar studies in other local environments.

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